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Escola Tècnica Superior d'Enginyeria
de Telecomunicació de Barcelona

NETWORK DEPLOYMENT STUDIES IN 5G USING ATOLL RADIO PLANNING TOOL

A Master's Thesis

Submitted to the Faculty of the

Escola Tècnica d'Enginyeria de Telecomunicació de Barcelona

Universitat Politècnica de Catalunya

by

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In partial fulfilment

of the requirements for the degree of

MASTER IN TELECOMMUNICATIONS ENGINEERING

Advisor: Anna Umbert Juliana, PhD

Barcelona, January 2021

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Title of the thesis: Network deployment studies in 5G using Atoll radio planning tool.

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Abstract

This thesis is intended to study the deployment of 5G NR in different scenarios or cases using the professional radio planning tool called Atoll. The first case is to improve an existing LTE network in a region of Barcelona by placing it a 5G NR network on top that will improve the performance of the first. In the second case study, it is intended to cover the same region using a 4G/5G network at the same time as carrying out a coverage of a mass concert taking place in a small area of the region.

The results in terms of users rejected by the network have been very satisfactory and in terms of capacity per user have been mostly satisfactory except in two specific services.

In the conclusion, these results are discussed, the limitations of this work are explained and lines of future development are proposed.

Resum

Aquesta tesi té la intenció d'estudiar el desplegament de 5G NR en diferents escenaris o casos utilitzant l'eina de planificació radio professional anomenada Atoll. El primer cas tracta de millorar una xarxa LTE existent a una regió de Barcelona col·locant-hi una xarxa 5G NR superposada que faci que el rendiment de la primera millori. En el segon cas d'estudi s'intentarà fer el cobriment de la mateixa regió utilitzant una xarxa 4G/5G al mateix temps que, també es dona cobertura a un concert multitudinari que s'està duent a terme en una petita àrea de la mateixa.

Els resultats en termes d'usuaris rebutjats per la xarxa han estat molt satisfactoris i en termes de capacitat per usuari han estat majoritàriament satisfactoris excepte en dos serveis en concret.

En la conclusió es discuteixen aquests resultats, s'expliquen les limitacions d'aquest treball i es proposen línies de desenvolupament futur.

Resumen

Esta tesis tiene la intención de estudiar el desarrollo de 5G NR en diferentes casos o escenarios utilizando la herramienta de planificación radio profesional llamada Atoll. El primer caso trata de mejorar una red LTE existente en una región de Barcelona colocando una red 5G NR superpuesta que haga que el rendimiento de la primera mejore. En el segundo caso de estudio se intentará hacer el cubrimiento de la misma región utilizando una red 4G / 5G a la vez que, además, se da cobertura a un concierto multitudinario que se está llevando a cabo en una pequeña área de la misma.

Los resultados en términos de usuarios rechazados por la red han sido muy satisfactorios y en términos de capacidad por usuario han sido mayoritariamente satisfactorios excepto en dos servicios en concreto.

En la conclusión se discuten estos resultados, se explican las limitaciones de este trabajo y se proponen líneas de desarrollo futuro.

Dedication: I would like to dedicate this thesis to my family, my partner and my friends who have always supported me and guided me through the entire career and master. Without them, I could not have achieved it.

Acknowledgements

I would like to thank my supervisor Anna Umbert, who has been very attentive to me and this thesis throughout the course and always dedicated me the time I needed. Also, I am grateful to Juan Manuel Garcia and Sergio Garcia for helping me whenever I encountered an error due to Atoll or its server.

Revision history and approval record

Revision	Date	Purpose
0	10/12/2020	Document creation
1	18/01/2021	Document revision
2	22/01/2021	Document revision
3	26/01/2021	Final document revision

Written by:		Reviewed and approved by:	
Date	25/01/2021	Date	26/01/2021
Name	Marc Mas Ferrer	Name	Anna Umbert Juliana
Position	Project Author	Position	Project Supervisor

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1. Introduction

1.1. Context and motivation

For the last decades, users have been used to have wireless network connection in their smartphones or smartwatches among others. The mobile communications have gone through an evolution, starting from the analogical first generation (1G) which used circuit switched technology passing through the third generation (3G) which introduced packet switching and finally evolving to the most recent fifth generation (5G).

As the mobile communication's users have a constant increase in demand and requirements, the technology is pushed to evolve into the consumers' needs. Nowadays we are observing a great number of new services and applications that we have never seen before such as autonomous driving vehicles, artificial intelligence or remote surgery. To face the new services, the wireless carriers had to be prepared to support a rise of three orders of magnitude in terms of data traffic. To do so, researchers had to find greater capacity in further new wireless spectrum.

The new wireless spectrum requires to have a greater amount of available bandwidth, so the considered spectrum on the 5G New Radio (5G NR) technology will include frequencies known as millimetre-wave. Two types of frequency range are defined in Third-Generation Partnership Project (3GPP) for 5G NR: Sub 6 GHz range is called Frequency Range 1 (FR1) and includes 450 MHz $\leq f \leq$ 6000 MHz and millimetre wave range is called Frequency Range 2 (FR2) and includes 24250 MHz $\leq f \leq$ 52600 MHz. The FR1 comprises channel bandwidths from 5 MHz to 100 MHz and the FR2 from 50 MHz to 400 MHz [1].

Future 5G networks will include multiple technology advances such as massive MIMO, mmWave beam steering, flexible time and frequency intervals, bandwidth parts and mmWave propagation.

Prior to the deployment of any communications system, planning is required. The network planning and optimisation process is crucial for wireless network operators.

Atoll is a commercial multi-technology wireless network design and optimisation software that allows operators to streamline planning and optimisation activities by combining predictions and live network data. Atoll has modular and advanced 5G NR radio technology modelling capabilities, along with the support for mmWave propagation, massive MIMO, and 3D beamforming, provide operators with a flexible and evolutionary framework for the design and deployment of 5G networks.

1.2. Objectives

The aim of this master thesis is to perform, using Atoll, the 5G network deployment in different scenarios such as a concert or event and for daily users. First we want to study an upgrade from a 4G network to a 5G one and second we want to study a 4G/5G deployment in which there will be both macrocells and small cells to cover the event.

More specifically the objectives defined for this thesis are the following:

- To learn how to use the professional Atoll radio planning tool.

- To identify and understand the parameters used by Atoll to model an LTE/5G NR network.
- To choose different case studies to carry out using Atoll and make its corresponding network deployment.
- To test the performance of the network in terms of rejected users and obtained throughput.
- To compare the obtained results with the design requirements and understand why they have been met or not.

1.3. Document structure

This document is divided into five different chapters:

- The first chapter serves as an introduction to the motivation to do this thesis as well as the specific objectives.
- The second chapter is used to give insights on the fundamental concepts of the 5G NR and in some cases explain the difference with its predecessor LTE.
- The third chapter presents Atoll radio planning tool, it explains the key capabilities that allow to understand the development of the thesis.
- The fourth chapter will describe the two network deployments case studies as well as its modelling of the network in terms of traffic and services.
- Finally, in the fifth chapter the conclusions are presented at the same time as suggesting some future development lines.

2. 5G New Radio fundamentals

In this section, the fundamentals of 5G New Radio (5G NR) will be covered. Starting with a brief introduction to 5G NR along with its main use cases and following with the main features of its physical layer and finally by explaining its main procedures [2].

2.1. Introduction to 5G NR

5G NR (New Radio) is the new radio access technology developed by the Third-Generation Partnership Project (3GPP) designed to be the new standard for the air interface of the fifth generation of mobile networks.

5G NR presents many improvements when compared to LTE, the previous radio access technology. Some of the improvements are:

- The operation on higher frequency bands, aiming to use wider transmission bandwidths and, therefore, higher data rates.
- Its ultra-lean design reduces the amount of "always-on" signals, enhances the energy efficiency and reduces the interference.
- The forward compatibility allows 5G NR to prepare for future use cases and technologies by maximizing the time/frequency resources that can be flexibly utilized.
- Latency decrease up to 1 ms.
- Extensive use of beamforming and massive MIMO used for both control and user plane.

2.1.1. 5G NR use cases

In contrast to LTE, 5G presents three main use cases from the beginning:

- enhanced Mobile BroadBand (eMBB): It is the straightforward evolution of mobile networks; it pushes further the network throughput and enhances user experience. It includes services demanding high data rates and high traffic volumes. Human-centric communications
- massive Machine-Type Communications (mMTC): includes a massive number of devices such as various sensors and meters, remote equipment monitoring and so on. Very low energy consumption and small amount of transmitted data, so it does not require high data rates. Machine-centric communications.
- Ultra-Reliable and Low Latency Communications (URLLC): It is partially about machine-to-machine communications focused on high reliability and ultra-low latency. Some services that could be included in this use case are the ones related to traffic safety (V2X), self-driven cars, factory automation or e-health services.

2.2. Physical layer features

In this section, an explanation on the main physical layer features and differences with its predecessor will be made. Firstly, by describing its multiple access technique, following by commenting its time domain and frequency domain structure, its different duplex schemes and finally its multi-antenna transmissions and physical channels along with the reference signals.

2.2.1. Multiple access

OFMDA (Orthogonal Frequency-Division Multiple Access) is the multiple access technique used in both the uplink and the downlink of the 5G NR. In the UL there is the possibility to use a DFT-precoded OFDMA technique as SC-FDMA, however, this is not mandatory as in LTE as it is beneficial to maintain symmetry between the DL and the UL.

In 5G NR there is support for the so-called numerologies, which are different subcarrier spacings (Δf). Each numerology carries a different symbol duration and cyclic prefix:

Subcarrier spacing (Δf)	Symbol duration	Cyclic prefix
15 kHz	66.67 µs	4.69 µs
30 kHz	33.33 µs	2.34 µs
60 kHz	16.67 µs	1.17 µs
120 kHz	8.33 µs	0.59 µs
240 kHz	4.17 µs	0.29 µs

Table 1. 5G NR numerologies.

For low frequencies, low values of Δf (15 kHz, 30 kHz and 60 kHz) are better because they allow a longer cyclic prefix which is better to counter the larger delay spread of the bigger cells. However, at high frequencies, high values of Δf (60 kHz, 120 kHz and 240 kHz) come in handy to counter frequency errors and phase noise. Usually, the delay spread is not a problem because the higher frequencies are used in smaller cells.

A recurrent concept in 5G is the Resource Element (RE), which refers to one subcarrier in the frequency domain (Δf) and one symbol duration in the time domain. Also, Resource Blocks (RB) which refer to 12 consecutive subcarriers in the frequency domain. As both depend on Δf, both depend on the numerology.

2.2.2. Time domain structure

The frames in 5G NR comprise 10 ms, each one is split into 10 subframes of 1 ms. Each subframe has one or multiple slots depending on the numerology as 1 slot includes 14 OFDMA symbols.

A schematic representation of the time relations between frames, subframes and slots is shown below.

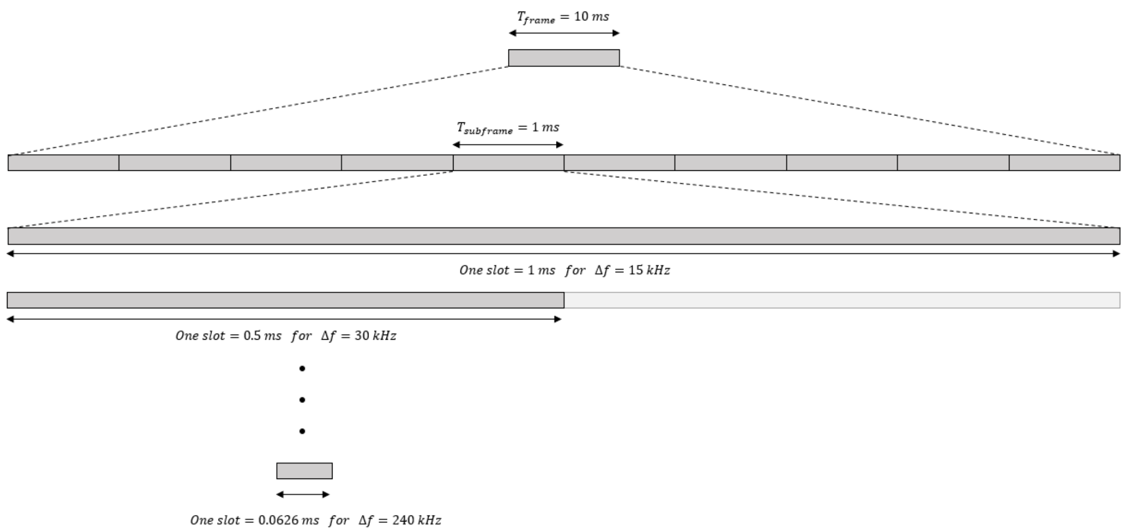


Figure 1. Time structure in 5G NR frames.

2.2.3. Frequency domain structure

5G NR is designed to operate in several bands which, as explained in the thesis introduction, can be separated into two Frequency Ranges (FR). These bands along with their respective frequency ranges and duplex mode are listed in the table below.

NR operating band	Uplink (UL) operating band	Downlink (DL) operating band	Duplex Mode
n1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
n2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
n3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
n5	824 MHz – 849 MHz	869 MHz – 894 MHz	FDD
n7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
n8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
n12	699 MHz – 716 MHz	729 MHz – 746 MHz	FDD
n20	832 MHz – 862 MHz	791 MHz – 821 MHz	FDD
n25	1850 MHz – 1915 MHz	1930 MHz – 1995 MHz	FDD
n28	703 MHz – 748 MHz	758 MHz – 803 MHz	FDD
n34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD
n38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
n39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD
n40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD
n41	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	TDD
n50	1432 MHz – 1517 MHz	1432 MHz – 1517 MHz	TDD1
n51	1427 MHz – 1432 MHz	1427 MHz – 1432 MHz	TDD
n66	1710 MHz – 1780 MHz	2110 MHz – 2200 MHz	FDD
n70	1695 MHz – 1710 MHz	1995 MHz – 2020 MHz	FDD
n71	663 MHz – 698 MHz	617 MHz – 652 MHz	FDD
n74	1427 MHz – 1470 MHz	1475 MHz – 1518 MHz	FDD
n75	N/A	1432 MHz – 1517 MHz	SDL
n76	N/A	1427 MHz – 1432 MHz	SDL
n77	3300 MHz – 4200 MHz	3300 MHz – 4200 MHz	TDD
n78	3300 MHz – 3800 MHz	3300 MHz – 3800 MHz	TDD
n79	4400 MHz – 5000 MHz	4400 MHz – 5000 MHz	TDD
n80	1710 MHz – 1785 MHz	N/A	SUL
n81	880 MHz – 915 MHz	N/A	SUL
n82	832 MHz – 862 MHz	N/A	SUL
n83	703 MHz – 748 MHz	N/A	SUL
n84	1920 MHz – 1980 MHz	N/A	SUL
n86	1710 MHz – 1780MHz	N/A	SUL
n257	26500 MHz – 29500 MHz	26500 MHz – 29500 MHz	TDD
n258	24250 MHz – 27500 MHz	24250 MHz – 27500 MHz	TDD
n260	37000 MHz – 40000 MHz	37000 MHz – 40000 MHz	TDD
n261	27500 MHz – 28350 MHz	27500 MHz – 28350 MHz	TDD

Table 2. 5G NR operating bands.

The first frequency range (FR1) comprises frequencies starting at 450 MHz and ending at 6000 MHz, and the second one (FR2) starts at 24.25 GHz and finishes at 52.6 GHz. In the FR1, the allowed numerologies are the ones corresponding to Δf = 15 kHz, 30 kHz and 60 kHz, as to the FR2, the allowed numerologies are the ones corresponding to Δf = 60 kHz, 120 kHz and 240 kHz.

As the maximum channel bandwidth in LTE is 20 MHz, it is assumed that any User Equipment (UE) can support it. However, in 5G NR, the maximum available bandwidth is 400 MHz in case of the mmWave bands so that assumption cannot be made anymore as there are devices that use much less bandwidth (IoT devices) and also the use of a 400 MHz channel causes a big energy consumption.

To solve this problem, 5G NR introduced the so-called BandWidth Parts (BWPs) which allow some UEs to operate in a portion of the channel. Each UE is able to be configured with up to 4 BWPs in the UL and 4 in the DL in a cell, however, only one of the four can be active at the same time. As in LTE, there is the possibility to use Carrier Aggregation (CA) which allows a UE to transmit or receive using multiple Component Carriers at the same time and, therefore, increasing the total bandwidth. In total, 16 carriers can be aggregated forming a maximum bandwidth of $16 \cdot 400\ MHz = 6.4\ GHz$. One of the carriers is the primary cell and the other ones are secondary cells.

2.2.4. Duplex schemes

5G NR presents a great flexibility in terms of duplex schemes. In LTE, a different frame structure is used in FDD and TDD, however, in 5G NR only one structure is used and relies on Dynamic TDD in which a slot (or parts of a slot) can be dynamically allocated to DL or UL in the scheduling process.

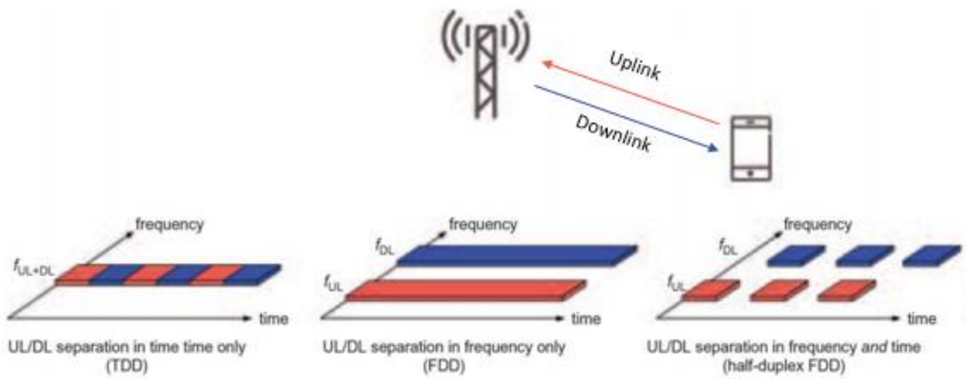


Figure 2. Duplex schemes operating modes.

The Dynamic TDD mode is very useful in small cells with dense deployments, as the number of UEs in a cell is reduced and dynamic TDD facilitates tracking the rapid traffic variations. Also, it is easy to coordinate the interference due to scheduling decisions because the transmit powers of the UEs and the cell ones are of the same order.

However, in macrocells it is recommended to use either FDD or static TDD to avoid the Base Station-to-Base Station interference that occurs when one is operating in UL and another one is operating in DL nearby.

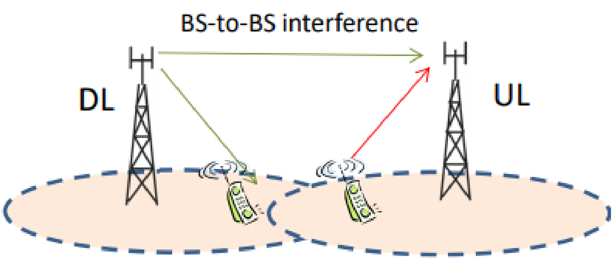


Figure 3. Graphical representation of BS-to-BS interference.

2.2.5. Multi-antenna transmission

Multi-antenna transmission is a key feature in 5G NR, especially in the operation at mmWave frequencies. It supports massive MIMO with up to hundreds of antenna elements separated by a small distance (as the operation frequencies are high).

In low frequencies (FR1), as the propagation conditions are better but the bandwidth is smaller (up to 100 MHz), MIMO can exploit spatial multiplexing, transmitting several layers of information in parallel in order to increase capacity (up to 8 layers per UE in single-user MIMO).

However, in higher frequencies (FR2), the situation is very different as the propagation conditions are much worse but the capacity is not a problem due to the very high bandwidth (up to 400 MHz). Then, MIMO can exploit beamforming to increase substantially the directivity and compensate for the higher propagation losses.

Multi-antenna transmission assumes a linear transformation W applied to the N_L layers to determine how the information is mapped onto each antenna element $y_{1,2,\dots,N_T}$. This model admits three different implementations depending on where the matrix W is applied: analog, digital or hybrid implementation.

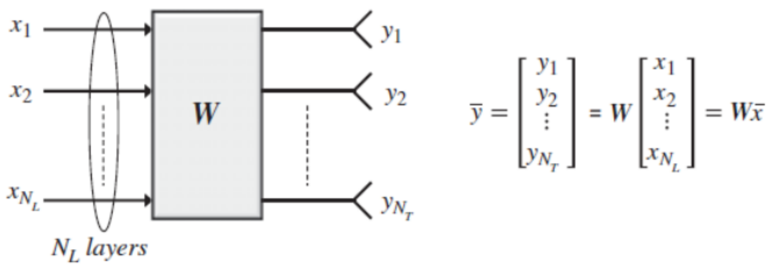


Figure 4. Multi-antenna transmission transformation and mapping scheme.

In the analog implementation, matrix W is applied after the Digital to Analog Converter (one DAC in each layer) and it is especially useful at high frequencies (FR2) where the number of antennas is large. The processing involves per-antenna phase shifts which allow analog beamforming which at the same time enables the compensation of high propagation losses.

Analog beamforming implies that beams to UEs located in different directions have to be transmitted separated in time.

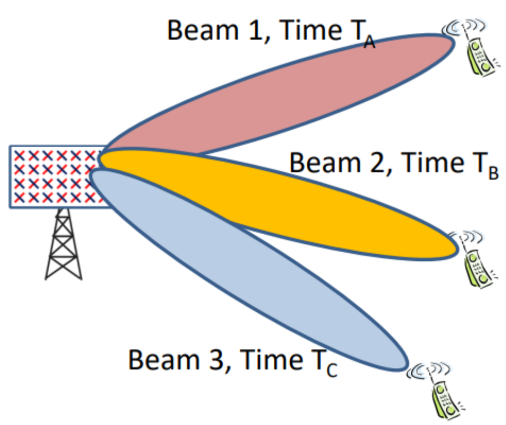


Figure 5. Representation of analog beamforming.

In the digital implementation, the DAC is applied after the processing. It is difficult to be implemented at high frequencies, it is very useful at lower frequencies (FR1). The pre-coding matrix W allows the control of gain and phase which enables spatial multiplexing (transmission using several layers with the same frequency resources) and digital beamforming (transmission using a single layer with the aim of maximizing the useful signal at the receiver and trying to reduce the interference).

The digital beamforming allows transmitting to different users at the same time using different frequency resources, it provides more flexibility than analog beamforming but it is not feasible for hundreds of antenna elements.

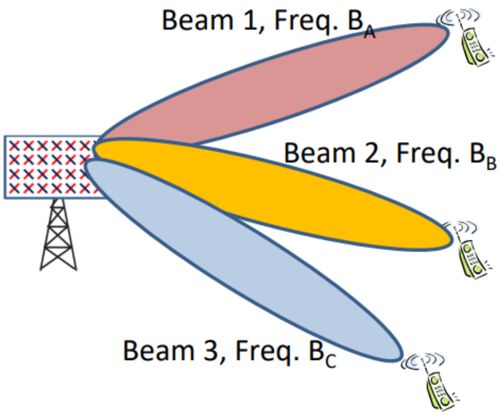


Figure 6. Representation of digital beamforming.

2.2.6. Physical channels and reference signals

5G NR architecture is divided into the user plane and the control plane. The user plane takes care of the user data and the control plane is in charge of connection setup, mobility and security.

The user plane can be divided into layers, these layers being: the physical layer (PHY), the medium access control layer (MAC), the radio link control layer (RLC), the packet data convergence protocol layer (PDCP) and the service data adaption protocol layer (SDAP).

The time and frequency resources that carry information from higher layers than the PHY are called physical channels. These are the ones listed below:

- Physical Downlink Shared Channel (PDSCH): It is the main channel used for transmitting downlink unicast data and it can also be used to transmit paging information.
- Physical Broadcast Channel (PBCH): carries system information that must be used by the devices to be able to access the network.
- Physical Downlink Control Channel (PDCCH): It is used to transport the downlink control information as scheduling decisions.
- Physical Uplink Shared Channel (PUSCH): is the uplink counterpart to the PDSCH.
- Physical Uplink Control Channel (PUCCH): used by the device to send acknowledgements, to send channel-state reports and to request resources to transmit uplink data.

- Physical Random-Access Channel (PRACH): used by the UE to request connection setup referred to as random access.

Each channel supports different modulations and coding schemes which are listed in the table below.

Physical channel	Modulation	Channel coding
PDSCH	QPSK, 16QAM, 64QAM, 256QAM	LDPC (Low Density Parity Check) coding
PBCH	QPSK	Polar coding
PDCCH	QPSK	Polar coding
PUSCH	QPSK, 16QAM, 64QAM, 256QAM	LDPC coding for data
PUCCH	pi/2-BPSK, BPSK, QPSK depending on PUCCH format and information bit size	Depends on the UCI size
PRACH	N/A	N/A

Table 3. Modulation and channel coding for each channel.

The DL and UL transmissions between the UEs and the RAN works as described next.

In the DL, the UE monitors de PDCCH once per slot until it detects a valid PDCCH. Then, the UE receives a unit of data on the PDSCH according to the scheduling decision of the gNB (the RAN node). Finally, the UE responds with a hybrid ARQ acknowledgement to indicate if the data was successfully decoded or not.

In the UL, the UE requests over the PUCCH its scheduling to transmit data to the gNB. The gNB sends its response over the PDCCH with its scheduling in which it gives permission to the UE to use certain resources. Then, following this scheduling, the UE transmits its data over the PUSCH and when the data is received in the gNB, responds with a hybrid ARQ acknowledgement to indicate if the data was successfully decoded or not.

Reference signals (RS) can have different functionalities such as channel estimation, coherent demodulation among others. In the downlink, LTE only uses one RS to cover all the different functions and also the RS are always-on. However, in 5G NR there are multiple RS to cover different purposes and they are only transmitted when needed.

The Reference signals in 5G NR are the following:

- DeModulation Reference Signals (DM-RS): supports channel estimation as part of coherent demodulation.
- Phase-tracking Reference Signals (PT-RS): supports the compensation of the phase noise generated by the oscillators.
- Channel State Information Reference Signals (CSI-RS): Used by the UE in the downlink to determine channel state.
- Sounding Reference Signals (SRS): UL reference signals used for uplink channel estimation.

- Tracking Reference Signals (TRS): Non-recurring reference signals used to assist the device in time and frequency tracking.

The different RSs are mapped onto some resource elements of the resource grid of each antenna port.

2.3. Procedures

In this section, some key procedures in 5G NR will be briefly explained. That is to say, the cell search, the random access and the scheduling procedures.

2.3.1. Cell search

This paragraph will cover the functions and procedures used by a UE to find new cells when it enters the system and also continuously when moving within it.

The whole cell search procedure is based on the detection of the Synchronization Signal Block (SSB) sent by each cell. This SSB is composed by a Primary Synchronization Sequence (PSS), a Secondary Synchronization Sequence (SSS) and a Physical Broadcast CHannel (PBCH).

First, the UE will search for the PSS, which provides synchronization up to the periodicity of the SSB and then it will search for the SSS which determines the Physical Cell Identifier (PCI). The PBCH carries the Master Information Block with the minimum information needed to obtain the rest of broadcast info through the PDSCH.

The SSB can be located in specific frequencies within each band, the UE just has to look for these to find the SSB which will include the information regarding its relative position in the channel bandwidth.

2.3.2. Random access

The Random Access (RA) process is used by a UE to make its initial access to the network when it is in idle mode or inactive. The process is described as it follows.

A UE selects a Random Access Preamble and transmits it to the gNB, then the gNB sends a RA response through the PDCCH. The UE sends uplink scheduling information over the PUSCH and a contention resolution timer of 4 ms starts. If the contention resolution timer expires, the UE considers the contention resolution failed and it has to perform RA again.

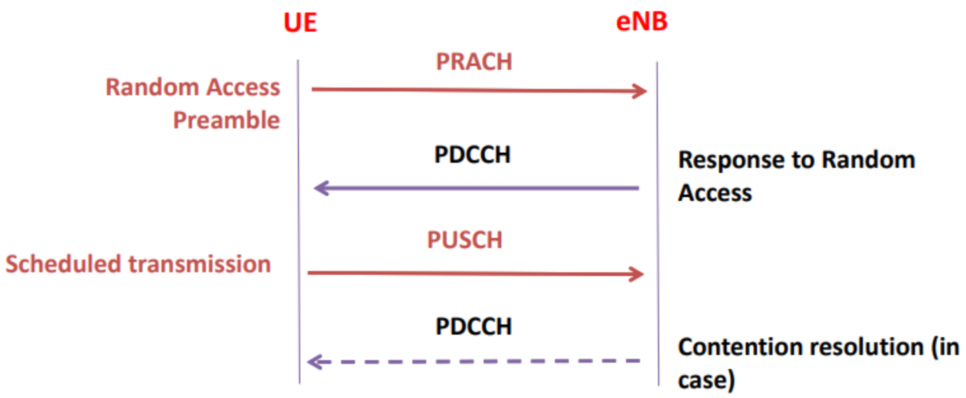


Figure 7. Random access procedure scheme.

2.3.3. Scheduling

The scheduling procedure aims to determine the time, frequency and spatial resources to be assigned to each UE and the transmission parameters to use. 5G NR does not standardize the scheduling algorithm but it provides supporting mechanisms for vendor-specific scheduling strategies.

5G NR supports dynamic scheduling in which the scheduler determines which UEs transmit or receive every Transmission Time Interval (TTI) and semi-static scheduling in which the transmission parameters are provided to the UE a priori and not in a dynamic basis.

5G NR presents some different aspects in this procedure with respect to the one in LTE, these are:

- The possibility to prioritize the urgent data. This is specifically used in services that require very low delay and high priority. Urgent transmissions can pre-empt some symbols of an already ongoing transmission.
- Dynamic TDD, in which needs coordination between cells to avoid interference and the scheduling has to decide if the transmission is UL or DL.
- Bandwidth adaptation, in which the scheduling has to take into consideration the BWP used by each UE.

3. Atoll radio planning tool

Atoll is a product by the company Forsk which provides a multi-technology wireless network design and optimisation software that helps wireless operators though the process of network lifecycle from the design to the optimisation. It supports multiple technologies including 5G NR, LTE, NB-IoT, UMTS, GSM and CDMA and the latest advances as massive MIMO, 3D beamforming and mmWave propagation.

In this section, the key Atoll features and parameters will be presented and explained in order to be able to have a better understanding of the network deployment that follows at section 4.

3.1. General configuration parameters

To design the network, Atoll presents the possibility to model several parameters along with equipment. In this configuration, there are three main layers to take into consideration, the sites configuration, the transmitters configuration and equipment and finally the cells configuration.

The site is the point where the Base Station (BS) and the transmitters are located and it has a few configurable parameters as the name of the site, its x/y position and the altitude.

The configuration capabilities of the transmitters are larger than the sites. Firstly, in the general tab, the name, the belonging site, the frequency band and the antenna position.

In the transmitter tab, in the transmission/reception section the transmission and reception losses due to the Tower-Mounted Amplifier (TMA), the feeder cables and the transmitter equipment can be configured.

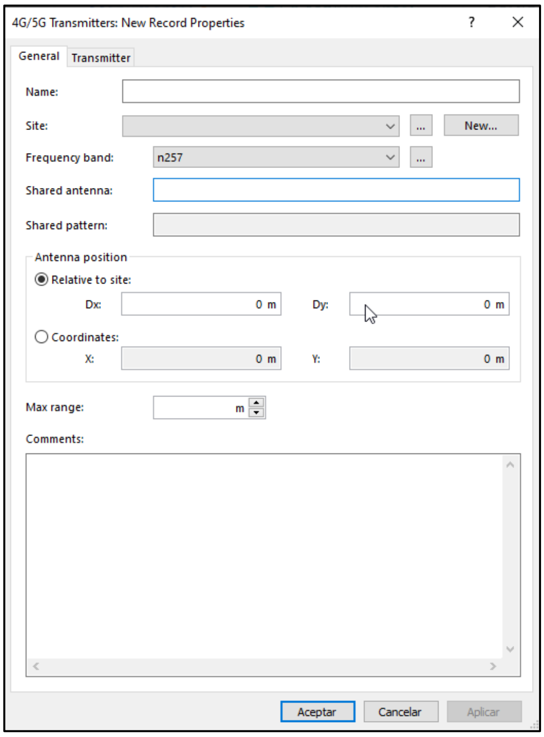


Figure 8. New transmitter's general tab.

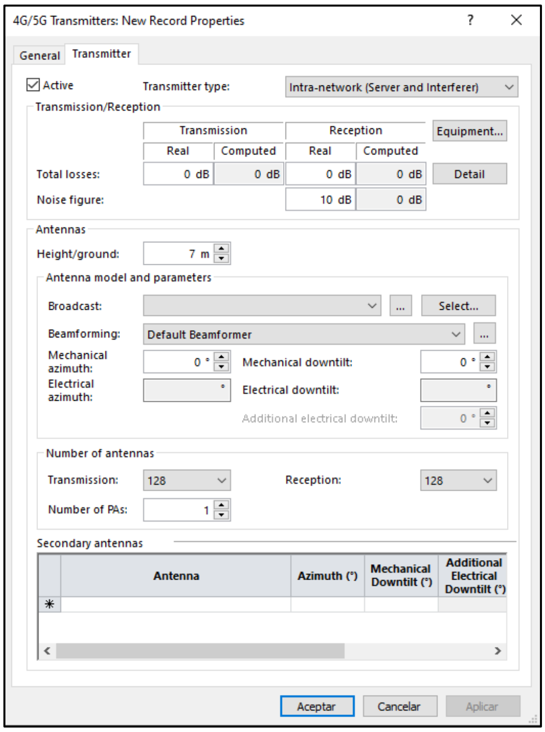


Figure 9. New transmitter's transmitter tab

Then, in the antennas section either a broadcast antenna or a beamforming antenna can be selected. If both a broadcast antenna and a beamforming antenna are defined, only the broadcast antenna is considered for path loss calculation. The height of the antenna can also be configured along with the number of antennas and the mechanical azimuth and downtilt.

As to the cell's configuration, there are lots of possibilities to configure. First of all, in each transmitter, one or more cells of different technologies can be defined. Then, in each cell, there are a lot of configuration capabilities, the key ones are listed below [3].

- **Name**: By default, Atoll names the cell after its transmitter, adding a suffix in parentheses.
- **Carrier**: The carrier of the cell in the frequency band.
- **Physical Cell ID**: The physical cell ID, or PCI, of the cell. It is an integer value from 0 to 1007.
- **Max Power (dBm)**: The cell's maximum transmission power.
- **Layer**: The network layer to which the cell belongs. This information is used in determining the serving cell.
- **Cell Type**: This indicates whether the cell is configured as primary PCell, a secondary SCell (UL), or a secondary SCell (DL).
- **Cell Individual Offset (dB)**: Specify the cell individual offset (CIO) to use for cell selection. The CIO is used in 5G NR networks in order to tune or bias the ranking of potential servers for cell selection in connected mode.
- **Cell Selection Threshold (dB)**: You can define the cell selection threshold to use for cell selection based on layer priority. The cell selection threshold is used in 5G NR networks in order to adjust the Min SS-RSRP threshold of cells belonging to different priority layers.
- **SS/PBCH Numerology**: The numerology used by the cell for SS/PBCH.
- **Traffic Numerology**: The numerology used by the cell for traffic channels (PDCCH, PDSCH and PUSCH).
- **Diversity Support (DL)**: The type of antenna diversity technique (none, transmit diversity, SU-MIMO, MU-MIMO) supported by the cell in downlink.
- **Diversity Support (UL)**: The type of antenna diversity technique (none, receive diversity, SU-MIMO. And MU-MIMO) supported by the cell in uplink.
- **Number of MU-MIMO Users (DL)**: The average number of MU-MIMO users that share the same resources on the downlink.
- **Number of MU-MIMO Users (UL)**: The average number of MU-MIMO users that share the same resources on the uplink.
- **Number of Users (DL)**: The number of users connected to the cell in the downlink.
- **Number of Users (UL)**: The number of users connected to the cell in the uplink.
- **Traffic Load (DL) (%)**: The downlink traffic load percentage.
- **Traffic Load (UL) (%)**: The uplink traffic load percentage.
- **Max Traffic Load (DL) (%)**: The downlink traffic load not to be exceeded.
- **Max Traffic Load (UL) (%)**: The uplink traffic load not to be exceeded.
- **PRACH RSIs**: The logical PRACH root sequences allocated to the cell.
- **Neighbours**: You can access a dialog box in which you can set both intra-technology and inter-technology neighbours by clicking the Browse button.

3.2. Aster propagation model

Atoll allows the possibility to use several propagation models, each one of them is suited for one or more specific conditions and frequency bands.

In the case of this thesis, the chosen propagation model is the Aster propagation model as it is optimised for urban areas (it can also be used for suburban and rural areas) and it is comprised in the frequencies from 150 MHz up to 5 GHz (the standard Aster propagation model) and in the frequencies from 5 GHz to 60 GHz (the mmWave Aster propagation model).

Aster requires geographical data to maximize the accuracy of the propagation model, so it needs a Digital Terrain Model (DTM) and a Above Surface Object Digital Model (clutter heights and/or clutter classes). Actually, the DTM and the ASODM are required by Atoll to work in any propagation model. It is important that the ASODM type and height are accurate in order to represent buildings and vegetation that create obstruction as well as the open areas where the signal can propagate freely.

The values from clutter class layers and vector files must be mapped to the available Aster propagation classes, which are listed in the tables below.

Propagation Class	Description	Calculation
Open	All open areas, streets, squares, flat parks, etc.	Open space, radio signals propagate freely.
Water	Sea, rivers, lakes, etc.	
Elevated Open	Elevated areas.	Filled obstruction area for radio signals. Reception done on top.
Trees	Trees, forests, etc.	Deterministic vegetation. Radio signals can go through with some loss, and are also diffracted and diffused.
Building type 1 Building type 2 Building type 3	Three types of buildings are defined to model different propagation effects.	Deterministic buildings that create an obstruction on which radio signals reflect and diffract. Radio signal levels are not calculated in a direct way but interpolated from signal levels in surrounding open areas.
Bridge	Bridges, highways, etc.	Radio propagation is calculated on top of bridges. Radio signals can propagate below bridges.

Table 4. Deterministic propagation classes.

Propagation Class	Description	Calculation
Mixed Vegetation	Parks or areas with a mixture of trees and open areas	Radio signals can go through with some loss and diffract vertically. The clearance area is considered at the receiver location and reception is done at ground level.
Sparse Buildup	Sparse building areas with a mixture of buildings and open areas.	
Dense Buildup	Dense building areas with a mixture of buildings and open areas.	

Table 5. Statistical propagation classes.

Then the data from the clutter classes is mapped to the propagation classes of the Aster propagation model as seen in the tab below.

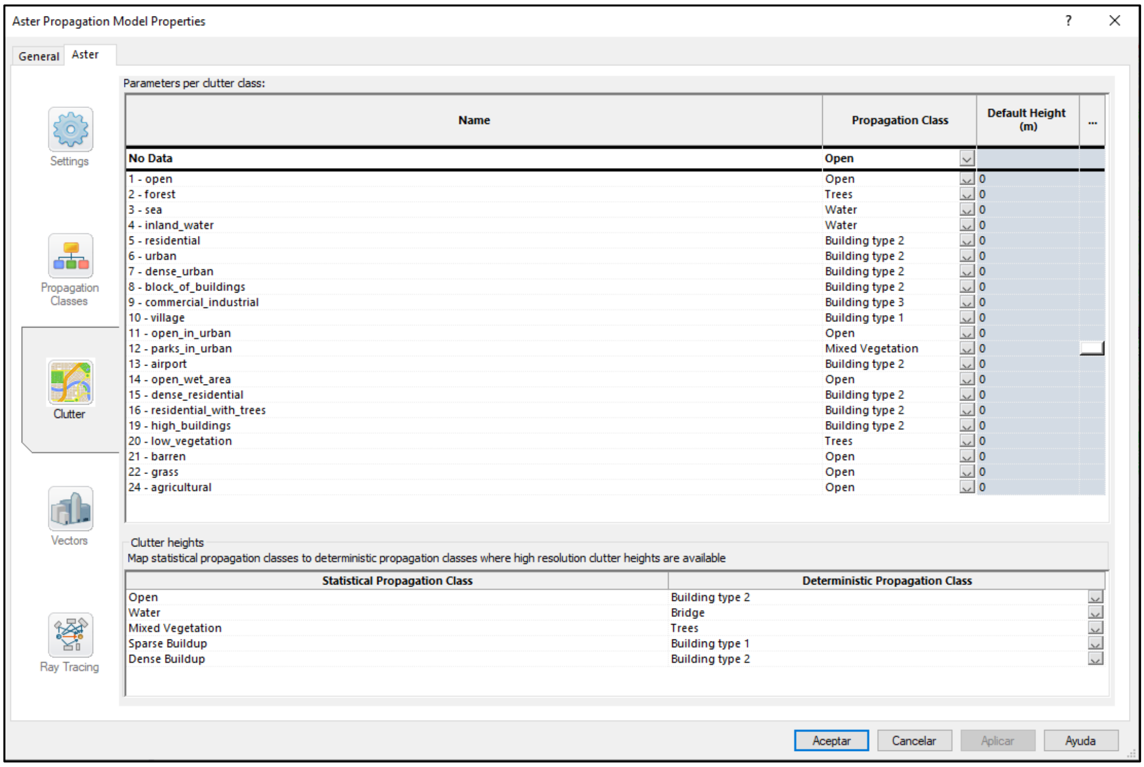


Figure 10. Mapping between clutter classes and propagation classes.

In the Settings tab, Aster also enables the possibility to take into consideration the indoor losses. When the indoor calculation is enabled, there are two different options: either to apply indoor losses or not to apply them.

When the indoor losses are applied, Aster will model the indoor losses by the sum of a penetration loss plus a linear loss applied from the building facade. If this option is set to "No", Aster will interpolate the signal levels from the surrounding streets or open areas when the "Building Type X" propagation class is the one to be applied.

3.3. Traffic parameters

When it comes to the traffic of the network, several parameters can be taken into account to make the simulations and predictions as accurate as possible.

Firstly, Atoll offers the possibility to define services. Services such as voice, mobile internet access among others can be either circuit-switched (voice) or packet-switched (data) depending on the radio access technology and the type of application.

In the new service window, there are many parameters to be configured to define the service. First of all, the type of service can be configured as voice, data or broadband, and for each one the supported technologies can be selected.

Both in the DL and in the UL, the average requested throughput along with the minimum and the maximum can be defined. Also, the lowest and highest modulation and coding rates.

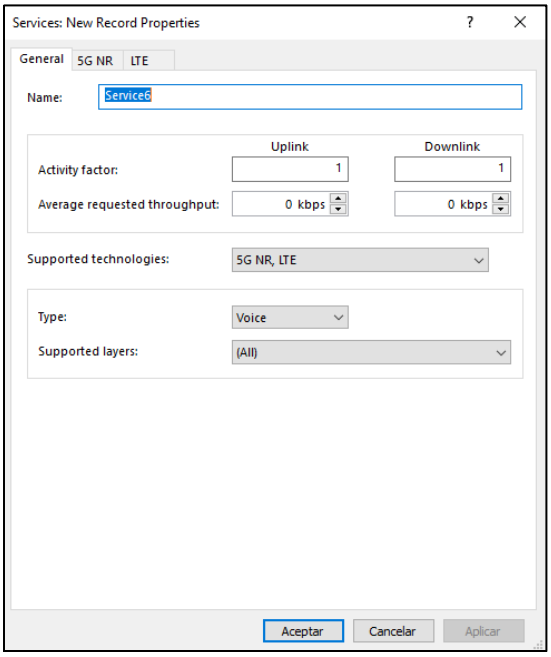


Figure 11. General tab of a new service.

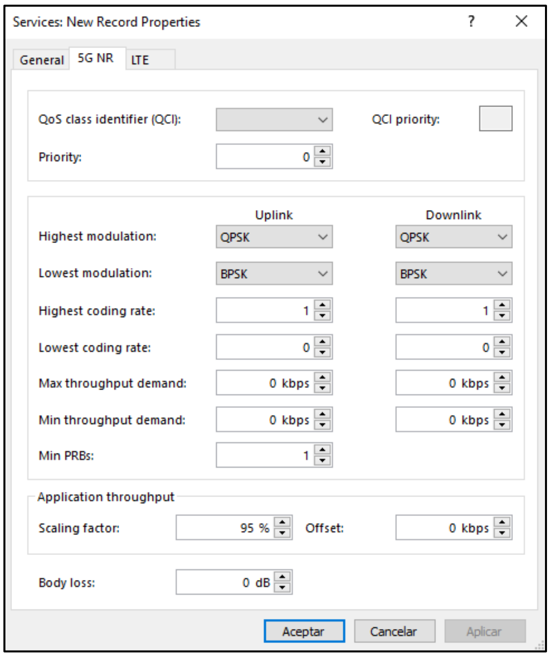


Figure 12. 5G NR tab of a new service.

After defining the services, the next step is to assign the services to types of users by creating different user profiles. To create a user in Atoll, the terminal, the calls per hour and the duration or the UL and DL volume are needed.

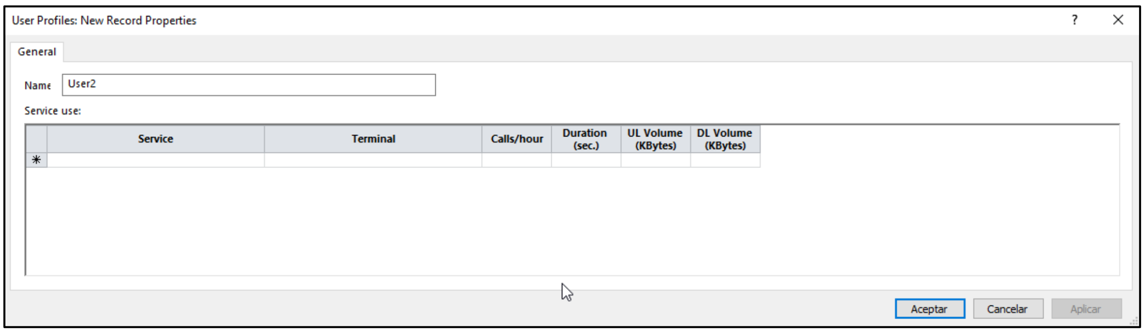


Figure 13. General tab of a new user.

In the terminal column, the type of terminal can be selected (5G terminal, 4G terminal…). In the calls/hour column, it can be determined how many requests does the user make every hour (e.g., how many calls per hour does a user make on a voice service?). In the duration column, if the service is of the type “voice”, the duration of each call has to be configured. Finally, if it is a data service, the UL and DL volume for each call has to be determined.

Then, we must define different environments that determine the density of subscribers of a given user profile and with a given mobility. For instance, in the residential area, the configuration of the number of users and their type is shown below.

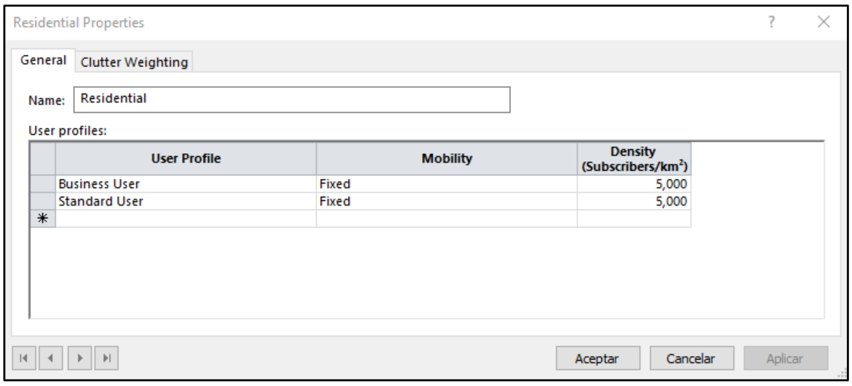


Figure 14. Residential environment.

The only thing left to be modelled in the traffic sense is the place where the users will be located within the map. To do this, a traffic map will be needed. A traffic map along with the environment parameters determines how many users and which type of user will be located in a specific place.

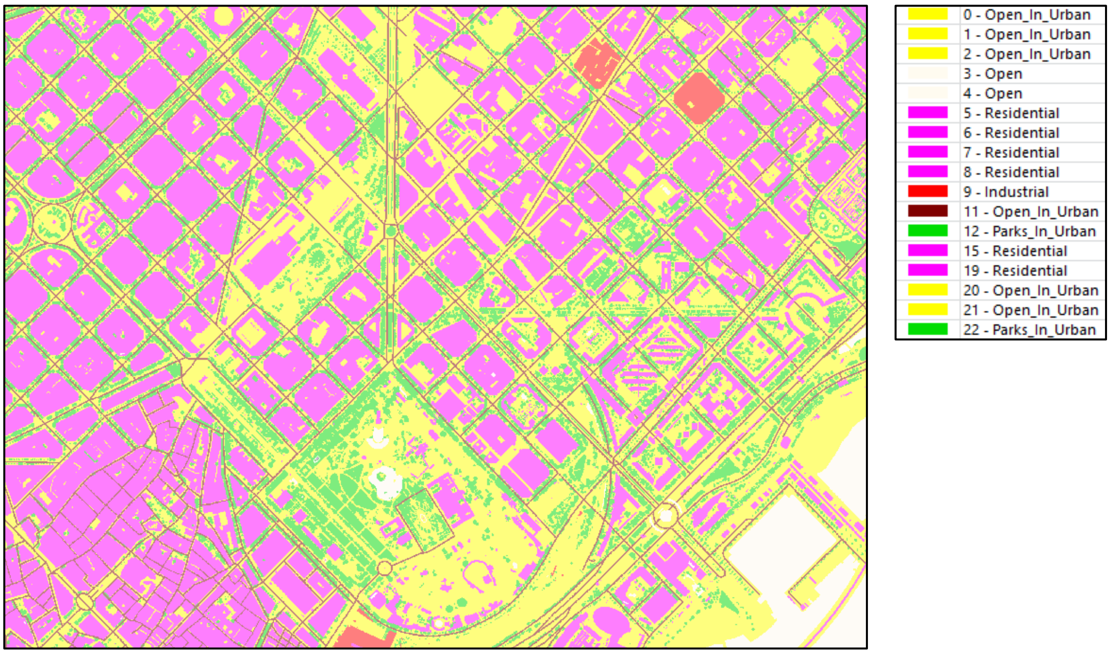


Figure 15. Traffic map in Ciutadella, Barcelona.

3.4. Predictions and simulations

Atoll allows to make different types of coverage predictions in order to analyse the signal levels, the signal quality and the network capacity. Atoll determines the serving cell for each pixel using the standard cell selection mechanism. Then, depending on the prediction definition, it calculates the required effective signal or parameter. Pixels are coloured if the display threshold condition is fulfilled.

Following next, a brief summary of these predictions is made:

- **UL and DL network coverage prediction**: predicts the effective signal levels of different types of signals in the part of the network being studied. These predictions can also be used to predict the best servers and cell-edge areas for these servers.
- **UL and DL network quality prediction**: predicts the interference levels and signal-to-interference levels in the part of the network being studied. Depending on the prediction definition, it calculates the interference from other cells, and finally calculates the C/(I+N).
  - In the DL, C/(I+N) is calculated for different channels using their respective transmission powers and by calculating the interference received by the resource elements that correspond to those channels from interfering cells.
  - In the UL, C/(I+N) is calculated using the terminal power calculated after power control and the uplink noise rise values stored either in the cell properties or in the selected simulation results.
- **UL and DL service areas prediction**: calculates and displays the bearers based on C⁄(I+N) for each pixel. In coverage predictions, the downlink or uplink service areas are limited by the bearer selection thresholds of the highest and lowest bearers of the selected service.
- **UL and DL network capacity prediction**: calculates and displays the channel throughputs and cell capacities based on C⁄(I+N) and bearer calculations for each pixel. These coverage predictions can also display cumulated cell throughputs if Monte Carlo simulation results are available.

To have better insights on the network's capacity, Atoll is also capable of making network simulations, these take into account the modelled network services and user distributions of the traffic maps.

The simulation process consists of several steps:

1. Obtaining a realistic user distribution based on traffic maps and weighted by a Poisson distribution.
2. Technology selection: for each mobile generated, Atoll searches for its serving cell in each technology.
3. Modelling network regulation mechanisms: Regulation mechanisms are modelled according to the technologies used in the network.

In case of a 4G/5G network, Atoll manages the 4G/5G resources as depicted in the following scheme.

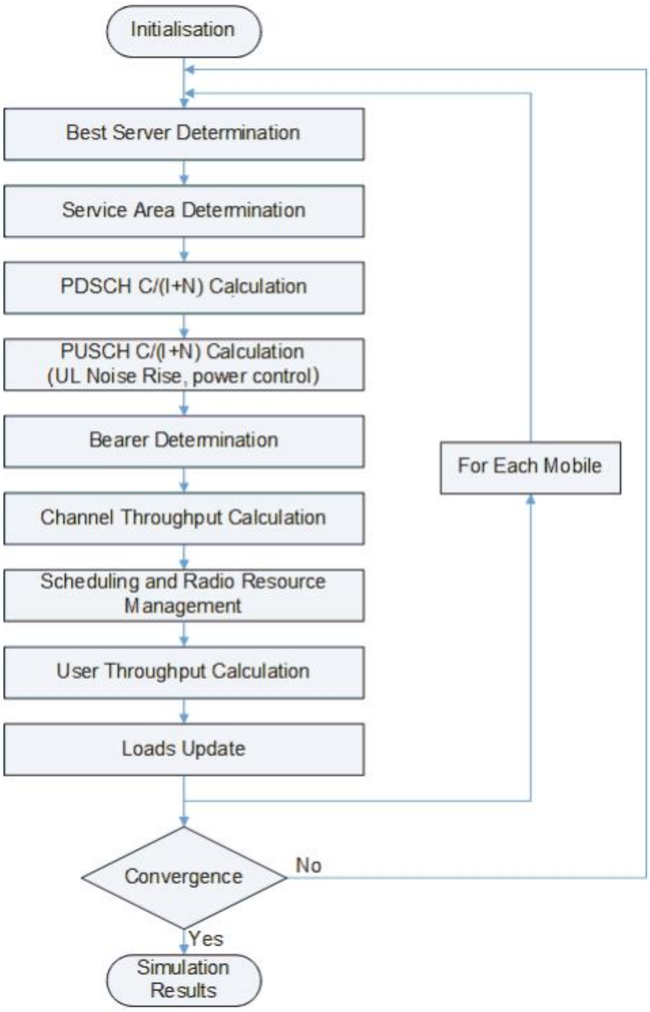


Figure 16. 4G/5G simulation algorithm scheme.

Users may be rejected:

- At the "Best Server Determination" step for "No Coverage".
- At the UL or DL calculations steps for "No Service" if the quality is too low to obtain any coding scheme.
- At the "Radio Resource Management" step for either "Scheduler Saturation" if the user is not among the users selected for resource allocation, "Resource Saturation" if all the cell's resources were used up by other users or "Backhaul Saturation" if the user was among the lowest priority service users served by a cell of a site whose defined maximum S1 interface throughputs were exceeded while allocating resources for the minimum throughput demands.

4. Network deployment

In this section, two different case studies will be analysed. The first one will be an upgrade from a 4G network to a 5G one and the second one will be a 4G/5G deployment in which there will be both macrocells and small cells to cover the territory as well as a crowded concert scenario.

Both case studies will take place in the same location, a surrounding zone around "el Parc de la Ciutadella", in Barcelona. As explained in the previous section, the Aster propagation model requires a Digital terrain model as well as an ASODM, in the case of this thesis, these data were provided by VISICOM Company.

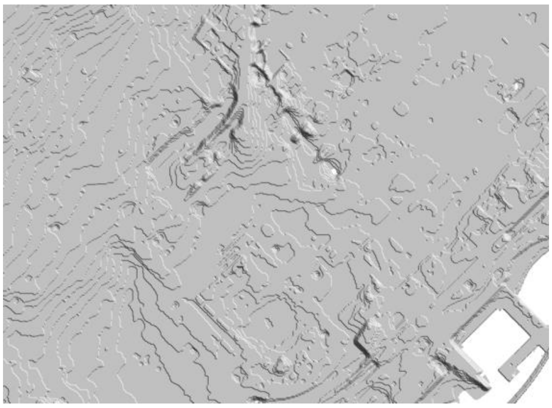


Figure 17. Digital terrain model.

Figure 18. Clutter classes model.

As Atoll has the possibility to make predictions and simulations, these will be used to model the network and get the desired results. However, before doing so, there are some parameters as the network services, the users and the traffic maps that have to be modelled.

4.1. Upgrade from 4G to 5G network

The first case study will cover an upgrade from a 4G to a 5G network in a realistic manner (i.e., designing a 4G network as it was the existing network and then upgrading it to a 5G one on top of the 4G).

4.1.1. Modelling services and users

The first step to initiate the network design is to define the services that will be covered in the simulations and predictions. Firstly, a new broadband service type named "Broadband service" was created, this is obviously a packet switched service. This service supports both LTE and 5G NR technologies and its configuration is shown in the images below.

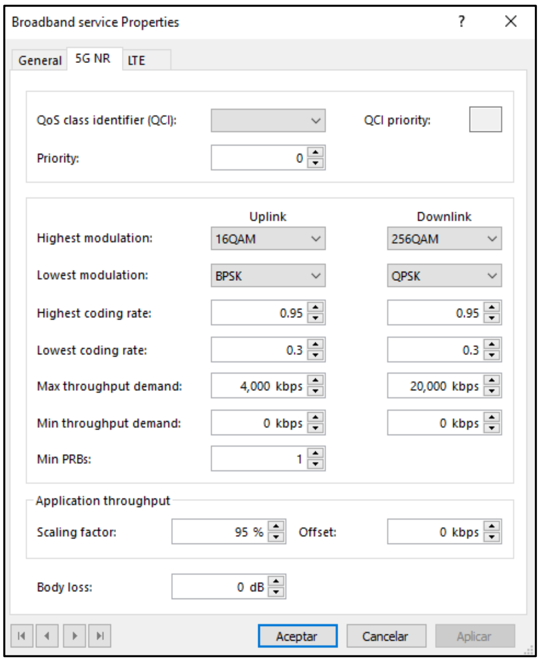


Figure 19. 5G NR Broadband service properties.

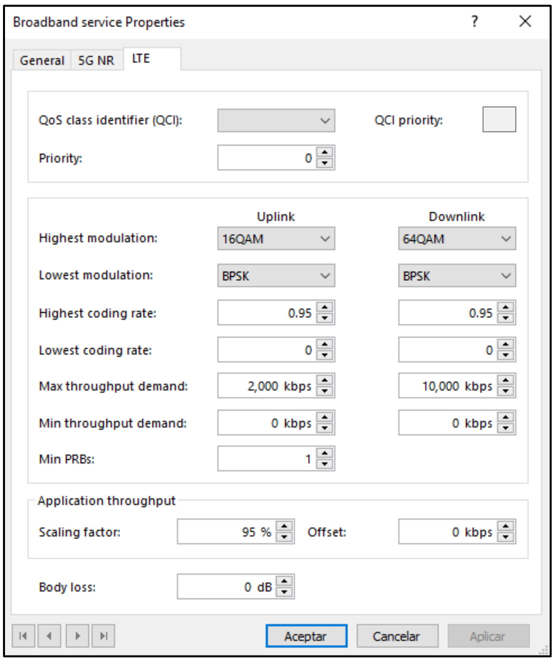


Figure 20. LTE Broadband service properties.

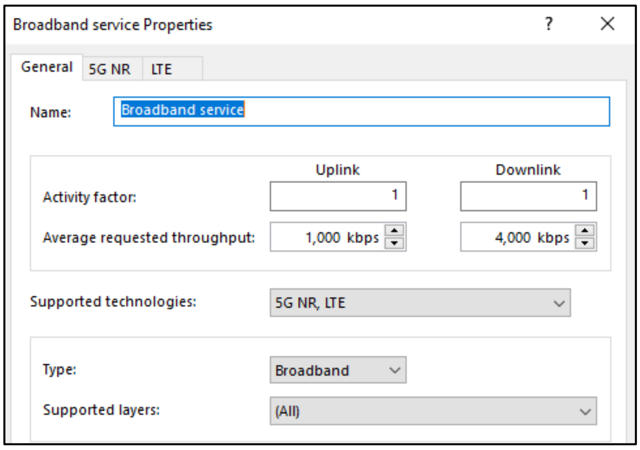


Figure 21. General tab of Broadband properties.

As seen in the figures 19 and 20, the maximum and minimum throughput demand varies in both technologies, 5G NR being more demanding. However, the general tab shows that the average demanded throughput does not depend on the technology and it is designed as 1000 kbps in the uplink and 4000 kbps in the downlink.

The remaining services were predefined in Atoll and were not modified, these are "Internet", "Voice Call" and "Video Call".

The Internet service is a data service that only supports LTE and has an average throughput much less demanding than the Broadband Service with 200 kbps in the uplink and 400 kbps in the downlink.

As this service does not support 5G NR, only the LTE properties are defined and are listed in the figure below.

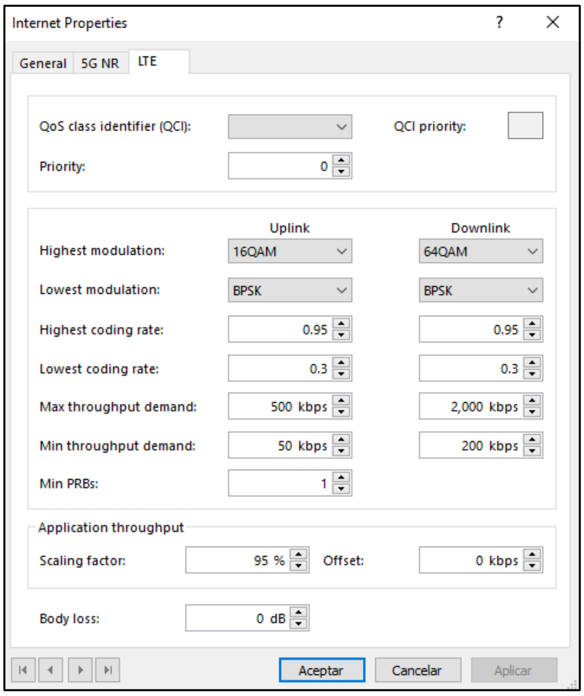


Figure 22. LTE Internet properties.

This figure makes clear that this service will be less throughput demanding compared to the Broadband service.

As to the other two services "Voice Call" and "Video Call", both are voice type services and both only support LTE technology. The difference between them is that the Video Call service demands more throughput than the Voice Call and that the Voice Call has an activity factor of 0.4 both in the uplink and in the downlink. The uplink and downlink activity factors determine the probability of activity for users accessing the service during simulations. Also, Video Call is a higher priority service than Voice Call (lower priority number means higher priority).

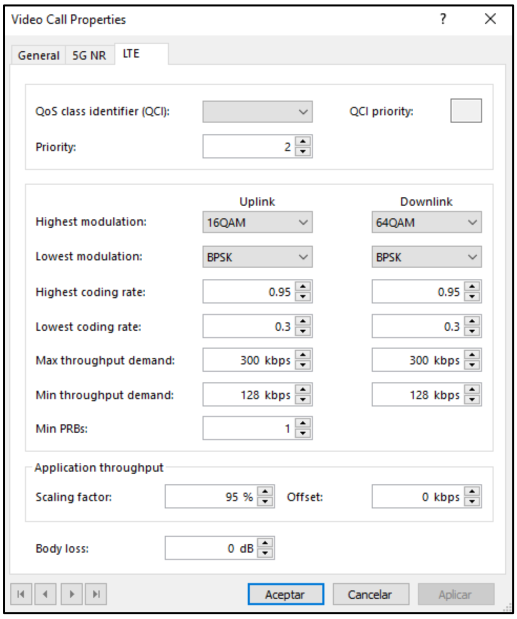


Figure 23. Video Call LTE properties.

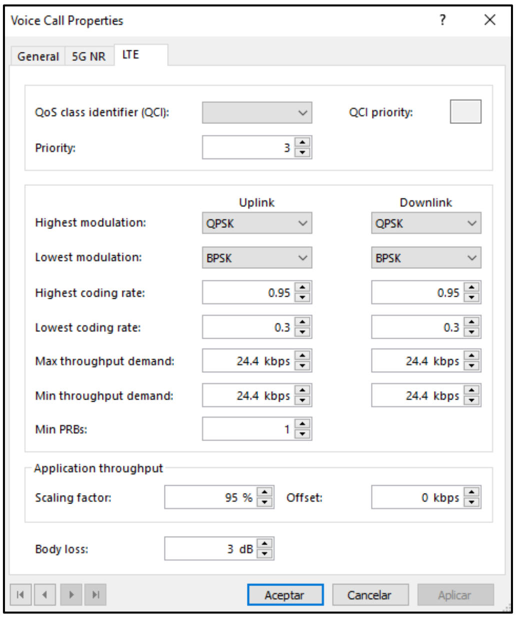
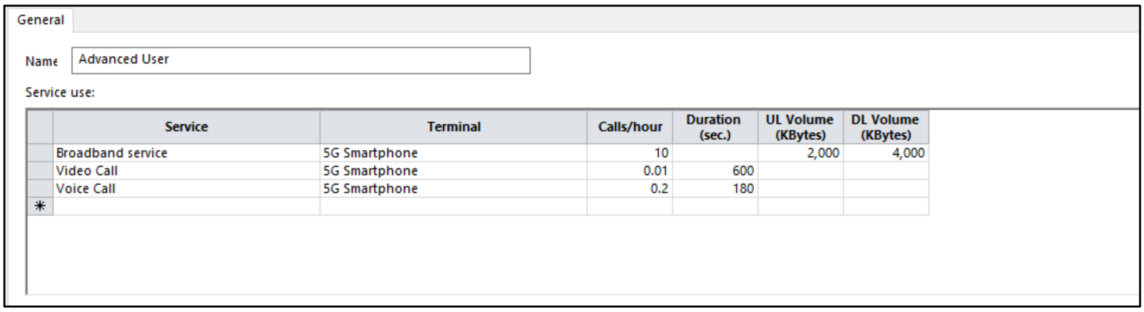


Figure 24. Voice Call LTE properties.

After modelling the services, the next step is to model the users that use these services. In this case, two different users were defined: an Advanced User and a Standard User.

The Advanced User is a profile user that uses mobile data very often to consult e-mails, to watch videos on streaming, to post pictures and also makes some voice calls and video calls every once in a while.

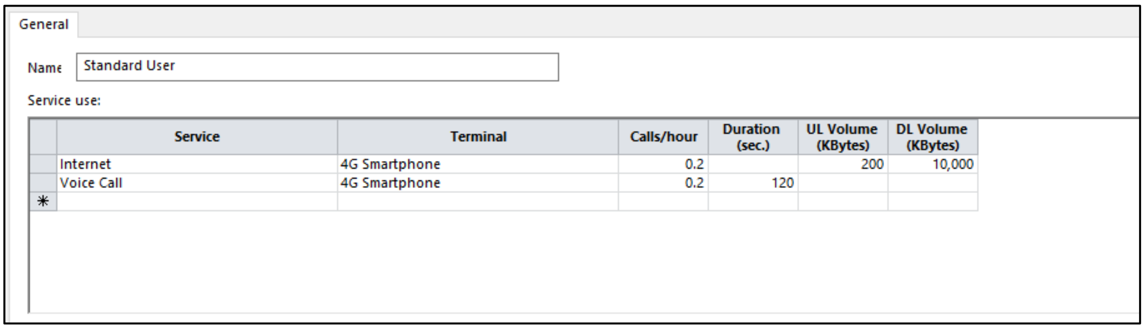


Service	Terminal	Calls/hour	Duration (sec.)	UL Volume (KBytes)	DL Volume (KBytes)
Broadband service	5G Smartphone	10		2,000	4,000
Video Call	5G Smartphone	0.01	600		
Voice Call	5G Smartphone	0.2	180		

Figure 25. Advanced User profile.

As seen on the figure above, the advanced user has a high number of calls per hour in the Broadband Service (4 MB in the downlink and 2 MB in the uplink every 6 min), makes a 3 min voice call once every 5 hours and a 10 min video call once every approximately 4 days.

As to the Standard User, is a user profile that does not use its mobile data as often as the Advanced user, however, it makes some internet consults every day as well as some voice calls.



Service	Terminal	Calls/hour	Duration (sec.)	UL Volume (KBytes)	DL Volume (KBytes)
Internet	4G Smartphone	0.2		200	10,000
Voice Call	4G Smartphone	0.2	120		

Figure 26. Standard User profile.

The Standard User is a casual phone user that consults its mobile once every 5 hours to make phone calls and to respond to its e-mails or text messages. The DL volume is higher than the one in the Advanced User as this user may have accumulated messages or e-mails that responds at once.

Finally, once the services and user profiles have been defined, the distribution of these among the map has to be made.

To do so, a traffic map (which can be observed at figure 15) and the environments are created. In the environments, the number and the type of users is defined. In this traffic map, there are five different environments: Open in Urban, Open, Residential, Industrial and Parks in Urban.

This is the user distribution for these environments:

Environment	User Profile	Mobility	Density (subscribers/km^2)
Open in Urban	Standard User	Pedestrian	8000
	Advanced User	Pedestrian	4000
	Standard User	50 km/h	2500
Open	-	-	0
Residential	Standard User	Fixed	5000
	Advanced User	Fixed	5000
Industrial	Advanced User	Fixed	5000
Parks in Urban	Standard User	Fixed	200
	Standard User	Pedestrian	300

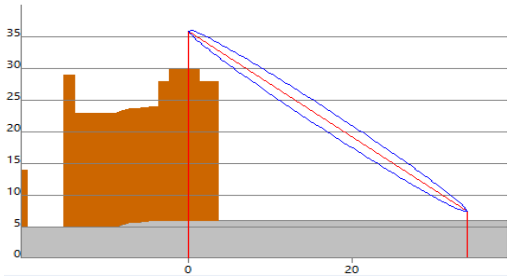
Table 6. User distribution for each environment.

The amount of subscribers in each environment is not a standardized number but it has been assumed by the student with the help of the population density of this part of Barcelona which is approximately 32.000 inhabitants per km^2 [4].

4.1.2. LTE cells deployment

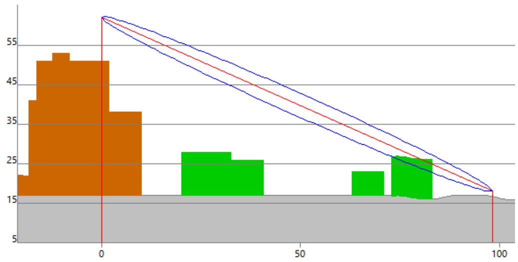
The site locations have been chosen to cover as much area as possible but also taking into account the possible interference from the neighbour sites. To make it as realistic as possible, the deployed sites are located where there is an actual telecommunications base station [5].

Figure 27. Site locations in the computation zone.



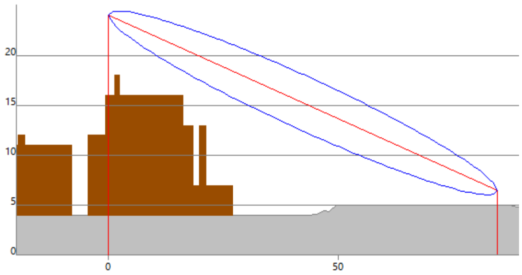
Site 0 is located on top of a 6 m tower on a 24 m building.

Using the existing station “TELEFONICA MOVILES ESPAÑA, S.A.U. - 0800940”.



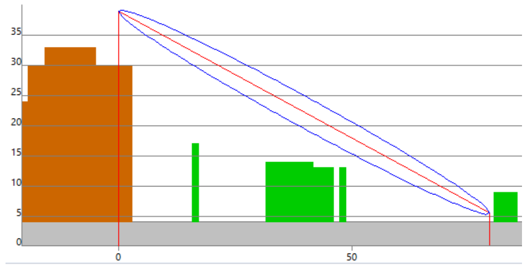
Site 1 is located on top of a 10 m tower on a 36 m building.

Using the existing station “TELEFONICA MOVILES ESPAÑA, S.A.U. - 0800591”.



Site 2 is located on top of a 10 m tower on a 12 m building.

Using the existing station “TELEFONICA MOVILES ESPAÑA, S.A.U. – 0802787”.



Site 3 is located on top of an 8 m tower on a 26 m building.

Using the existing station “TELEFONICA MOVILES ESPAÑA, S.A.U. – 0802937”.

Table 7. LTE stations location characteristics.

The LTE transmitters consist of 4 transmission and 4 reception antennas along with 1 power amplifier (PA). Each transmitter is configured the same way as the others except for the mechanical azimuth value, which is used to point towards a specific direction. All the transmitters use the “Default Beamformer” as their beamforming antenna and its main characteristics are listed below.

- **Columns (N):** 8.
- **Rows (M):** 8.
- **Transmission ports:** 64.
- **Reception ports:** 64.
- **Number of beams:** 60.
- **Azimuth range:** from -45º to 45º.
- **Tilt Range:** from -5º to 5º.
- **Boresight gain:** 26.0618 dB.

These transmitters will be operating in the E-UTRA 20 band which corresponds to the 800 MHz frequency band and their mutual cell's configuration is the following [6]:

- **Max Power (dBm)**: 43.
- **Layer**: Macro Layer.
- **Cell Type**: LTE.
- **Cell Individual Offset (dB)**: 0.
- **Cell Selection Threshold (dB)**: 0.
- **Cyclic Prefix Ratio**: 0-Normal.
- **Scheduler**: Proportional Fair.
- **Diversity Support (DL)**: Transmit Diversity and SU-MIMO.
- **Diversity Support (UL)**: Receive Diversity and SU-MIMO.

Then, for each cell there are parameters that vary between them which are depicted in the table below.

	Site 0 LTE Cell	Site 1 LTE Cell	Site 2 LTE Cell	Site 3 LTE Cell
Carrier	EARFCN 6250 – 20 MHz	EARFCN 6225 – 15 MHz	EARFCN 6300 – 10 MHz	EARFCN 6200 – 10 MHz
Physical Cell ID	411	467	0	444
PRACH RSI	10-19	0-9	91-100	724-733

Table 8. Individual LTE cell parameters.

The election of the E-UTRA 20 band over the other available options in Barcelona (E-UTRA 1, E-UTRA 3, E-UTRA 7 and E-UTRA 8) has been due to the fact that propagation on the lower frequencies is better than in the high ones and the 800 MHz band is the lowest among the possible options.

In this band, there are four possible channel bandwidths available, these being four 5 MHz channels, two 10 MHz channels, one 15 MHz channel and one 20 MHz channel. In order to reduce as much as possible the interference between the sites, each transmitter uses a different E-UTRA Absolute Radio Frequency Channel Number (EARFCN). The larger the channel bandwidth, the larger the number of users that will have service by connecting to that channel. This means that the larger channel has to be assigned to the cell that covers more area and therefore has more users connected to it.

To find out the area that covers each cell, we carry out an Atoll prediction called Coverage by Transmitter (as each cell corresponds to only one transmitter).

Figure 28. Coverage by LTE transmitters.

Cell	% Covered
Site 0_800	44.90%
Site 1_800	35.51%
Site 2_800	19.67%
Site 3_800	17.67%

Table 9. Covered area per LTE transmitter.

*The percentage of covered area exceeds the 100% as there are areas that are covered by two or more cells.

From the image and the table, it can be seen that the Site 0 is the one that should have the largest channel bandwidth, followed by the Site 1, the Site 2 and Site 3.

The Physical Cell IDs and the PRACH RSIs have been chosen using the Atoll's Automatic Allocation tool which is only available to use in LTE.

A coverage prediction is useful to see if the computation zone receives a good signal intensity and to detect if there are areas that are not covered. In this case, the chosen prediction is based on the Reference Signal Received Power (RSRP), which is a common indicator on coverage quality.

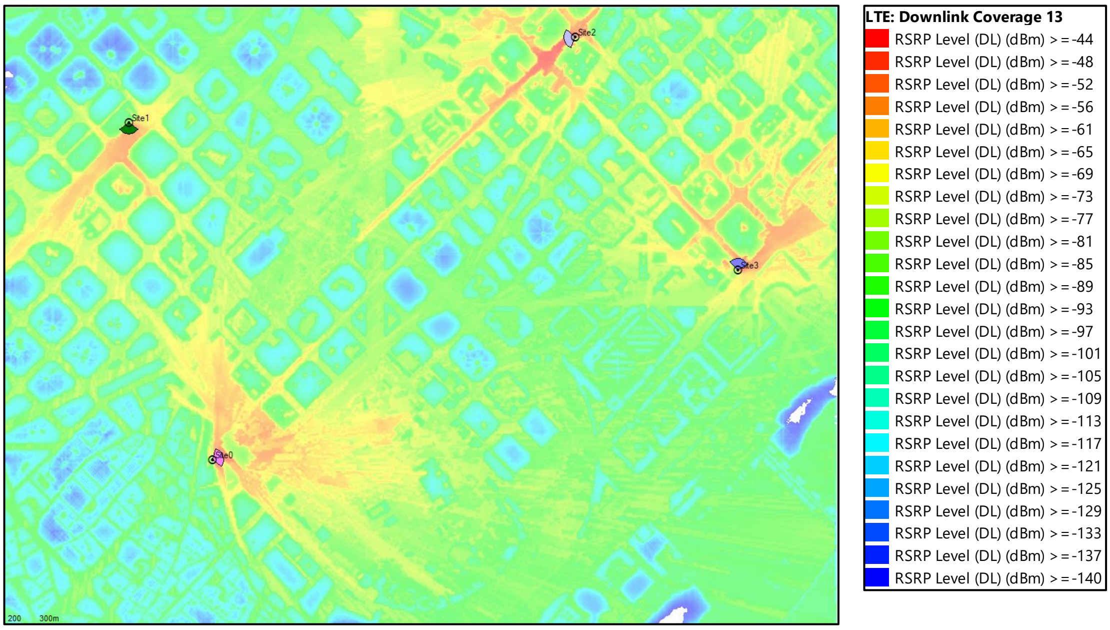


Figure 29. LTE stations coverage prediction.

In this figure, it appears that majority of the area is covered with relatively good received signal with the exception of some blue zones which correspond to locations inside buildings and small portions of the beach.

4.1.3. 5G NR cells deployment

The next step is to upgrade the existing LTE network to 5G NR. To do so, the same sites were used to deploy 5G transmitters on top of them, so the Table 7 is also valid for this deployment. This 5G NR network will work simultaneously with the LTE one as there are services that do not require 5G, as described in section 4.1.1. In this deployment, a new transmitter was added in Site 3 to support the huge amount of area that Site 0 and Site 1 had to cover. In this case, the site's distribution is as it follows.

Figure 30. 5G NR transmitters distribution.

By adding the new transmitter onto the Site 3, the distribution of the covered area only by the 5G transmitters is as it follows.

Cell	% Covered Area
Site 0	25.75%
Site 1	19.06%
Site 2	15.79%
Site 3_1	12.55%
Site 3_2	37.20%

Table 10. Covered area per 5G transmitter.

The 5G NR transmitters consist of 128 transmission and 128 reception antennas along with 1 PA. Once again, each transmitter is equally configured with the exception of the Mechanical azimuth value. Also, all these transmitters use the "Default Beamformer" as their beamforming antenna and their main characteristics are equal as the ones in the LTE transmitters.

These transmitters will work on the n78 frequency band which, as stated in section 2.2.3., comprises frequencies from 3300 MHz to 3800 MHz. In this case, the mutual cell properties are the following.

- **Max Power (dBm)**: 50.
- **Layer**: Macro Layer.
- **Cell Type**: Primary Cell.
- **SS/PBCH Numerology**: 0 (15 kHz).
- **Traffic Numerology**: 2 (60 kHz).
- **Scheduler**: Proportional Fair.
- **Diversity Support (DL)**: Transmit diversity, SU-MIMO, MU-MIMO.
- **Diversity Support (UL)**: Receive diversity, SU-MIMO, MU-MIMO.

There are also some parameters that are distinctive of each transmitter which are summed up in the table below.

	Site 0 5G NR Cell	Site 1 5G NR Cell	Site 2 5G NR Cell	Site 3 5G NR Cell 1	Site 3 5G NR Cell 2
Carrier	NR-ARFCN 622667 – 80 MHz	NR-ARFCN 623333 – 100 MHz	NR-ARFCN 622000 – 60 MHz	NR-ARFCN 622667 – 80 MHz	NR-ARFCN 623333 – 100 MHz
Cell Individual Offset	8	8	11	10	6
Physical Cell ID	50	51	52	53	54
PRACH RSI	50-59	60-69	70-79	80-89	90-99

Table 11. Distinctive 5G NR cell parameters.

In this case, the n78 band on 5G NR allows seven possible channel bandwidths, this being ten 10 MHz channels, six 15 MHz channels, five 20 MHz channels, two 40 MHz channels, two 50 MHz channels, one 60 MHz channel, one 80 MHz channel and one 100 MHz channel. In this case it is not necessary to assign different channels to each cell as the n78 band does not have as good propagation as the E-UTRA 20 band so the interference between far sites is not a problem. To have a better look at problematic zones where the sites' signals will collide, a DL Overlapping Zones was carried out.

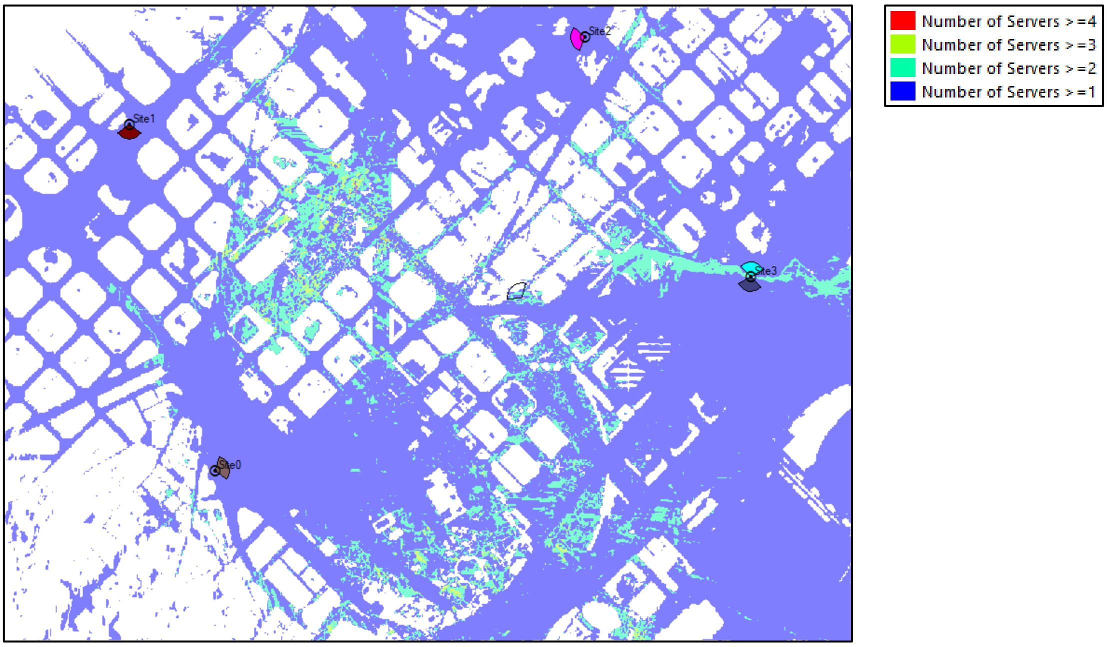


Figure 31. 5G NR Overlapping Zones prediction.

To allocate these channels in each cell, the steps were the following:

- Firstly, the largest channel bandwidth was assigned to the cell that covered more area according to the coverage prediction. Therefore, Site 3 5G NR Cell 2 was assigned a channel bandwidth of 100 MHz.
- Then, as seen in Figure 31, this channel should not be used again by neither Site 2 or Site 0 but it can be reused by Site 1 as it is sufficiently far from Site 3_2.
- The following largest channel is an 80 MHz one and it will be assigned to the Site 0's cell as it is the second one with the largest covered area. Site 3_1 can also use this 80 MHz channel as it is pointing north and the interference will not be large.
- Finally, the Site 2 should not be using any of the already used channels due to the interference, but it used a 60 MHz one.

The second parameter that was changed for each cell was the Cell Individual Offset, which as explained in section 3.1. is used to tune or bias the ranking of potential servers for cell selection.

The reason to change this is because as the 800 MHz band has a better propagation than the 3500 MHz one, the majority of users will be seeing an LTE cell as their best server and therefore will connect to it. By modifying this parameter, these cells will have some more dBs as offset with respect to the LTE ones so more users will be connecting to the 5G NR cells. The individual values of these offsets were set by testing the network in the simulations and tuning the parameters to get a better result.

Finally, the Physical Cell Identifiers and the PRACH RSIs were determined by the student with the restriction of them not colliding.

To make an analysis on how is the network working and to make a comparison between the LTE-only and the 4G/5G network, some simulations are carried out.

4.1.4. Simulations

The simulations are used to give more realistic insights on the network deployment as it takes into account the user profiles and the traffic distribution that was modelled before.

The first simulation is configured to only take into account the LTE radio access technology and have a maximum traffic load of 80% in both DL and UL. The result of this simulation is shown below.

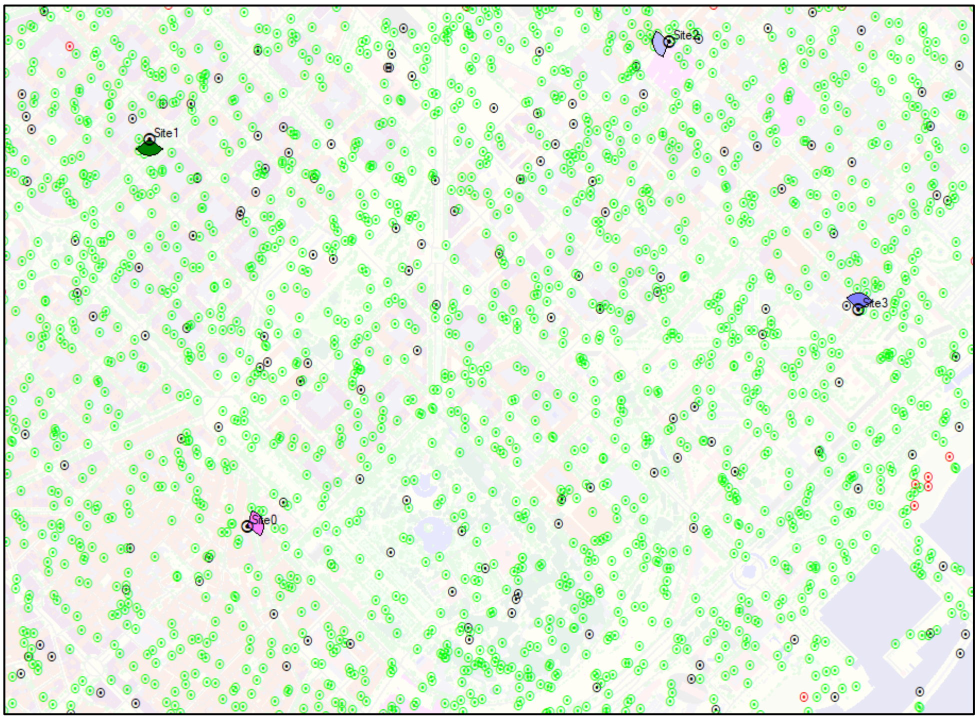


Figure 32. LTE-only simulation.

The simulation can be seen as a snapshot on a certain time of the state of the network, each point being a different user. Using the traffic map along with the user profiles, Atoll computes a number of users at a time in the network. In the case of this simulation, this number is 2022 users. The green dots correspond to users which are either Connected DL, Connected UL or Connected DL+UL and the red dots correspond to user which have either No service or No coverage. Finally, the black dots are inactive users.

In this case it seems clear that the majority of the users have connected successfully, but Atoll allows a deeper analysis with the Statistics tab of the simulations.

Total number of users not connected (rejected): 14 (0.7%)	
No Coverage:	13
No Service:	1
Scheduler Saturation:	0
Resource Saturation:	0
Backhaul Saturation:	0

Figure 33. Breakdown of rejected users in LTE-only simulation.

Only a 0.7% of the totality of users is rejected and the main reason is No Coverage. Hiding all the dots except the No Coverage ones, allows to see where the No Coverage users are located.

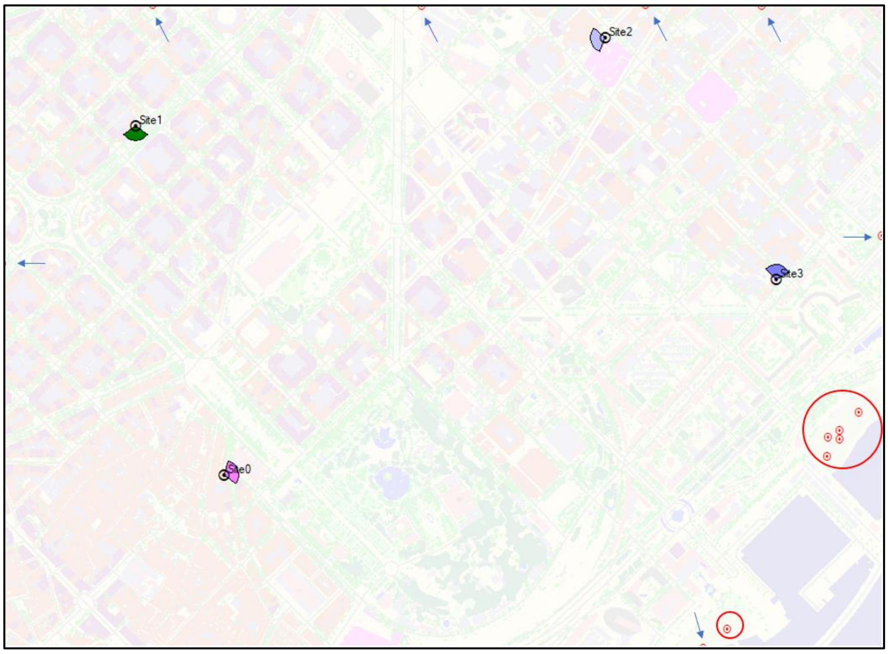


Figure 34. No Coverage users in LTE-only simulation.

This thirteen No Coverage users are either located in the edges of the computation zone (which is a bug because it always happens no matter if you locate a transmitter on the edge) or at the beach zone (red circles), which makes sense since it was one of the zones that did not have coverage in the Coverage Prediction in section 4.1.2.

In order to make a comparison, the 5G NR transmitter were activated and another simulation was carried out. In this case, the figure resulting from this simulation is shown below.

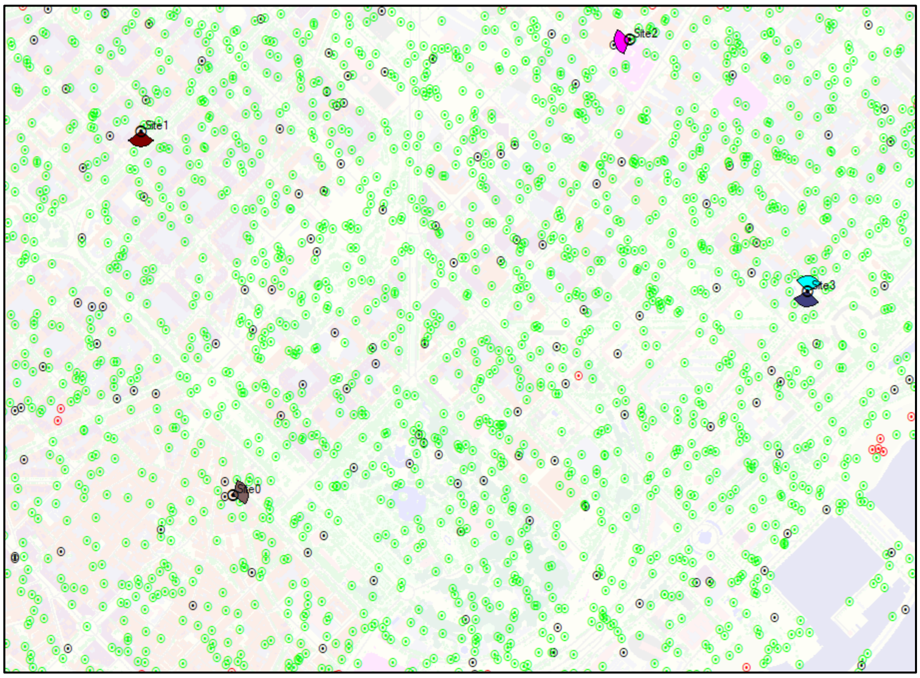


Figure 35. 4G/5G simulation.

As the throughput has increased and the users consume a fixed number of data volume (as seen in section 3.3), the number of total users has decreased because they consume this data quicker than before. In this case the number of users 1960 of which 19 users have been rejected.

Total number of users not connected (rejected): 19 (1%)	
No Coverage:	11
No Service:	8
Scheduler Saturation:	0
Resource Saturation:	0
Backhaul Saturation:	0

Figure 36. Breakdown of rejected users in the 4G/5G simulation.

As seen in this figure, 1% of the users have been rejected due to two different reasons: 11 of them have No Coverage due to the computation zone edges and the beach zone and 8 of them have No Service because they could not be allocated a sufficient number of resources to obtain any coding scheme.

The increased number of No Service users is due to the Cell Individual Offset parameter of the 5G cells. By tunning this parameter, the cell selection was modified to prioritize the 5G cells accordingly to the number of dBs introduced. This can lead to the fact that a user is connecting to a cell that is not providing a good-enough signal to obtain any codec.

The next comparison will be between the demand and the obtained results for each service in the LTE-only and the 4G/5G simulations.

	Demanded connected users	Obtained connected users	Min Throughput demand (UL) (Mbps)	Max Throughput demand (UL) (Mbps)	Obtained Throughput (UL) (Mbps)	Min Throughput demand (DL) (Mbps)	Max Throughput demand (DL) (Mbps)	Obtained Throughput (DL) (Mbps)
Internet	463	459	1	10	4.72	8.86	886	137.02
Video call	28	28	3.58	8.4	7.49	3.58	8.4	6.3
Voice call	421	416	4.07	4.07	3.68	4.10	4.1	3.89
Broadband Service	1110	1105	0	1530	138.25	0	3680	44.06

Table 12. Comparison between throughput demand and the cumulated throughput in the LTE-only simulation.

	Demanded connected users	Obtained connected users	Min Throughput demand (UL) (Mbps)	Max Throughput demand (UL) (Mbps)	Obtained Throughput (UL) (Mbps)	Min Throughput demand (DL) (Mbps)	Max Throughput demand (DL) (Mbps)	Obtained Throughput (DL) (Mbps)
Internet	510	503	0.85	8.5	4.9	98.6	986	155.07
Video call	26	25	3.33	7.8	6.9	3.33	7.8	5.63
Voice call	388	385	3.78	3.78	3.43	3.93	3.93	3.71
Broadband Service	1036	1028	0	1774	804.43	0	4540	1592.86

Table 13. Comparison between throughput demand and the cumulated throughput in the 4G/5G simulation.

Table 12 sums up the comparison between the demand and the results in terms of cumulated throughput and rejects for every service in the LTE-only simulation. It can be seen that the obtained cumulated application throughput for each service is located between the minimum and the maximum throughput demand with the exception of the voice call service, that does not achieve the minimum throughput due to the 5 rejected users.

As to the Broadband Service, the obtained throughput stands between the minimum and the maximum demand, however, this is only because the minimum throughput demand is 0 kbps as the obtained throughput is very low.

Now, taking a look to the Table 13, the obtained results are quite similar to the ones in the LTE-only simulation when focusing on the Internet, Video Call and Voice Call services, however, looking at the Broadband Service, the obtained application throughput in both the UL and the DL adjusts more at what could be expected as it nearly is an intermediate point between the maximum and the minimum demand.

Now, to see if this obtained throughputs would satisfy the needs of the users, another comparison is made, where the average of the obtained throughput is faced with the average requested throughput for each service in both simulations.

	Average Throughput demand/user (UL) (Mbps)	Average obtained Throughput/user (UL) (Mbps) LTE-only	Average obtained Throughput/user (UL) (Mbps) 4G/5G	Average Throughput demand/user (DL) (Mbps)	Average obtained Throughput/user (DL) (Mbps) LTE-only	Average obtained Throughput/user (DL) (Mbps) 4G/5G
Internet	0.2	0.33	0.3	0.4	0.311	0.318
Video call	0.128	0.267	0.276	0.128	0.276	0.225
Voice call	0.0244	0.022	0.022	0.0244	0.023	0.023
Broadband Service	1	0.183	1.164	4	0.12	4.47

Table 14. Comparison between the average throughput demand and the average obtained throughput.

It is interesting to see that in this case the average obtained throughput does not achieve the demand per user in case of the DL Internet service in both simulations and in both UL and DL in the Voice call service, however, the margin with the average demand is not very large.

As to the Broadband Service, the average obtained throughput in the LTE-only simulation represents only an 18.3% of the demand in case of the UL and a 3% in case of the DL. In this case the users would not be satisfied even though the minimum demand was fulfilled. However, when introducing 5G in the network, and taking into account that the Broadband Service is the only one that supports both technologies, the average obtained throughput shifts from not achieving the average demand to surpassing it by a low margin: 116.4% in the UL and 111.7% in the DL.

4.2. Crowded scenario coverage

In this second case study, a new scenario is proposed: on top of a 4G/5G network similar as the one in the case before, a crowded concert is intended to be covered. In this case, the cooperation of macro cells and small cells will be needed as well as the introduction of the mmWave bands of 5G NR.

4.2.1. New traffic map

As stated, this new case introduces a new scenario in which there is a concert, this means that a new traffic map which contemplates a large concentration of people must be added to the traffic map previously created.

Firstly, the ubication in which the concert will take place has to be decided. As the Barcelona city festival “Festes de la Mercè” concerts take place in a specific part near the “Parc de la Ciutadella”, this is the location that will be chosen to simulate the concert.

Then, the traffic map is drawn as accurately as possible and it is divided in two different parts in order to make it as realistic as possible.

Figure 37. New traffic map.

Each part will allocate a different environment:

- The red part corresponds to the High-density concert environment and is the one nearest to concert’s platform and its user density will be very high. The density for this environment is 800000 $subscribers/km^2$ in which all the subscribers will be “concert users”.
- The purple part corresponds to the Mid-density concert and it is the back part of the concert where normally there is not as much density of people as the front one, for this reason the user density will not be as high as the red part. The density for this environment is 400000 $subscribers/km^2$ in which all the subscribers will be “concert users” once again.

Taking into consideration the density of subscribers and the area that covered by each environment, the resulting number of users is ≈ 16000 which is a number that matches the typical assistance of a concert in Barcelona [7].

4.2.2. Modelling services and users

Some of the services were reused from the already explained first case but there are some that are either new or have been redefined. Video Call, Voice Call and Internet services remain configured as the Upgrade from 4G to 5G network case study.

The Broadband Service was redefined to not be as demanding as the section before. It still supports both LTE and 5G NR technologies and the average, minimum and maximum throughput demand is as before, but the lowest coding rate on both DL and UL for the 5G NR technology was set to 0 in opposition to 0.3 as it was before.

A new service called "Concert Service" has been introduced. This will be the service that most users of the concert will be using and it is thought to cover the typical network uses in a concert with a high experienced data rate.

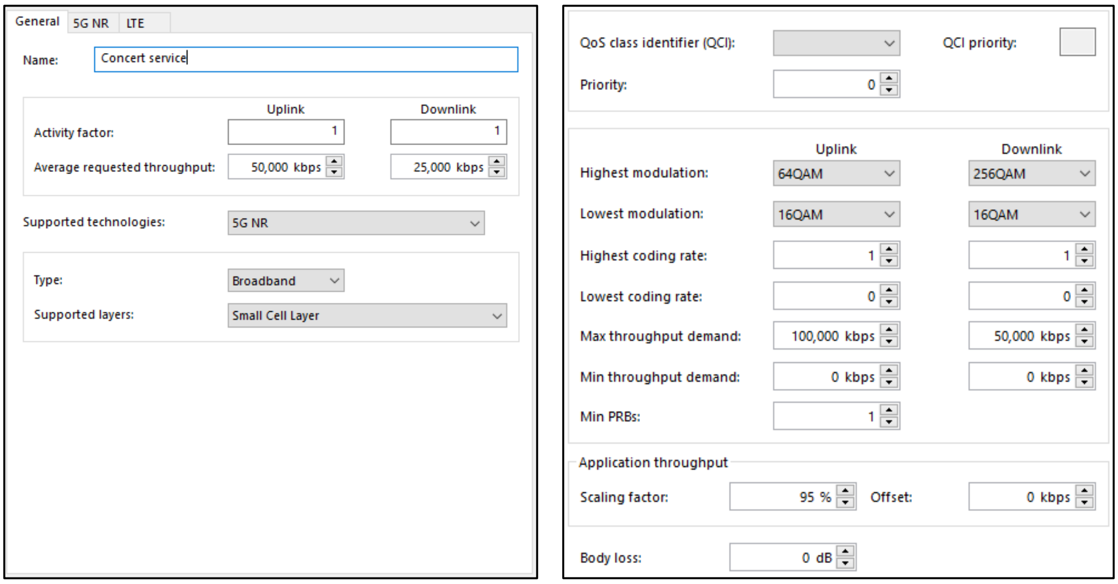


Figure 38. Concert service parameter configuration.

As seen in these images, the demanded throughput is higher in the UL than in the DL, this is due to the fact that a concert user is more likely to use its terminal to either upload a photo/video to its social networks or to send it to its friends rather than downloading a photo/video during the concert. This service only supports 5G NR as its technology and also only Small Cell Layers.

As to the user profiles, the Advanced User and the Standard User from the first case remain equal in terms of configuration. To model the typical behaviour of a concert user, a "Concert user" was created with the following configuration.

Service	Terminal	Calls/hour	Duration (sec.)	UL Volume (KBytes)	DL Volume (KBytes)
Voice Call	5G Smartphone	0.5	30		
Concert service	5G Smartphone	5		80,000	40,000
Broadband Service	5G Smartphone	2		2,000	4,000

Figure 39. Concert User configuration.

In this figure, the different services that a Concert User will make use are listed with its duration or data volume.

A Concert User will probably make a voice call once every two hours in case it needs to find its friends or in order to reunite with other people, also it may look something up on the internet or in its social networks twice every hour (Broadband Service) and finally, it is likely that the user may want to record a video or take a photo of the concert to share it in its social networks. In this case, the Concert Service volume was computed by recording a 30 second 1080p MPEG-4 video with a smartphone and checking its weight which was approximately of 80 MB.

Then, the user distribution for each environment was the same as the first case except for the Concert User which is only mapped into the High-density and Mid-density concert environment as explained in section 4.2.1.

4.2.3. Macro cells deployment

Once again, the sites' locations have been chosen to cover as much area as possible intending to have a uniform distribution of users among all the cells. The LTE transmitters will be covering much more area than the 5G NR ones as their carrier frequency will be lower.

The LTE coverage will be carried out by 5 different transmitters located in 4 different sites which also correspond to real station locations in real life [5].

Figure 40. Distribution of the LTE transmitters.

As seen, there are 4 sites that will be radiating macro cells. However, some of these transmitters will be sharing site with 5G NR transmitters as it is shown in the figure below.

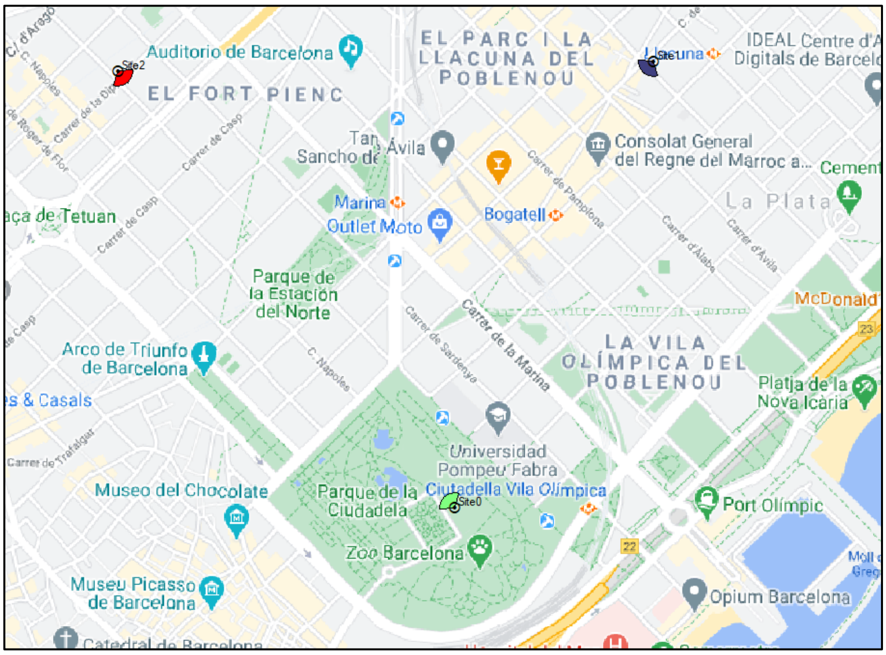


Figure 41. Distribution of 5G NR transmitters.

Site 0 and Site 4 have an extra LTE transmitter with respect to 5G that will be used to cover specific areas with high building density or open areas that makes the 5G signal propagation difficult.

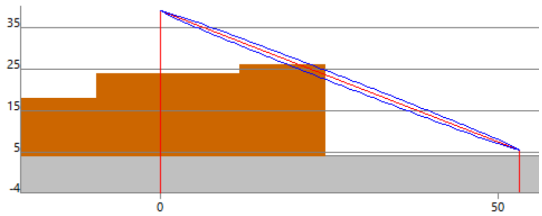
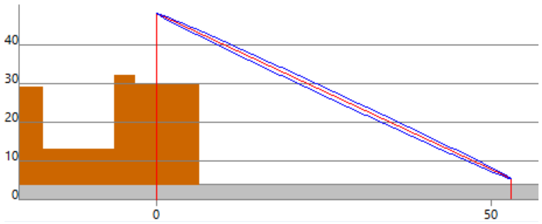
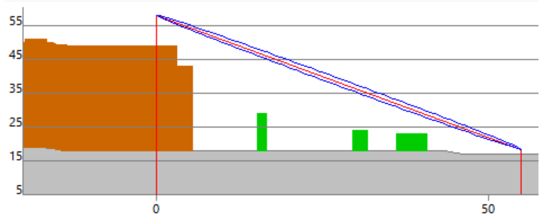
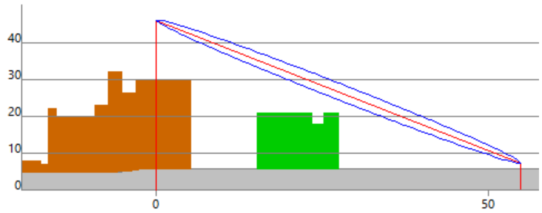
	Site 0 is located on top of a 12 m tower on a 20 m building. Using the existing station “TELEFONICA MOVILES ESPAÑA, S.A.U. – 0803588”.
	Site 1 is located on top of a 15 m tower on a 26 m building. Using the existing station “TELEFONICA MOVILES ESPAÑA, S.A.U. – 0804481”.
	Site 2 is located on top of an 8 m tower on a 30 m building. Using the existing station “TELEFONICA MOVILES ESPAÑA, S.A.U. – 0801258”.
	Site 4 is located on top of a 15 m tower on a 24 m building. Using the existing station “TELEFONICA MOVILES ESPAÑA, S.A.U. – 0800940”.

Table 15. Stations location characteristics.

All the transmitters in both LTE and 5G NR use the "Default Beamformer" as their beamforming antenna with their parameters set like in section 4.1.2. However, the LTE transmitters use 4 transmission and 4 reception antennas while 5G NR transmitter use 128 transmission and 128 reception antennas. Finally, the mechanical azimuth value is used in each transmitter to point towards a specific location.

The cells' configuration explanation will be split into the LTE cells and the 5G NR cells to make it simpler.

4.2.3.1. LTE macro cells

All the LTE transmitters will be operating at the E-UTRA 20 band which corresponds to the 800 MHz frequency band in order to have a better propagation due to the low frequency [6].

The cell configuration is nearly the same for each one, but there are some parameters varying from cell to cell. Following next, the main parameters that remain the same for each cell are presented.

- **Max Power (dBm)**: 43.
- **Layer**: Macro Layer.
- **Cell Type**: LTE.
- **Cell Individual Offset (dB)**: 0.
- **Cell Selection Threshold (dB)**: 0.
- **Cyclic Prefix Ratio**: 0-Normal.
- **Scheduler**: Proportional Fair.
- **Diversity Support (DL)**: Transmit Diversity and SU-MIMO.
- **Diversity Support (UL)**: Receive Diversity and SU-MIMO.

However, there are some parameters that have to be tuned for each cell in order to optimize the behaviour of the network and will be shown below.

	Site 0_2 Cell	**Site 0_3 Cell**	**Site 1_2 Cell**	**Site 2_2 Cell**	**Site 4_1 Cell**
Carrier	EARFCN 6200 – 10 MHz	EARFCN 6225 – 15 MHz	EARFCN 6250 – 20 MHz	EARFCN 6300 – 10 MHz	EARFCN 6225 – 15 MHz
Physical Cell ID	15	16	17	18	19
PRACH RSI	50-59	0-9	60-69	37-46	20-29

Table 16. Tuned LTE cell parameters.

By assigning different channels to each cell, the interference between cells will be reduced. Similarly to the first case study, the carrier for each cell was chosen following the criteria of covered area per transmitter. This means that the transmitter that covers the largest amount of area should get the largest channel bandwidth in order to have the possibility to serve more users.

In this band, there are four possible channel bandwidths available, these being four 5 MHz channels, two 10 MHz channels, one 15 MHz channel and one 20 MHz channel.

By using Atoll's predictions, it can be determined the percentage of area that each transmitter covers and, with that information, each carrier will be allocated.

The results of the “Coverage by transmitter” simulation are shown below.

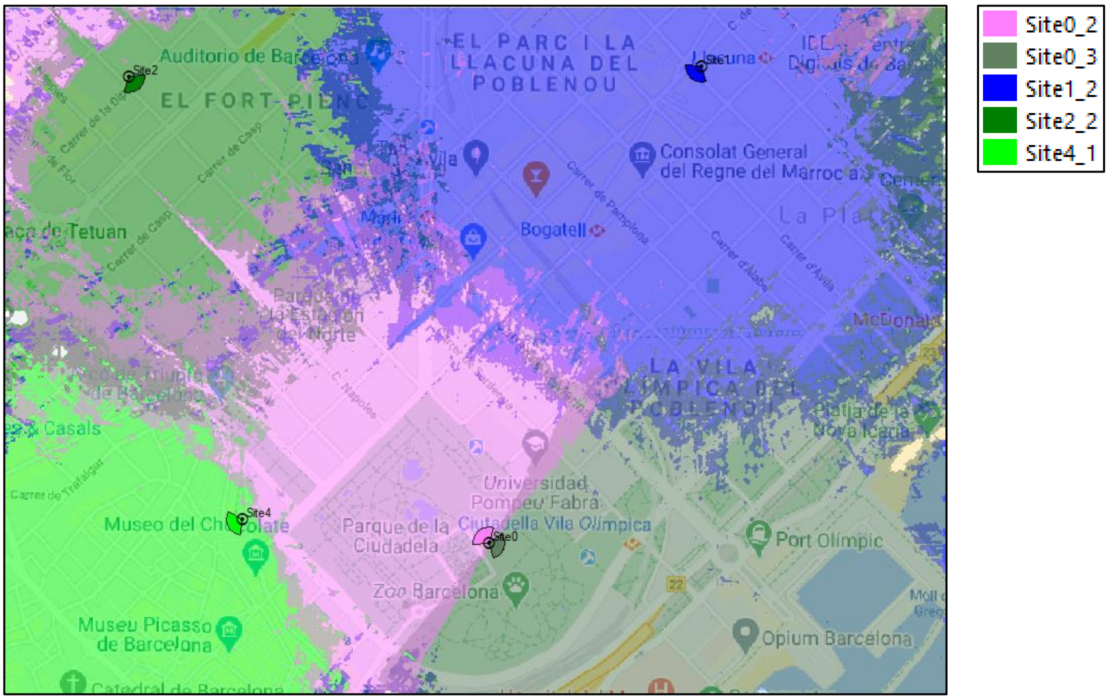


Figure 42. Coverage by LTE transmitters.

Transmitter	% Covered Area*
Site 0_2	26.13%
Site 0_3	27.01%
Site 1_2	36.98%
Site 2_2	22.47%
Site 4_1	14.90%

Table 17. Percentage of covered area by each LTE transmitter.

Using this table, the largest channel bandwidth (20 MHz) will be assigned to Site 1_2, following next, Site 0_3 will be allocated the 15 MHz channel which can be reused by Site 4_1 because their transmitters are pointing to opposite directions, finally Site 0_2 and Site 2_2 will use two different 10 MHz channels.

The Physical Cell Identifiers and the PRACH RSIs were assigned by using the automatic allocation tool that Atoll provides.

The LTE transmitters are thought to cover the majority of the territory, while the 5G NR transmitters will provide an extra level of throughput to the network, then, to check if the area is covered by the LTE transmitters, a Downlink Coverage prediction was carried out.

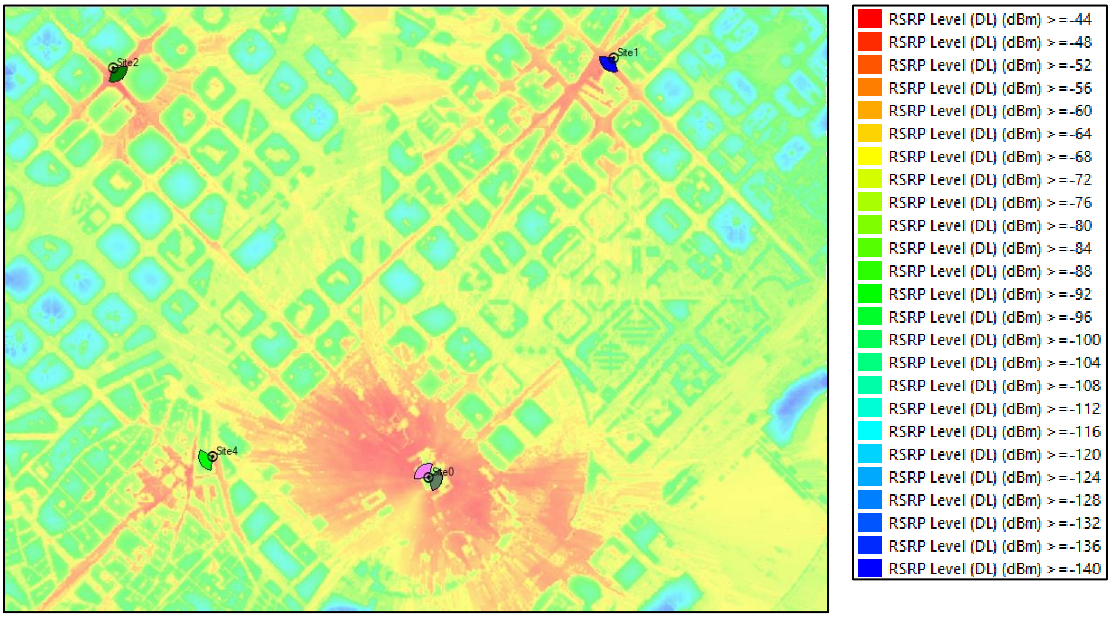


Figure 43. Downlink Coverage prediction with LTE transmitters.

It can be seen that the DL RSRP level is sufficiently good in almost all the locations except for the beach zone as well as some buildings in the left-hand side. The addition of the Site 0_3 and Site 4_1 was helpful to have a better coverage of the beach zone as well as the dense building down-left side.

4.2.3.2. 5G NR macro cells

The 5G NR macro cells were deployed to give an extra boost in terms of throughput and also help the LTE cells by desaturating the network due to the huge number of users connecting to a single LTE cell.

All 5G NR macro cells will be operating once again at band n78, which as seen at section 2.2.3., correspond to frequencies between 3300 MHz and 3800 MHz. These cells will also have a mutual configuration and a distinctive one. For the configuration that is equal to all 5G NR cells, its summary is listed below.

- **Max Power (dBm)**: 50.
- **Layer**: Macro Layer.
- **Cell Type**: Primary Cell.
- **Cell Individual Offset (dB)**: 25.
- **Cell Selection Threshold (dB)**: 0.
- **SS/PBCH Numerology**: 0 (15 kHz).
- **Traffic Numerology**: 2 (60 kHz).
- **Scheduler**: Proportional Fair.
- **Diversity Support (DL)**: Transmit diversity, SU-MIMO, MU-MIMO.
- **Diversity Support (UL)**: Receive diversity, SU-MIMO, MU-MIMO.

The next table will summarize the different configuration for each cell and its explanation on why that decision was made.

	Site 0_1	Site 1_1	Site 2_1
Carrier	NR-ARFCN 623333 – 100 MHz	NR-ARFCN 623333 – 100 MHz	NR-ARFCN 622667 – 80 MHz
Physical Cell ID	30	10	20
PRACH RSI	10-19	110-119	20-29

Table 18. 5G NR macro cell configuration.

Assigning different channels to each cell helps to reduce the interference between them, however, in this configuration 2 cells (site 0's and site 1's) have the same channel and site 2's has another one. To assign each channel, once again the Coverage by Transmitter prediction was used.

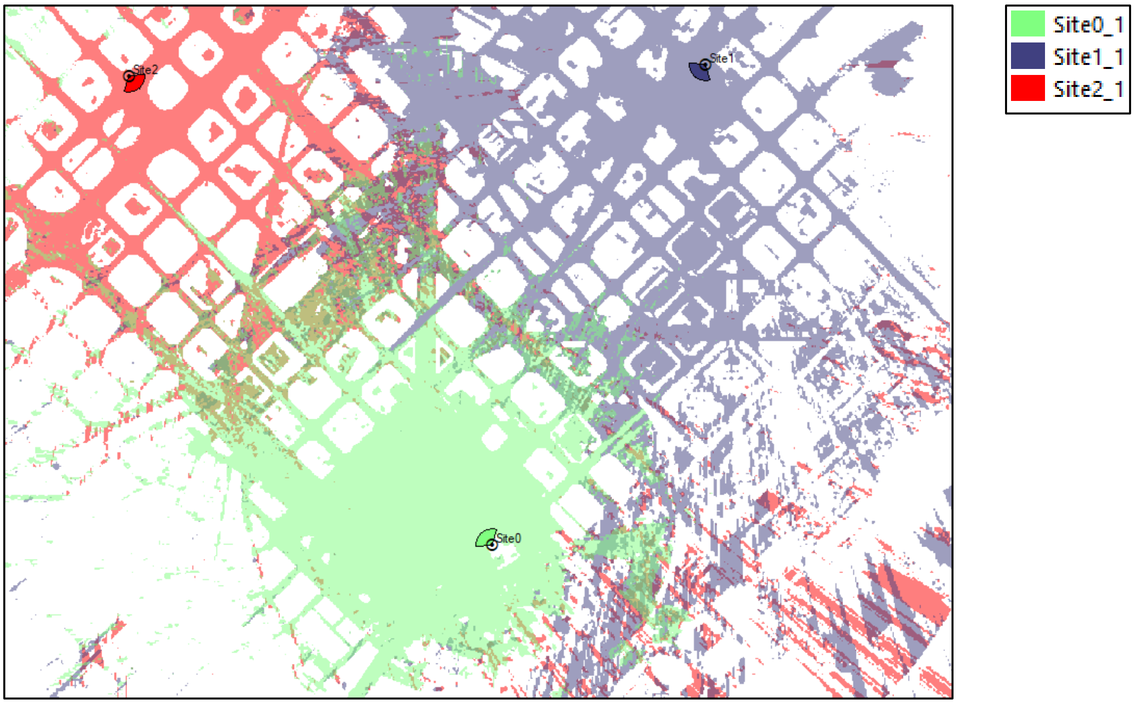


Figure 44. Coverage by 5G NR transmitters.

Transmitter	% Covered Area
Site 0_1	38.73%
Site 1_1	49.04%
Site 2_1	31.81%

Table 19. Percentage of coverage for each transmitter.

From the figure and the table, it seems clear that all cells should use a different channel, being Site 1_1 the one that gets the largest channel bandwidth. However, by doing a 5G NR Downlink Quality prediction and by making use of the Atoll's Point Analysis tool, the perspective changes.

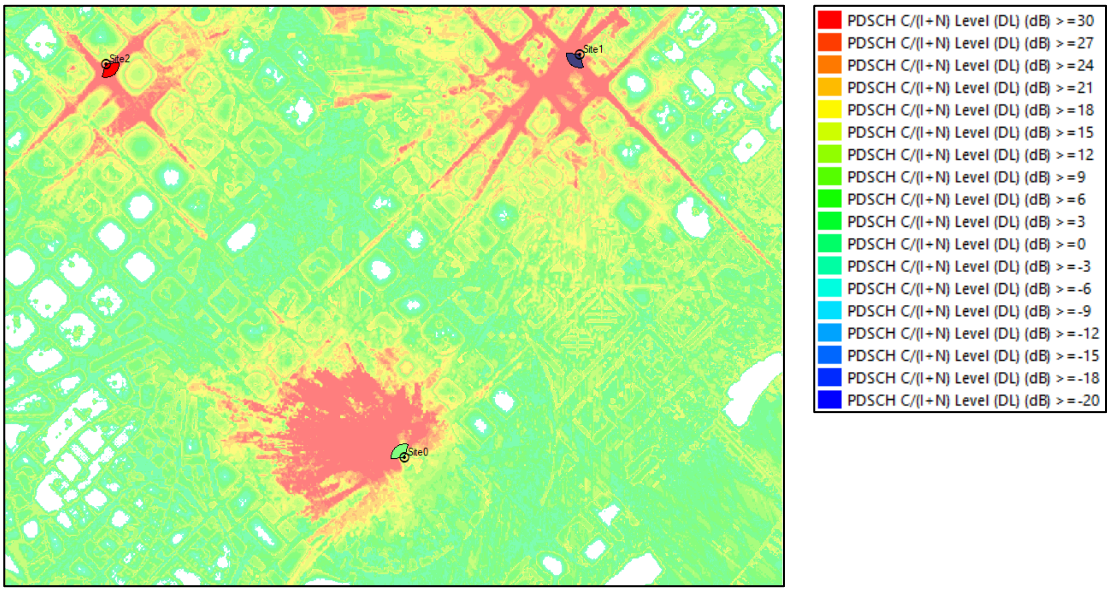


Figure 45. 5G NR Downlink Quality prediction.

By looking at this figure, it can be seen that the area between Site 1 and Site 0 has relatively better signal quality than the one between Site 0 and Site 2 as the colour is generally yellow. To ensure this, the Point Analysis tool will be used in the problematic zones (the zones between the sites).

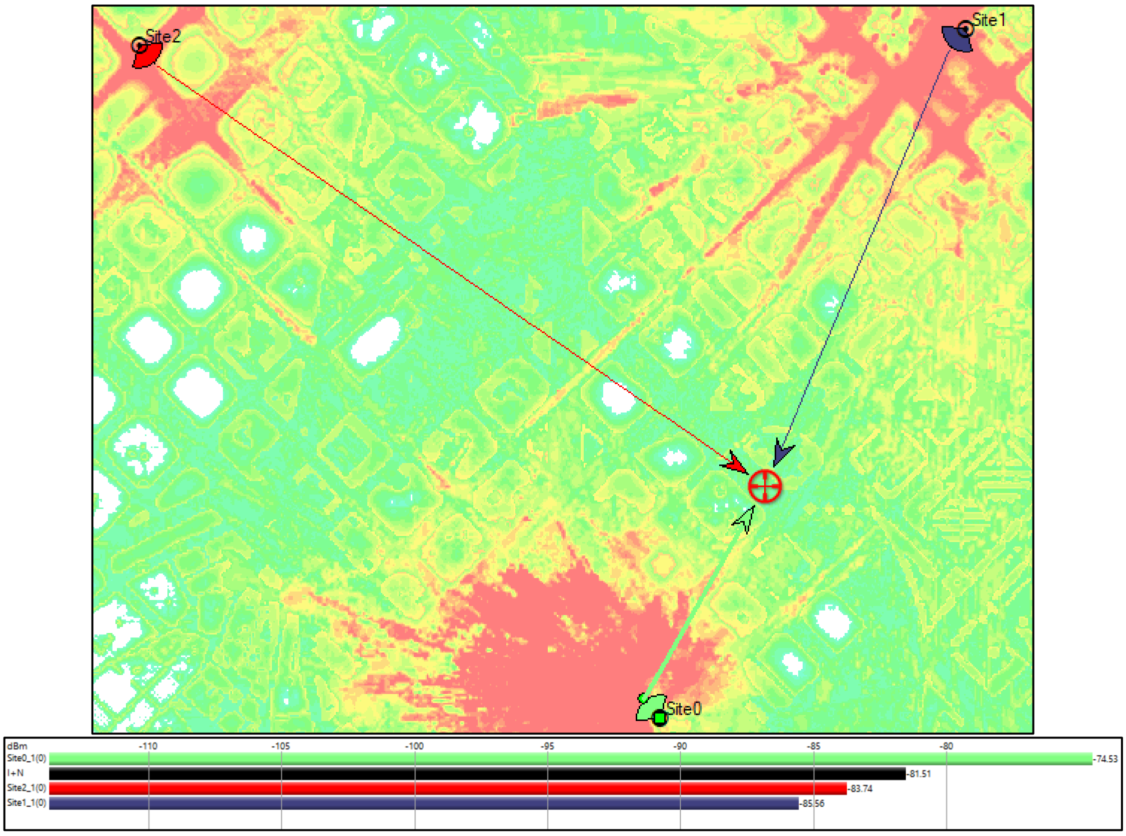


Figure 46. Point analysis between Site 0 and Site 1.

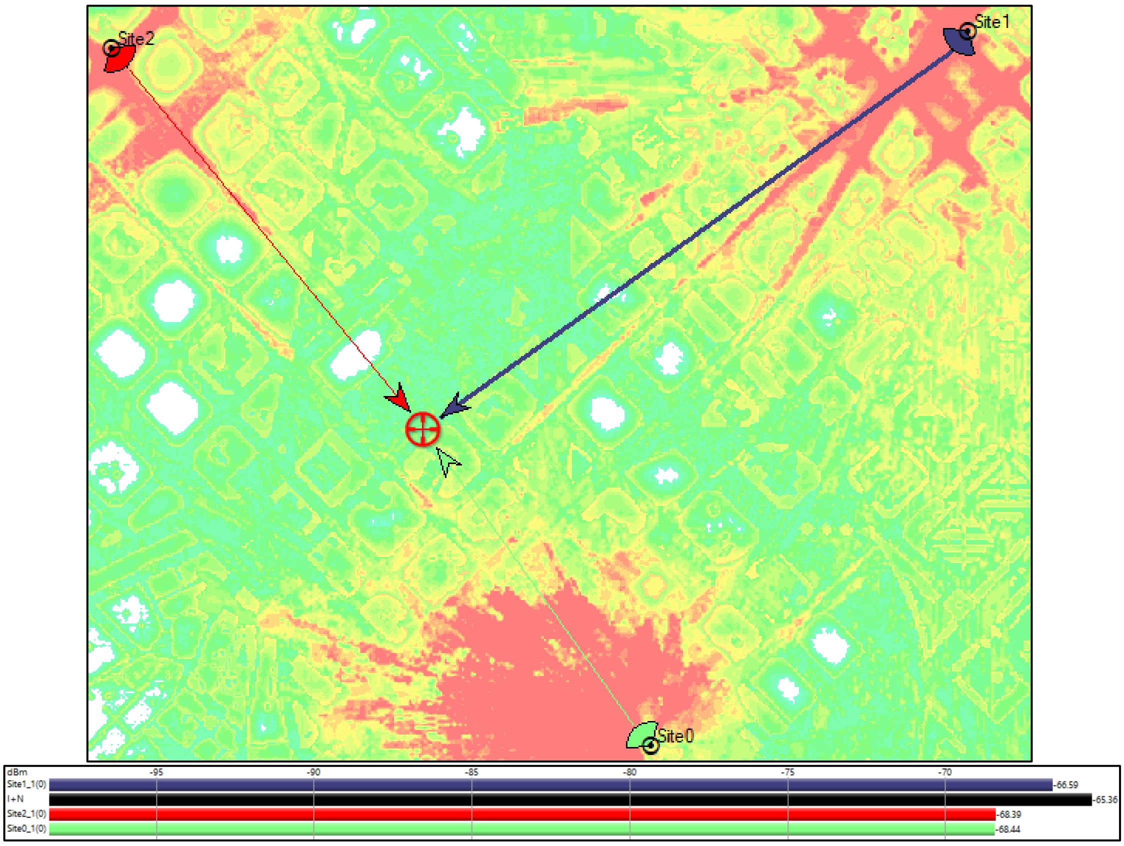


Figure 47. Point analysis between Site 0 and Site 2.

From these point analysis, two conclusions can be extracted:

- Site 0_1 and Site 1_1 can use the same channel (in this case the 100 MHz channel) because their point analysis in the most problematic zone indicates a difference of approximately 7 dB between the PDSCH signal level and the Interference + Noise signal level.
- Site 0_1 and Site 2_1 have to use different channels because in that case the Interference + Noise level was higher than the best server's PDSCH signal level.

The other two parameters have been chosen by the student with the restriction to not collide with any other cell.

As to the Cell Individual Offset, in this case have all been set to 25 dB so the LTE cells do not monopolize all the traffic and this can be shared among the other cells.

All macro cells have now been configured; the only thing left is to set up the small cells in order to cover the concert.

4.2.4. Small cells deployment

As the concert will be located in a relatively small area, the chosen method to cover it has been to deploy small cells at higher frequencies.

Small cells consist of small radio equipment that can be placed on structures such as traffic lights or on the side of a building. Following the criteria to cover as much concert area as possible while trying to keep the site-to-site interferences low, the small cells deployment around the concert is as it follows.

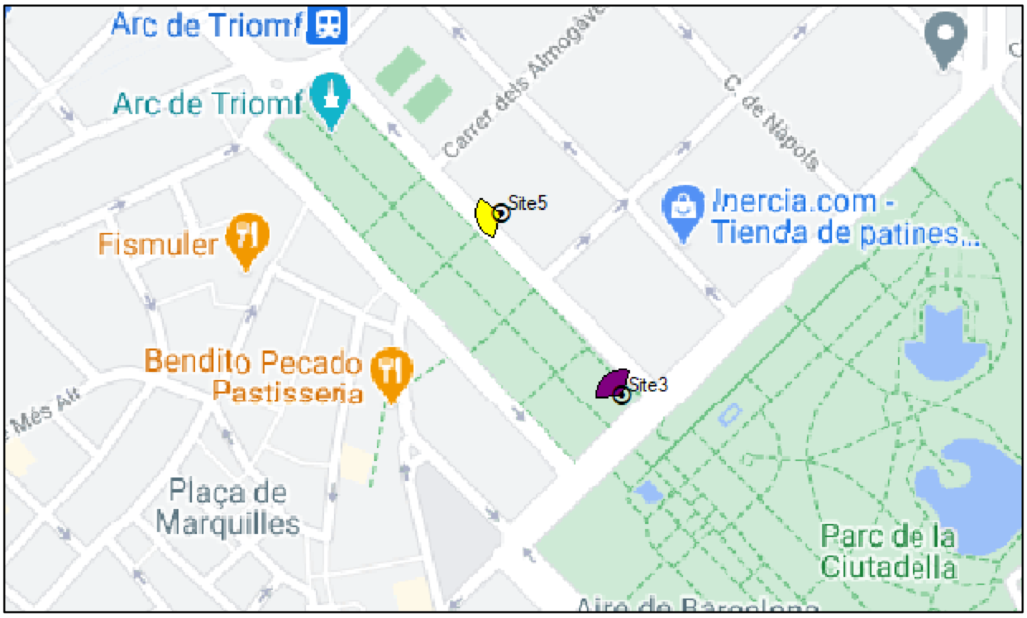


Figure 48. Small cells deployment.

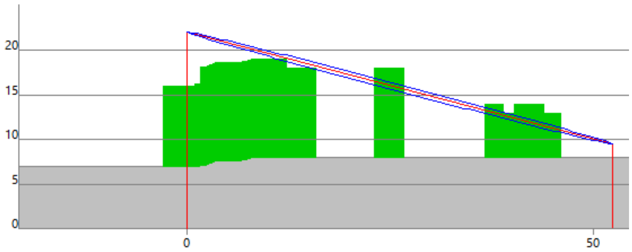
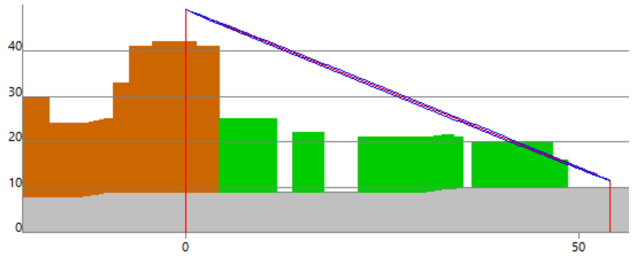
	Site 3 will be located on top of a 15 m platform (streetlight or traffic light). Using the existing station "TELEFONICA MOVILES ESPAÑA, S.A.U. – 0801075".
	Site 5 will be located on top of a 9 m tower on a 31 m building Using the existing station "TELEFONICA MOVILES ESPAÑA, S.A.U. – 0804339"

Table 20. Small cells' sites location.

These transmitters will use 128 transmission and 128 reception antennas and the Default Beamformer that was explained before as its beamforming antenna. Site 5's transmitter will be facing down mechanically in order to point directly to the concert using the parameter Mechanical Tilt set to 40º.

The small cells will be operating at mmWave bands, specifically at band n257 which, by looking at the Table 2 at section 2.2.3., comprises the frequencies from 26.5 GHz to 29.5 GHz. The criteria to choose this band is the following: if this sites will have to cover a large amount of people located in a reduced area; the bandwidth that will be needed in each cell will have to be as large as possible and band n257 has channel bandwidths up to 400 MHz, and moreover, as the area is small the propagation losses will not be an issue.

As seen in the section 4.2.2., the new service called Concert Service will only be admitting the small cells layer. This means that the Concert Users using this service will be connecting only to Site 3 and Site 5. To check if the whole concert can be covered with only two small cells, a 5G NR Downlink Coverage prediction was made and is shown below.

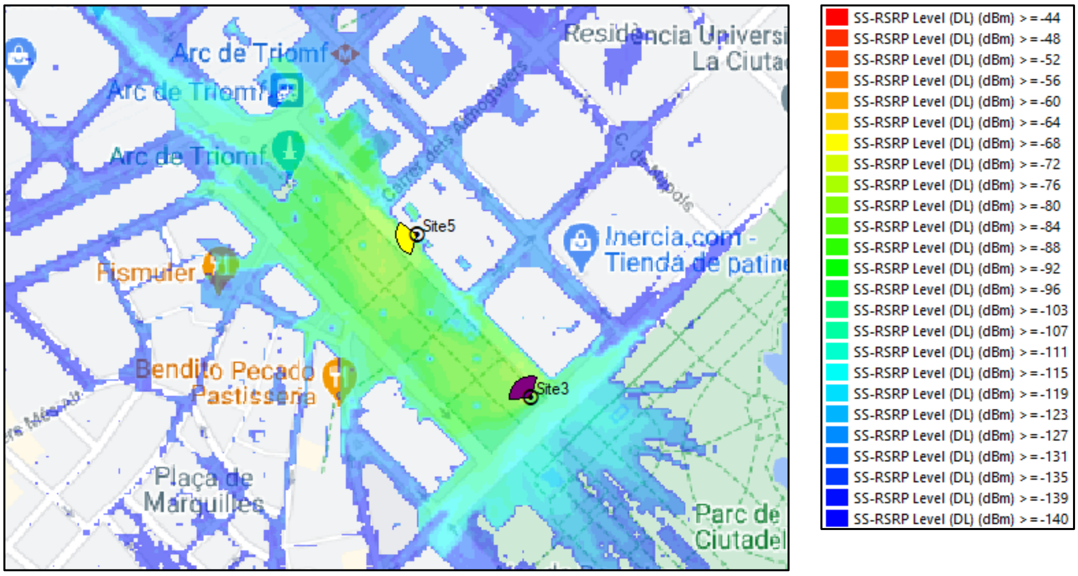


Figure 49. Small cells coverage prediction.

This figure shows that the concert area will be covered with an acceptable SS-RSRP level of approximately -90 dBm.

The cells configuration in this case will be quite different from the ones before and it is shown below.

- **Carrier:** 400 MHz – NR-ARFCN 2057499.
- **Max Power (dBm)**: 34.
- **Layer**: Small Cell.
- **Cell Type**: Primary Cell.
- **Cell Individual Offset (dB)**: 25.
- **Cell Selection Threshold (dB)**: 30.
- **SS/PBCH Numerology**: 3 (120 kHz).
- **Traffic Numerology**: 3 (120 kHz).
- **Scheduler**: Proportional Fair.
- **Diversity Support (DL)**: Transmit diversity, SU-MIMO, MU-MIMO.
- **Diversity Support (UL)**: Receive diversity, SU-MIMO, MU-MIMO.

As the maximum transmission power is 34 dBm and the operating frequency corresponds to mmWave bands, the emitted signal by each transmitter will not be propagating as far as the macro cells. For this reason, the collision zones of these transmitters will be very few as it can be seen on the Overlapping Zones prediction.

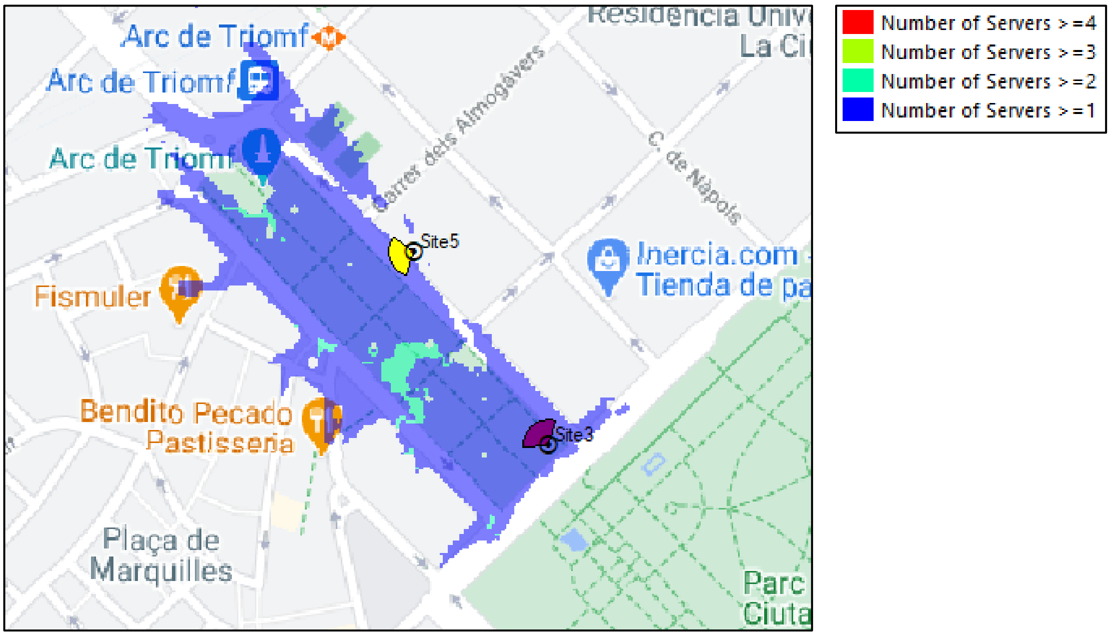


Figure 50. Overlapping zones of the small cells.

The image helps to see that the two servers only collide in small sections of the concert. According to this and also knowing that band n257 supports eight 50 MHz channels, four 100 MHz channels, two 200 MHz channels and one 400 MHz channel, both transmitters can use the same 400 MHz channel in order to provide more capacity to each user.

Now it is time to see how well do these sites behave when they are joined by the macro cells in a simulated scenario.

4.2.5. Simulations

The simulations will help to see if the deployment was successful or if the macro cell and small cell distribution is not good enough to cover a concert at the same time as the coverage of this computation zone.

This simulation was carried out by utilizing the two traffic maps previously created and also limiting the DL/UL traffic load of each cell to an 80%.

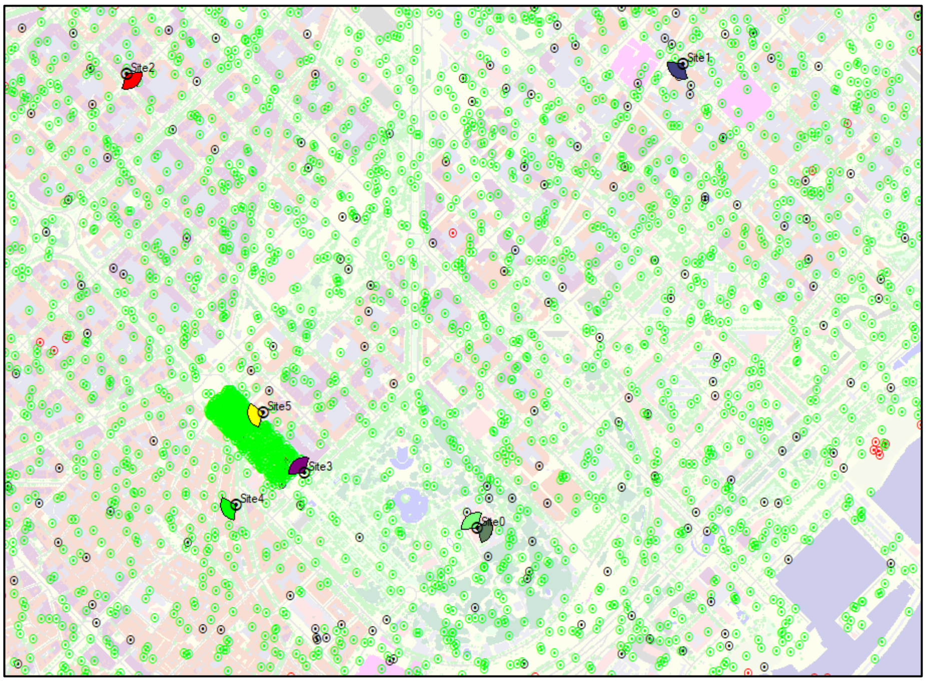


Figure 51. Macro cell and small cell simulation.

The total number of users in this simulation is 2880 and this figure denotes that the majority of them are on connected mode (green dots) but there is a small percentage that have either no coverage or no service. In the figure below, the details of these percentages is shown.

Total number of users not connected (rejected): 27 (0.9%)		
No Coverage:	9	
No Service:	18	
Scheduler Saturation:	0	
Resource Saturation:		0
Backhaul Saturation:		0

Figure 52. Breakdown of the rejected users.

The total number of rejected users is 27 out of 2880, this results on a percentage of rejected users of a 0.9%. In the Figure 52, it can be seen that 9 of them have no coverage and 18 have no service.

There are 18 users that have no service so the quality of the signal they received was not good enough to achieve any coding scheme. Most of these users are located in the beach zone or inside buildings, where the propagation of the signal gets difficult. Also, as it was explained in the last case study, the reason of these No Service users is due to the Cell Individual Offset parameter which is used so the users do not connect only to LTE cells.

Similarly as in the first case study, the No Coverage users are located on the edges of the map which is due to an Atoll bug that happens in every simulation.

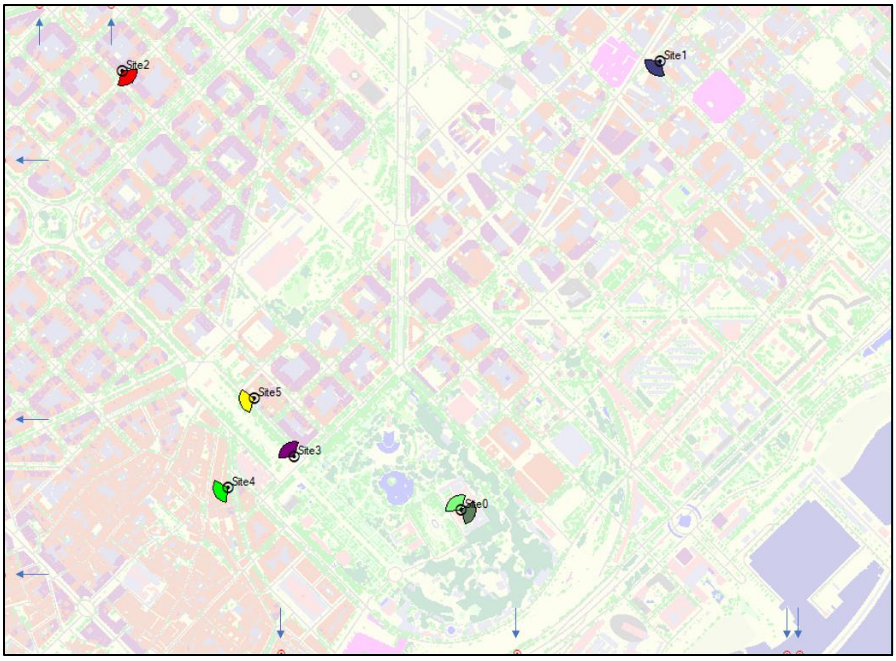


Figure 53. Location of the nine No Coverage users.

As to the concert users, the figures above do not capture whether the concert users where able to connect to the network or they were rejected, so a zoomed image will be shown below.

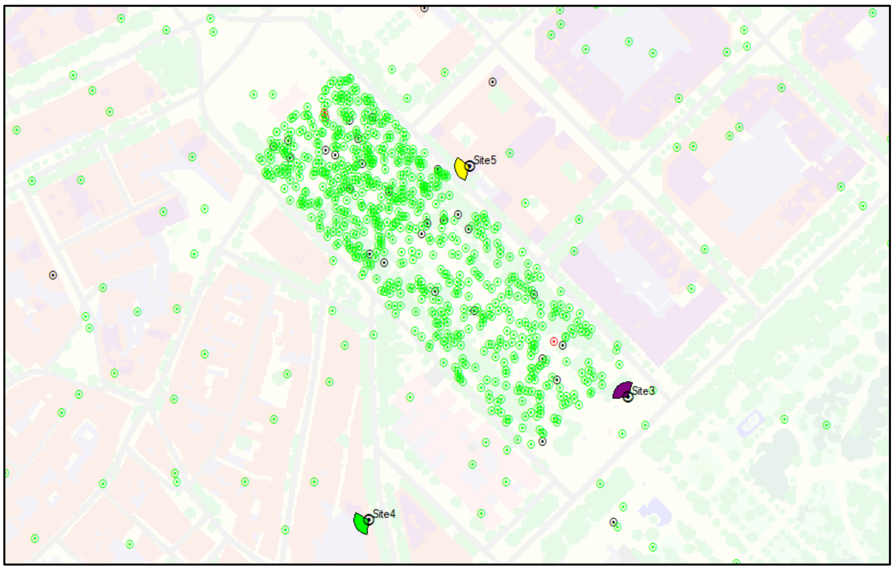


Figure 54. Simulated concert users.

Only three concert users were rejected from the network due to No Service, which looks to be a good percentage, but to make a more accurate analysis, comparative tables will be shown below.

The first table will compare the minimum and maximum demand with the obtained results for each service.

	Demanded connected users	Obtained connected users	Min Throughput demand (UL) (Mbps)	Max Throughput demand (UL) (Mbps)	Obtained Throughput (UL) (Mbps)	Min Throughput demand (DL) (Mbps)	Max Throughput demand (DL) (Mbps)	Obtained Throughput (DL) (Mbps)
Internet	577	567	8.15	81.5	56.03	83	830	186.2
Video call	24	24	3.07	7.2	6.7	3.07	7.2	5.94
Voice call	524	520	5.39	5.39	5.02	4.86	4.86	4.61
Broadband Service	1257	1247	0	2596	1450.56	0	6640	2142.05
Concert Service	498	495	0	24100	8336.52	0	12950	6164.06

Table 21. Comparison between demand and results of the simulation.

The table shows that each obtained cumulated throughput sits between the minimum and maximum demand of their respective service with the exception of the voice call service that does not achieve the minimum demand because it is the same value as the maximum demand, and therefore, by having any rejected user, the minimum is not achieved.

An interesting comparison would be to face the average obtained throughput per user to the average requested throughput per user to see if users would be satisfied with the performance of the network.

	Average Throughput demand/user (UL) (Mbps)	Average obtained Throughput/user (UL) (Mbps)	Average Throughput demand/user (DL) (Mbps)	Average obtained Throughput/user (DL) (Mbps)
Internet	0.2	0.35	0.4	0.456
Video call	0.128	0.279	0.128	0.247
Voice call	0.0244	0.0227	0.0244	0.0231
Broadband Service	1	1.71	4	5.05
Concert Service	50	34.74	25	23.98

Table 22. Comparison between the average throughput demand per user and the average obtained throughput per user.

In the same manner as the first case study, this table is useful to see if the performance of the network was good enough in general terms and specifically, in the case of the concert scenario.

The Internet and the Video Call services surpass by a short margin the average demand per user, which can translate to users using those services being satisfied. The Broadband Service also exceeds the average demand per user with a larger margin than in section 4.1.4. (the first case study), in that case the obtained throughput per user was a 116% of the demanded one in the UL and a 112% in the DL. However, in this simulation, the average obtained throughput per user represents a 171% of the demanded one in the UL and a 126% in the DL. This difference can be due to the fact that some of the Broadband Users are connected to the small cells, which are operating at mmWave frequencies and are probably enjoying a much larger bandwidth available.

As expected, the average throughput per user in case of the Voice Call service does not achieve the demanded one as the cumulated throughput did not achieve the minimum demand as was seen before.

The Concert Service does not achieve the average demand per user neither in the UL or in DL. In the downlink, the margin between the demanded and the obtained throughput is sufficiently small to be considered negligible in terms of user perceived capacity.

However, in the uplink, the average obtained throughput represents approximately a 70% of the demanded one. To have a better understanding on the reason of this difference, the mobile tab on the simulations provide a detailed description of every terminal that either is connected or was rejected by the network.

Exporting these data to Excel and filtering it, it can be observed that in the UL, the Concert Service users that are not experiencing data rates as high as the demanded ones are users that are located the lowest number of resource blocks (bandwidth) on the UL.

The reason on why they are allocated the least amount of resource blocks is due to the Received PUSCH & PUCCH Power, which these users average a value of -78.6 dBm because of the high path losses value of 127.4 dB. Comparing these values to the ones obtained by users which are allocated 3 or more resource blocks, these are -63.5 dBm in case of the Received PUSCH & PUCCH Power and 112.6 dB of path losses. These represent a massive 15 dB difference between the users with one resource block and the ones with 3 or more resource blocks.

By knowing this, it can be concluded that the users who are located further from the transmitters are suffering too much path losses and are not allocated a large enough number of resource blocks to achieve the average demand. To solve this problem, a possible new site could be configured in the opposite site of the concert, trying to minimize the interference with the other two and giving service to these users.

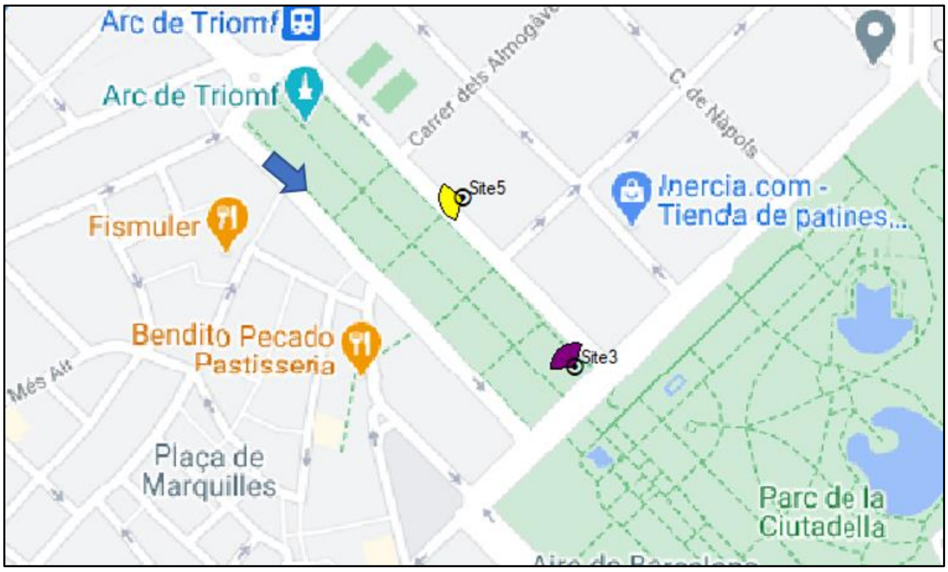


Figure 55. Possible solution.

This possible Site 6 could be pointing towards the direction of the figure 55's arrow and would be another small cell and would give the necessary Received PUSCH & PUCCH Power in order to be allocated a large amount of resource blocks.

5. Conclusions and future development

On this thesis, Atoll was used to design and test a network, including the modelling of services and users, the configuration of the transmitters and cells, the predictions that can be used either as a support to design or as a tool to test the network, and finally the simulations which bring all these together to create a realistic environment to fully examinate the behaviour of the network.

In the first case study the natural evolution from LTE to 5G NR networks was intended to be simulated and tested. The results in that case were successful as it was shown that the behaviour of the network shifted from below the average to above it in most of the services including the Broadband. This service was the most demanding one and its behaviour in terms of average throughput per user was multiplied by 6.4 in the UL and by 37.25 in the DL. With the addition of 5G NR cells, the requirements in terms of throughput were fulfilled at the same time as the percentage of rejected users was maintained at a reasonable level (1%).

Additionally, it must be said that the deployment was not realistic at its maximum because it presented some limitations. The operators in real life deploy a much larger number of sites, specifically in this zone of Barcelona, Movistar has 21 different sites in an area of 1.15 km^2, which proportionally would lead to approximately 79 sites in this Atoll computation zone (4.32 km^2). In this thesis, only 4 sites were deployed among the computation zone, which is a value significantly smaller than the real one, this is one of the reasons on why the LTE results were so poor. Another reason is that in this thesis, only one operator was considered to cover the totality of users, however in real life there are 4 operators that distribute their transmitters over the area, so the cells are not as densified as they were in the case studies [5].

On the other hand, the second case study provided once again the coverage of the same region via a 4G/5G network but this time around also including the challenge of covering a scenario of a concert containing a great amount of people densified in a small area. The results in terms of rejected users in this case were successful as the network presented a percentage of not connected users of 0.9% including the No Coverage ones located on the edges of the map. Then, in terms of throughput, the majority of the users of the different services were satisfied with the performance of the network with the exception of the Concert Service (specially on the UL). As it is explained in section 4.2.5., the allocated bandwidth per terminal is the differential factor to achieve or not the average throughput requirements of the service: when a terminal was allocated a bandwidth of 1 or 2 resource blocks, the obtained throughput was not enough to meet with the requirements but if the allocated bandwidth per terminal was higher than 3 resource blocks, the obtained user application throughput satisfied the requirements of the Concert Service user.

However, and in the same terms as it was explained before, this deployment was not as densified as it is in reality. It may happen that one operator has the small cells deployment as the one showed in this thesis, but maybe another operator has its site located in the opposite site of the concert, and their clients are able to connect to that cell.

Finally, as future development, it would be interesting to explore the possibility to deploy a 4G/5G network design including macro cells and small cells, and make it as densified as in reality in terms of sites and cells. By doing so, the real behaviour of the network could be tested obtaining more significant results.

Also, another line of future development would be to exploit all the possibilities that Atoll brings in terms of design capabilities on 3D beamforming and massive MIMO in both the FR1 and more interestingly, in FR2. It would be interesting to see how far 3D beamforming can be exploited in order to counter the effects of propagation losses on the mmWave bands.

Finally, as Atoll incorporates a functionality that allows to make 3D traffic simulations, it would be interesting to exploit this characteristic and see how signal is signal is propagated inside buildings in 3D.

Bibliography

[1]: Share Technote, 5G/NR – FR/ Operating Bandwidth. [Online] Available: http://www.sharetechnote.com/html/5G/5G_FR_Bandwidth.html

[2]: Chapter 5 5G New Radio (5G NR) – 5G Mobile Communications Systems (5GMCS), Jordi Pérez-Romero, UPC.

[3]: Forsk, "Atoll 3.4.0: User Manual for Radio Networks", 2019.

[4]: Oficina Municipal de Dades, "El Fort Pienc, Eixample", July 2020. [Online] Available: http://www.bcn.cat/estadistica/catala/documents/barris/05_EI_FortPienc_2020.pdf

[5]: Gobierno de España, Infoantenas. [Online] Available: https://geoportal.minetur.gob.es/VCTEL/vcne.do

[6]: "TS 36.101: Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception"(16.7.0 ed.). 3GPP. 2020-10-09. Retrieved 2020-10-21

[7]: Ajuntament de Barcelona, "Informe d'assistència i participació les festes de la Mercè". [Online] Available: https://barcelonadadescultura.bcn.cat/wp-content/uploads/2017/11/Informe-Merce-2017.pdf

Abbreviations and acronyms

3GPP	3rd Generation Partnership Project.
4G	4th Generation.
5G NR	5th Generation New Radio.
ARFCN	Absolute Radio-Frequency Channel Number.
ASODM	Above Surface Object Digital Model.
BS	Base Station.
BWP	BandWidth Part.
CA	Carrier Aggregation.
CDMA	Code Division Multiple Access.
CIO	Cell Individual Offset.
CSI-RS	Channel State Information Reference Signals.
DAC	Digital to Analog Converter.
DFT	Discrete Fourier Transformation.
DL	DownLink.
DM-RS	DeModulation Reference Signal.
DTM	Digital Terrain Model.
EARFCN	E-UTRA Absolute Radio Frequency Channel Number.
eMBB	enhanced Mobile Broadband.
E-UTRA	Evolved UMTS Terrestrial Radio Access.
FDD	Frequency Division Duplex.
GSM	Global System for Mobile communications.
LTE	Long Term Evolution.
MAC	Medium Access Control.
MIMO	Multiple-Input Multiple-Output.
mMTC	massive Machine Type Communication.
MPEG-4	Moving Picture Experts Group 4.
MU-MIMO	Multi-User MIMO.
NB-IoT	Narrow-Band Internet-of-Things.
OFDMA	Orthogonal Frequency-Division Multiplexing Access.
PA	Power Amplifier.
PBCH	Physical Broadcast Channel.
PCI	Physical Cell Identifier.
PDCCH	Physical Downlink Control Channel.
PDCP	Packet Data Convergence Protocol.
PDSCH	Physical Downlink Shared Channel.
PHY	Physical Layer.
PRACH	Physical Random-Access Channel.
PSS	Primary Synchronization Signal.
PT-RS	Phase Tracking Reference Signal.
PUCCH	Physical Uplink Control Channel.
PUSCH	Physical Uplink Shared Channel.
RA	Random Access.
RAN	Radio Access Network.
RB	Resource Block.
RE	Resource Element.
RLC	Radio Link Control.
RS	Reference Signal.
RSI	Root-Sequence Index.

RSRP	Reference Signal Received Power.
SC-FDMA	Single Carrier Frequency Division Multiple Access.
SDAP	Service Data Adaption Protocol.
SRS	Sounding Reference Signal.
SSB	Synchronization Signal Block.
SS-RSRP	Synchronization Signal RSRP.
SSS	Secondary Synchronization Signal.
SU-MIMO	Single User MIMO.
TDD	Time Division Duplex.
TMA	Tower Mounted Amplifier.
TRS	Tracking Reference Signals.
TTI	Transmission Time Interval.
UE	User Equipment.
UL	UpLink.
UMTS	Universal Mobile Telecommunication System.
URLLC	Ultra-Reliable and Low Latency Communications.
V2X	Vehicle-to-Everything.