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5G RADIO FREQUENCY PLANNING AND OPTIMIZATION

A Bachelor Degree Project
Submitted to the faculty of Engineering and Technology
Future University

Prepared By : Mohammed Ali Al-Moafaa
Supervisor :Dr. Saleem Al-Saydi

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بسم الله الرحمن الرحيم

قال تعالى:

﴿يَرْفَعَ اللهُ الَّذِينَ آمَنُوا مِنكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ﴾

(المجادلة: ١١)

To my great family, friends and colleagues…

To everyone who always supports me …

To my beloved ones…

Abstract

The main purpose of this project is to study and develop a model for cellular planning for 5G-NR networks. The goal is to compute the number of required cells to cover a given target area, with well-defined reference model parameters and different traffic profiles. The model was developed considering coverage and capacity planning characteristics related to 5G-NR, for the 700 and 3500 MHz bands, in a specific urban area in Sana'a city with the inclusion of different numerology configurations. With the developed simulator, one can easily assess the impact of varying input parameters, such as user density, target area, frequency band, bandwidth, numerology, throughput at cell edge, traffic profile, among others, on the number of cells. Regarding capacity dimensioning, the process of resource allocation has been redeveloped from scratch due to the inclusion of numerology configurations. An increase on the total number of cells is observed when the density of users increases or when the available bandwidth decreases, and with more users more resources are needed to fulfil coverage and capacity requirements. Most of the cells in urban scenarios are limited by capacity regardless of the frequency band.

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List of Acronyms

1G	second generation
3G	Third Generation of mobile communications
3GPP	Third Generation Partnership Project
4G	Fourth Generation of mobile communications
5G	5th Generation of Mobile Communications
16 QAM	Quadrature Amplitude Modulation (4 bits per symbol)
64 QAM	Quadrature Amplitude Modulation (6 bits per symbol)
256 QAM	Quadrature Amplitude Modulation (8 bits per symbol)
ARFCN	Absolute Radio-Frequency Channel Number
BH	Backhaul
BPSK	Binary Phase Shift Keying
BS	Base station
CA	Carrier Aggregation
CDMA	Code Division Multiple Access
CINR	Carrier to Interference and Noise Ratio
CN	Core Network
CP	Control Plane
CP	Cycle Prefix
CSI-RS	Channel State Information Reference Signal
DL	Downlink
DM-RS	Demodulation Reference Signal
DN	Data Network
DTM	Digital Terrain Model
EIRP	Effective Isotropic Radiated Power
EPC	Evolved Packet Core
EPRE	Energy Per Resource Element m
EPS	Evolved Packet System

E-UTRAN	Evolved Universal Terrestrial Radio Access
FDD	Frequency Division Duplex
FDD	Frequency Division Duplex
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FH	Fronthaul
FTP	File Transfer Protocol
GGSN	Gateway GPRS Support Node
GPRS	General Packet Radio Services
GPRS	General Packet Radio System
GSM	Global System for Mobile
GSM	Global System for Mobile Communications
GSM	Global System for Mobile communications
HRPD	High Rate Packet Data
HSDPA	High Speed Downlink Packet Access
HS-DSCH	High Speed Downlink Shared Channel
HSPA	High Speed Packet Access
HS-PDSCH	High Speed Physical Downlink Shared Channel
HS-SCCH	High Speed Shared Control Channel
HSUPA	High Speed Uplink Packet Access
ICT	Information and Communication Technology
IMT-2020	International Mobile Telecommunications 2020
IoT	Internet of Things
ITU	International Telecommunications Union
ITU-R	International Telecommunications Union-Radio Communications Sector
LTE	Long-Term Evolution
MAC	Medium Access Control
MAPL	Maximum Allowed Path Loss
MBB	Mobile Broadband
MIMO	Multiple-Input Multiple-Output
TDD	Time Division Duplex

MME	Mobility Management Entity
mMTC	Massive Machine Type Communication
MT	Mobile Terminal
MU-MIMO	Multi-User
MVNO	Mobile Virtual Network Operator
NB_IoT	Narrow Band IoT
NFV	Network Functional Virtualization
NG-RAN	New Generation Radio-Access Network
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexer
P2P	Peer-to-peer
PBCH	Physical Broadcast Channel
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDSCCH	Physical Downlink Shared Control Channel
PHY	Physical Layer
PRACH	Physical Random-Access Channel
PRB	Physical Resource Block
PSS	primary Synchronization Signal
PT-RS	Phase Tracking Reference Signal
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying (2 bits per symbol)
RAN	Radio Access Network
RAT	Radio Access Technology
RB	Resource Block
RLB	Radio Link Budget
RLC	Radio Link Control
RNC	Radio network controller
ROM	Residential, Office and Mix scenario

SCS	Sub-carrier spacing
SDAP	Service Data Adaption Protocol
SDN	Software-Defined Network
SINR	Signal to Interference Noise Ratio
SISO	Single-Input Single-Output
SNR	Signal to Noise Ratio
SPM	Standard Propagation Model
SRS	Sounding Reference Signal
SS	Synchronization Signal
SS-RSRP	SS Reference Signal Received Power
SSS	Secondary Synchronization Signal
SU-MIMO	Single-User
TDD	Time Division Multiplex
TMA	Tower Mounted Amplifier
TP	Throughput
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunication System
UP	User Plane
UPF	User Plane Function
URLLC	Ultra-Reliable Low-Latency Communication
VNF	Virtual Network Function
VoIP	Voice over IP
VoLTE	Voice over LTE
WiMAX	Worldwide Interoperability for Microwave Access

CHAPTER 1:

INTRODUCTION

1.1 Preface:

We are living in modern technology. We are living in mobile data revolution era. We cannot think a single moment without technology. Modern technology makes our life easy and comfortable. Modern world is being compressed due to the development of Modern science and its technologies. During the last few decades, the world has seen phenomenal changes in the telecommunications field. We have different mobile and wireless communication technologies, which are mass deployed, such as *WiMAX*, Wi-Fi, LTE, 3G mobile technology, and 4G in addition to accompanying networks, such as personal area networks (e.g., Bluetooth, ZigBee) or sensor networks. Mobile terminals include variety of interfaces, such as GSM is one, which are based on old-fashioned circuit switching, the technology that is going into its last decade of existence. These differences have been noticed in previous generations (1G, 2G, 2.5G and 3G etc.). In accordance too, we are exploring the most advance cellular technology, could be 5G, since a subscriber becomes more aware of the mobile phone technology, he/she will seek for an appropriate package all together, including all the advanced features of a cellular phone can have. This project is designated to harness the momentum of the mobile telecommunications industry to a fifth generation of technologies. Since these technologies will allow completing the consolidation of services, content distribution, communications and computing into a complex distributed environment for connectivity, processing, storage, knowledge and intelligence. This consolidation is responsible for a blurring of roles across the board, with computing and storage being embedded in communication infrastructure, process control being distributed across the Internet and communication functions moving into centralized cloud environments.

1.2 The project common obstacles:

Through this project, we seek to explain an overview about the fifth generation technology and it is associated to these technologies and try to apply this technology as a radio planning and cell studies for specific region in Sana'a city and in the future this project would be developed. ISP Yemen net provides internet services (IS) by using wired network as (Dial, DSL and ADSL) that has many malfunctions as following:

- Lack of coverage at some areas in Sana'a city because of the tough geographical areas, especially those which are suburb and high spread of buildings.
- Installation and maintenance of the networks are difficult and expensive.
- Limited bandwidth that means limited speeds and limited number of subscribers.
- Less reliability because of cables may be born, outages, and malfunction problems.

1.3 Problems to be solved:

1) Leakage of academic researches, or modern technology information in Yemen.
2) Traditional communication in Yemen as GSM system which does not have modern needs for the subscribers, especially Internet and multimedia services that need high transfer rates.
3) Weakness of the communication parameters in Yemen as poor quality, mobility, and converge, and high latency.
4) Disability of linkage between communication technology and intelligent mobility, internet of things (IoT), advance control systems in industry, agriculture, and medical issues.

1.4 The project objectives:

1) Clarify and simplify the fifth generation technology concept, and provide the field of telecommunication engineering with ingenious and modern ideas, which will help academic researchers and technician.
2) Developing the traditional communication technology in Yemen that will increase number of subscriber.
3) The basic goal of this project is the cellular communication companies in Yemen will Improve the quality and performance of communication services such as latency, mobility, converge, ultra- reliable, and supporting real-time facilities like multimedia VOIP, video calls.... etc.
4) Having tremendous changes in technology in Yemen, including intelligent mobility, internet of things (IoT), advance control systems in industry, agriculture, and medical issues.

1.5 project general plan:

Table 1.1 Project general plans

Month	Assignment	
November	Analyzing and collection of information	Ch1.
December	Determination of the idea	Ch2.
January	Designing the project	Ch3.
February	Analyzing the system	Ch4.
April	Operating and examining the system	Ch5.
June	Handover	Ch6.

1.6 The project required tools:

Table 1.2 Project tools

Hardware	Software
- PC or laptop - Papers for printing	- PowerPoint - Word - Excel - Atoll simulation program - Matlab program - Google Earth program - Digital Map

CHAPTER 2:

INTRODUCATION TO MOBILE COMMUNICATION

2.1 History of wireless communications:

Guglielmo Marconi invented the wireless telegraph in 1896. In 1901, he sent telegraphic signals across the Atlantic Ocean (about 3200 km). His invention allowed two parties to communicate by sending each other alphanumeric characters encoded in an analog signal. Over the last century, advances in wireless technologies have led to the radio, the television, the mobile telephone, and communications satellites. All types of information can now be transformed to almost every corner of the world. Recently, a great deal of attention has been focused on satellite communications, wireless networking, and cellular technology. Wireless networking is allowing businesses to develop WANs, MANs, and LANs without a cable plant. The cellular or mobile telephone is the modern equivalent of Marconi's wireless telegraph, offering two-party, two-way communication. The first-generation wireless phones used analog technology. These devices were very heavy and the coverage was patchy, yet they successfully demonstrated the inherent convenience of mobile communications. The current generation of wireless devices is built using digital technologies. Digital networks carry much more traffic and provide better reception and security than analog networks.

2.2 Evolution of mobile communications

- The first version of a mobile radio telephone being used in 1924.
- In 1926 telephone service in trains on the route between Hamburg and Berlin was approved and offered to 1st class travelers.
- In 1935, Edwin Armstrong demonstrated FM and it has been the primary modulation technique used for mobile communication systems throughout the world.
- In 1946, the first public mobile telephone service was launched in 25 cities across the United States (543 users) by BELL Laboratories in USA. Early mobile systems used single high power transmitters with AM Modulation techniques to give coverage up to about 50 miles (only limited customers). Could get the service. This inefficient use of the radio

spectrum coupled with the state of radio technology at that time severely limited the system capacity.

- A solution to this capacity problem emerged during the 50's and 60's when researchers at Bell Laboratories developed the cellular concept.
- In 1973, Martin Cooper (a Motorola researcher and executive) made the first mobile telephone call from handheld subscriber equipment.
- In 1983, the first analog cellular system deployed in Chicago, USA.

2.3 Cellular Telephony:

Cellular telephony is designed to communicate between two moving units, which called mobile stations (MSs), or between one mobile unit and one stationary unit called a land unit. A service provider must be able to locate and track a caller, assign a channel to the call, and transfer the channel from base station to base station as the caller moves out of range.

To make this tracking possible, each cellular service area is divided into small regions called cells. Each cell contains an antenna and is controlled by a solar- or AC- powered network station, called the base station (BS). Each base station, in turn, is controlled by a switching office, called a mobile switching center (MSC). The MSC coordinates communication between all the base stations and the telephone central office. It is a computerized center that is responsible for connecting calls, recording call information, and billing.

2.3.1 First Generation (1G) systems:

The original cellular telephone networks provided analog traffic channels; these are now referred to as first-generation systems. Since the early 1980s the most common first-generation systems are AMPS, NMT, TACS, and NTT.

2.3.1.1 American Advanced Mobile Phone Service (AMPS):

- Two 25-MHz bands are allocated to AMPS.
- Each of these bands is split in two to encourage competition (i.e., so that in each market two operators can be accommodated). An operator is allocated only 12.5 MHz in each direction for its system.
- The channels are spaced 30 kHz apart, which allows a total of 416 channels per operator using FDMA.
- 21 channels are allocated for control, leaving 395 to carry calls.
- The control channels operating at 10 kbps which used BFSK.
- The conversation channels carry the conversations in analog using FM.

2.3.1.2 European Total Access Communication Systems (TACS):

- Deployed in 1985.
- Almost identical to AMPS except that the channel bandwidth is scaled to 25 kHz instead of 30 kHz as in AMPS.

1G Drawbacks:

- Poor voice quality.
- Poor battery life and large telephone size.
- Limited capacity (number of subscribers).
- No security because it’s an analog technology.
- Poor handoff reliability (transition between cells).

2.3.2 Second Generation (2G) systems:

Second-generation systems have been developed in early 90s to provide higher quality signals, higher data rates for support of digital services, and greater capacity. Moreover, the 2G systems provide many features as:

- Digital voice coding and modulation
- Security (Encryption and decryption).
- Error detection and correction.
- Multiple channels per cell.

The most popular 2G system was the Global System for Mobile Communications (GSM), that was originally designed as a Pan-European technology, but which later became popular throughout the world. Also remarkable was IS-95, another system was known as CDMA One, which was designed by Qualcomm, and which became the dominant 2G system in the USA. The success of 2G communication systems came at the same time as the early growth of the internet. It was natural for network operators to bring the two concepts together, by allowing users to download data onto mobile devices. To do this, so-called 2.5G systems built on the original ideas from 2G, by introducing the core network's packet switched domain and by modifying the air interface so that it could handle data as well as voice.

2.5G is a technology between the 2G and 3G; it is described as 2G technology before 3G implementation. A variety of 2.5G techniques are being employed to improve the speed of data for enhanced combined with GPRS. 2.5G is an interim solution designed to allow for improved data rates e-mail and Internet access.

The main features of the 2.5G are:

- Ability to send and receive Email messages.
- Web browsing,
- Speed: 64-144 kbps
- Furthermore, Built-in camera can be included in the mobile station (Camera phones).

The General Packet Radio Service (GPRS) incorporated these techniques into GSM, while IS-95 was developed into a system known as IS-95B. At the same time, the data rates available over the internet were progressively increasing. To apply this, designers first improved the performance of 2G systems using techniques such as Enhanced Data Rates for GSM Evolution (EDGE) and then introduced more powerful third generation (3G) systems in the years after 2000.

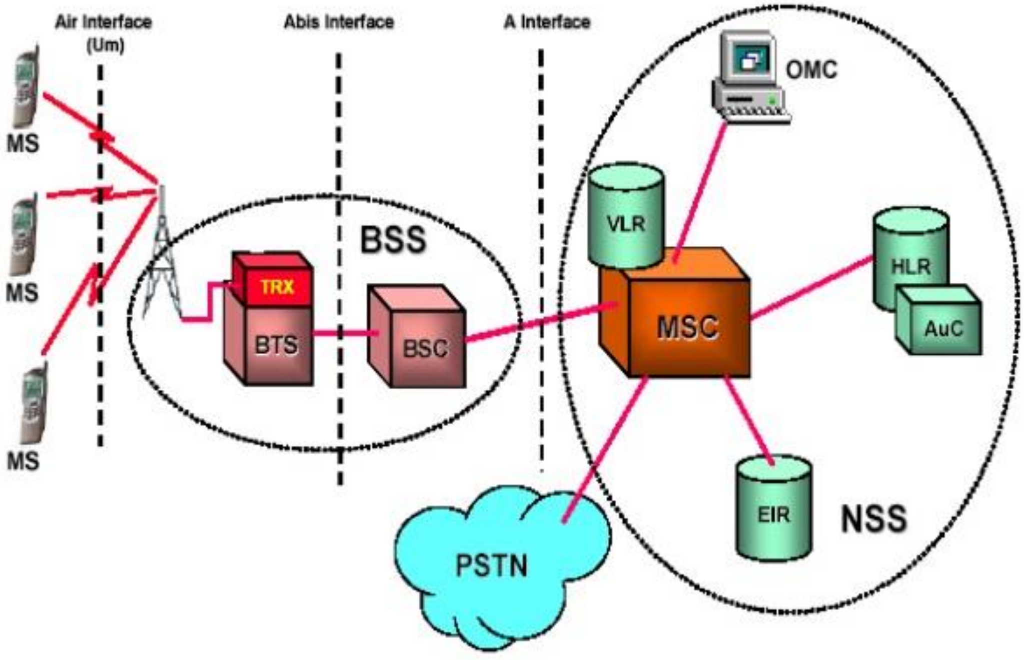


Figure 2. 1 Architecture of GSM

2.3.3 Third Generation (3G) systems:

The main objective of the third generation (3G) of wireless communication system is to provide fairly high speed wireless communications to support multimedia, data, and video in addition to voice. 3G developed in the early 2000s, the main features of the 3G systems are:

- High transmission rate and the support of multimedia services: Multiple-megabit internet services, video calls, and mobile TV Using a single mobile device.
- Peak Data rate: around 2Mbps. Bandwidth.

The ITU's International Mobile Telecommunications in the year 2000 (IMT-2000) initiative has defined the ITU's view of third-generation capabilities as:

- Voice quality comparable to the public switched telephone network.
- 144-kbps data rate available to users in high-speed motor vehicles over large areas.
- 384 kbps available to pedestrians standing or moving slowly over small areas.
- Support for 2.048 Mbps for office use.
- Support for both packet-switched and circuit-switched data services.
- An adaptive interface to the Internet

In this system, the air interface includes extra optimizations that are targeted at data applications, which increase the average rate at which a subscriber can upload or download information, at the expense of introducing greater variability into the data rate and the arrival time.

The world's dominant 3G system is the Universal Mobile Telecommunication System (UMTS). UMTS was developed from GSM by completely changing the technology used on the air interface, while keeping the core network almost unchanged. The system was later enhanced for data applications, by introducing the 3.5G technologies of high speed downlink packet access (HSDPA) and high speed uplink packet access (HSUPA), which are collectively known as high speed packet access (HSPA), which reduced latency**.** And is up to five times more system capacity in the downlink up to twice as much system capacity in the uplink compared with WCDMA.

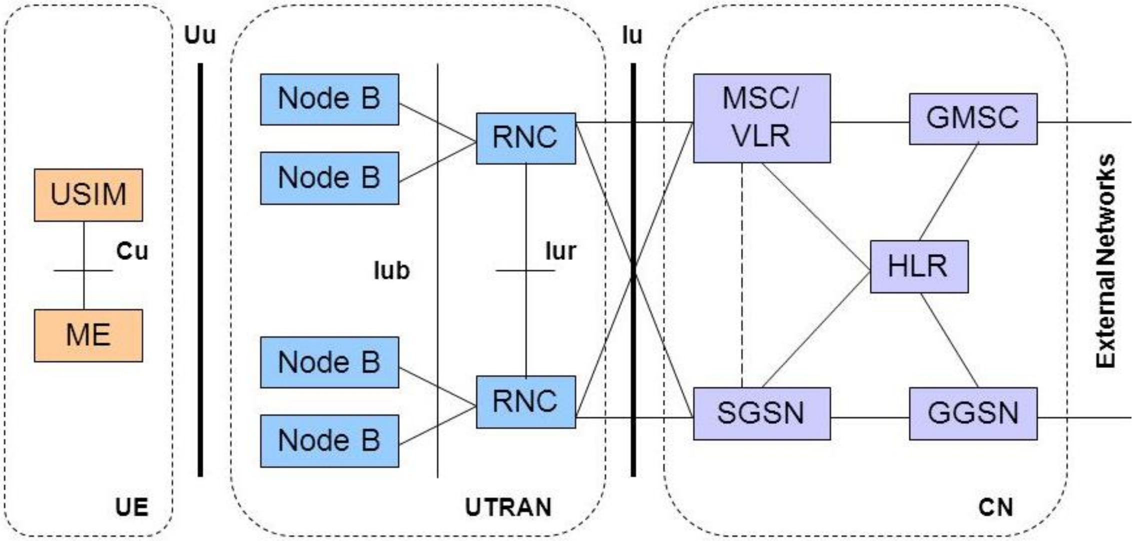


Figure 2.2 Architecture of UMTS

2.3.4 Pre-4G technology (3.9G):

The ITU specified a set of needs for 4G standards, called the International Mobile Telecommunications Advanced (IMT-Advanced) specification, setting higher speed requirements for 4G service as follows:

- 300 Mbps for high mobility communication (such as from trains and cars).
- 1Gbps for low mobility communication (such as pedestrians and stationary users).

Two 3.9G (Also known as 4G technology) standards are commercially deployed Mobile WiMAX standard (first used in South Korea in 2007), and Long Term Evolution (LTE) standard (first released in Oslo, Norway and Stockholm, Sweden since 2009). Since the first-release versions of Mobile WiMAX and LTE support much less than 1Gbps peak bit rate, they are not fully IMT-Advanced compliant, but are often called 4G by service providers.

Evolved HSPA (HSPA+) is a further improved 3GPP standard, which was released late in 2008 with subsequent worldwide adoption beginning in 2010. The newer standard allows bit-rates to reach as high as 337 Mbps in the downlink and 34 Mbps in the uplink. HSPA+ supported with multiple input, multiple output (2x2 MIMO) technologies and higher order modulation (64 QAM).

Long Term Evolution (LTE) is a standard for wireless communication of high-speed data for mobile phones and data terminals. It depends on the GSM/EDGE and UMTS network technologies, increasing the capacity and speed using a different radio interface together with core network improvements. The standard is developed by the 3GPP. The LTE features are:

- downlink peak rates of 300 Mbps
- uplink peak rates of 75 Mbps
- Quality of Service (QoS) provisions permitting a transfer latency of less than 5ms in the radio access network (RAN).
- Has the ability to manage fast-moving mobiles
- Supports scalable carrier bandwidths, from 1.4 MHz to 20 MHz

- Orthogonal frequency-division multiple access (OFDMA) for the downlink, Single carrier FDMA for the uplink to conserve power.
- Supports both FDD and TDD.

2.3.5 Fourth Generation (4G) systems:

4G provides mobile broadband Internet access, with higher data rate and expanded many multimedia services. The main features of the 4G systems are:

- Higher speed 0.1~1 Gbps.
- More security.
- Higher capacity.
- Lower cost than previous generations.
- Provides digital system with voice over-IP (VOIP) technology.
- IPv6 Core.
- Orthogonal frequency-division multiplexing (OFDM) is used instead of CDMA.

The 4G system are able to provide a comprehensive IP solution where voice, data and streamed multimedia can be given to users on an "Anytime, Anywhere" basis.

LTE Advanced (LTE-A) LTE Advanced is a mobile communication standard and a major enhancement of the Long Term Evolution (LTE) standard. It was formally submitted as a candidate 4G system to ITU in late 2009 as meeting the requirements of the IMT-Advanced standard, and was standardized by the 3GPP in March 2011.

There are many features of the LTE-Advanced including higher capacity, increased peak data rate 3Gbps for the downlink and 1.5Gbps for the uplink, LTE also has a higher spectral efficiency (30 bps/Hz), Increased number of simultaneously active subscribers, and LTE-Advanced can use up to 8x8 MIMO and 128 QAM in downlink direction.

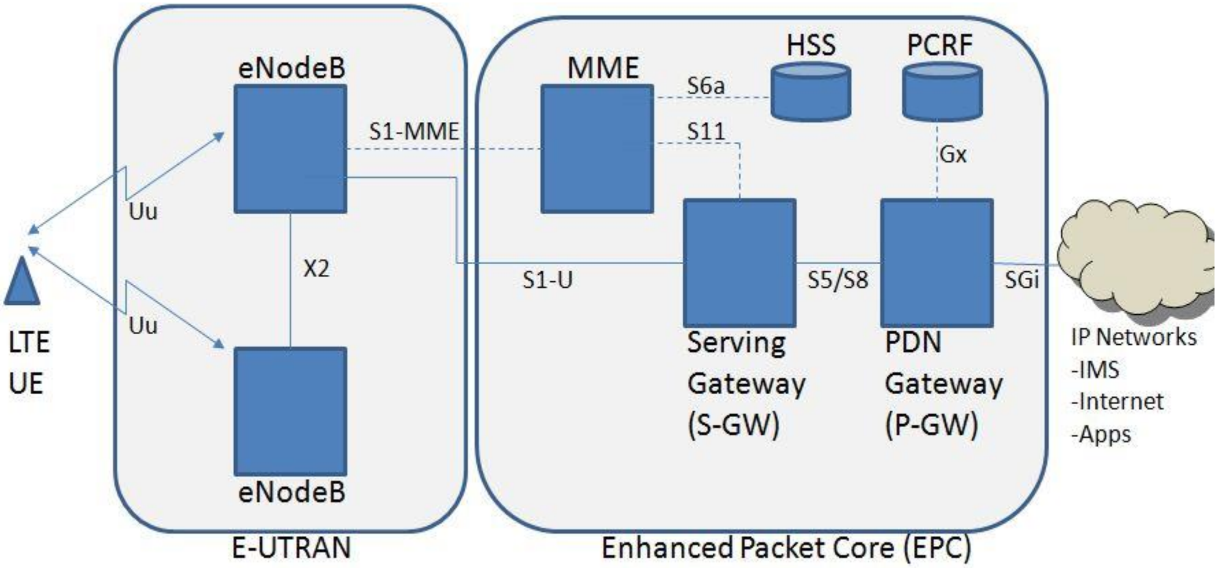


Figure 2.3 Architecture of LTE

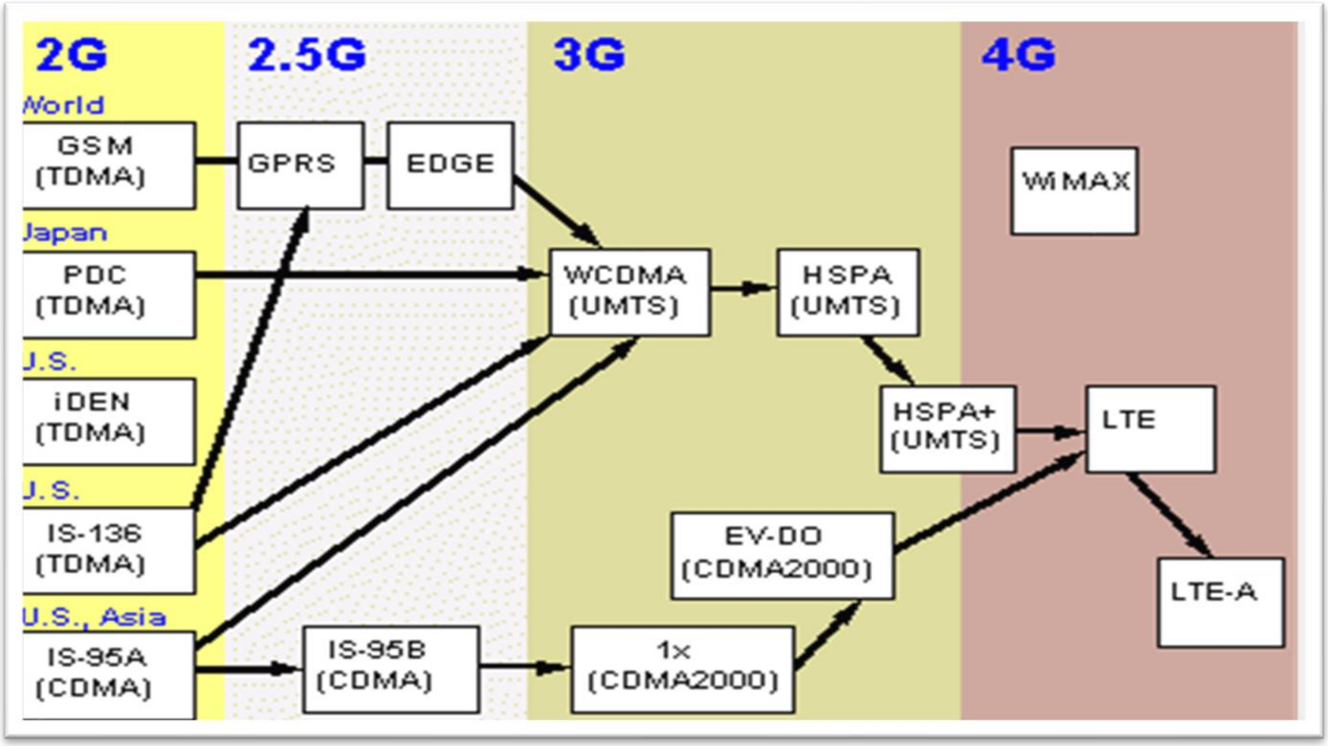


Figure 2.4 Evolution of mobile communication

2.3.6 5G Radio Technology fundamentals:

Wireless access is envisioned to enable a networked society, where information can be accessed and shared anywhere and anytime, by anyone and anything. This section explains concepts of some key features that are necessary to develop the 5G mmWave network planning. 5G shall provide wireless connectivity for anything that can benefit from being connected. To enable a truly networked society, there are three major challenges:

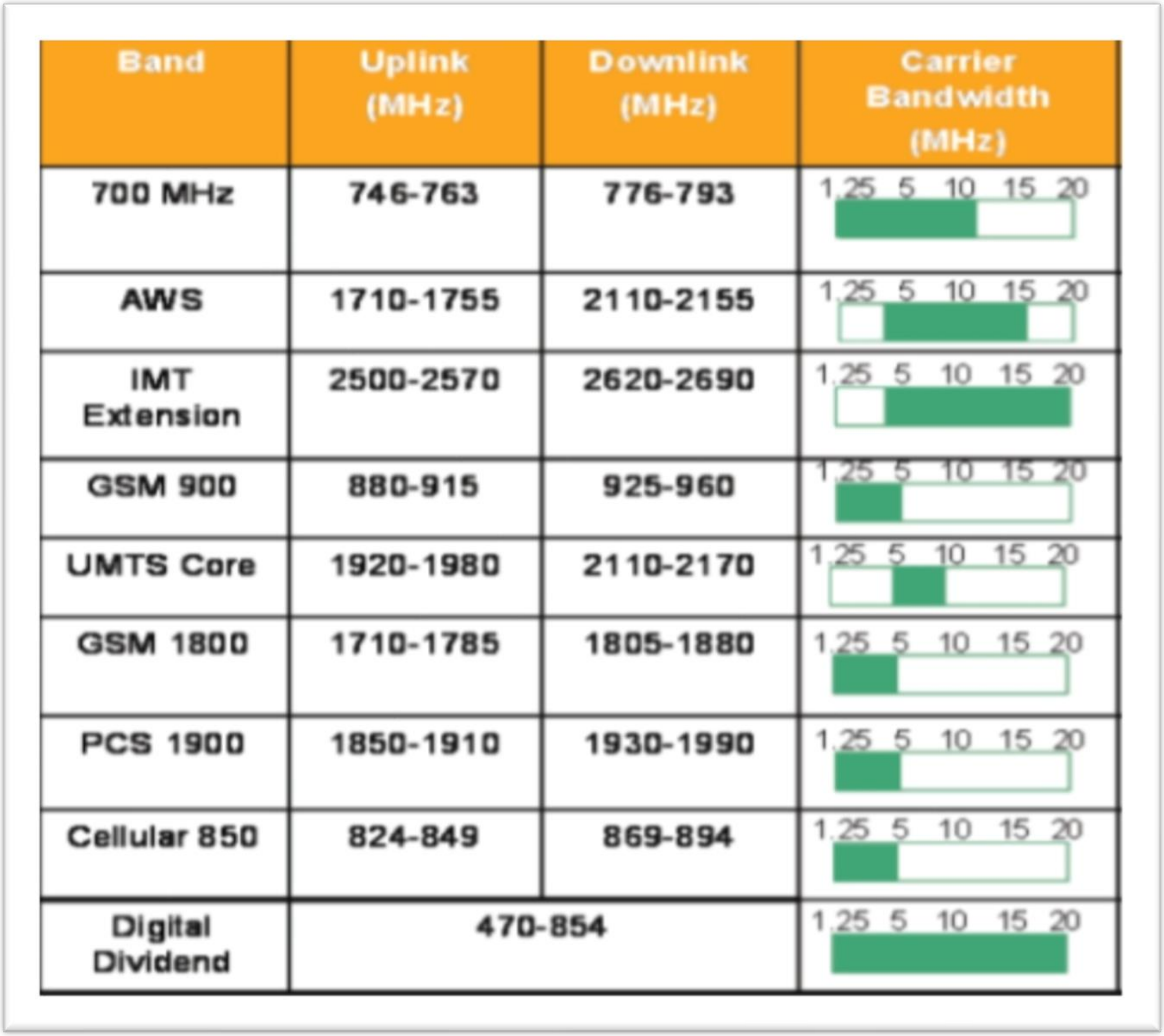
- A massive growth in the number of connected devices.
- A massive growth in traffic volume.
- A wide range of applications with diverse requirements and characteristics.

To address these challenges, 5G wireless access not only requires new functionalities but also substantially more spectrum and wider frequency bands.

The current cellular systems operate below 6 GHz. Third generation partnership project (3GPP) is currently developing a global standard for new radio access technology, 5G new radio (NR), which will operate in frequencies from below 1 GHz up to 100 GHz. 5G NR shall unleash new frequencies and new functionalities to support ever-growing human-centric and machine-centric applications.

2.3.6.1 Justification of the necessity of 5G in mmWave band:

Nowadays, mobile broadband networks are facing the growing consumer data rate demands and the exponential increasing of traffic volumes. Also, wireless service providers are limited to carrier frequency spectrum ranging between 700 MHz and 2.6 GHz. In Figure 2.5, the global spectrum bandwidth allocation for all cellular technologies does not exceed 780 MHz, where each major wireless provider has approximately 200 MHz across all of the different cellular bands of spectrum available to them.



Band	Uplink (MHz)	Downlink (MHz)	Carrier Bandwidth (MHz)
700 MHz	746-763	776-793	1.25 5 10 15 20
AWS	1710-1755	2110-2155	1.25 5 10 15 20
IMT Extension	2500-2570	2620-2690	1.25 5 10 15 20
GSM 900	880-915	925-960	1.25 5 10 15 20
UMTS Core	1920-1980	2110-2170	1.25 5 10 15 20
GSM 1800	1710-1785	1805-1880	1.25 5 10 15 20
PCS 1900	1850-1910	1930-1990	1.25 5 10 15 20
Cellular 850	824-849	869-894	1.25 5 10 15 20
Digital Dividend	470-854		1.25 5 10 15 20

Figure 2.5 Current 2G, 3G, and 4G spectrum and bandwidth allocations

Thus, an efficient radio access technology combined with more spectrum availability is essential to achieve the ongoing demands faced by wireless carriers. In the development and implementation of the new fifth generation (5G), there will be main differences compared to 4G. It is required the use of much greater spectrum allocations at untapped mmWave frequency bands, highly directional beamforming antennas, longer battery life, higher bit rates in larger portions of the coverage area, lower infrastructure costs, and higher aggregate capacity for many simultaneous users in both licensed and unlicensed spectrum (e.g. the convergence of Wi-Fi and cellular). The networks of 5G mm Wave wireless connections should allow fast deployment and connectivity with cooperation between base stations.

2.3.6.2 5G New Radio (NR):

The fifth generation of the wireless access technology is known as 5G New Radio (5G NR) and it has been developed by the Third-Generation Partnership Project (3GPP) over the past years with the goal to address a variety of scenarios to be enabled by future enhanced mobile technologies. Compared to LTE, the previous 4G radio access technology, 5G NR presents many benefits, such as:

- Exploitation of higher frequency bands in order to support very wide transmission bandwidths and very high data rates.
- Ultra-lean design to enhance network energy performance and reduce interference, avoiding the always-on transmissions.
- Support of multiple subcarriers spacing.
- Forward compatibility for the future, enabling new services yet unknown.
- Low latency to improve performance.
- Beam-centric design enabling extensive usage of beam forming and massive number of antenna elements not only for data transmission but also for control plane procedures.

2.3.6.3 5G NR use cases:

5G has been thought to cover three major use cases:

- **Enhanced mobile broadband (eMBB):** services that demand high data rates, high traffic volumes and wide-area coverage. The eMBB address human-centric communications.

- **Massive machine-type communication (mMTC):** services characterized by a massive number of devices, such as sensors, wearable, IoT devices, etc., that do not require high energy consumption and at a low cost. These devices consume and generate small amount of data, hence, support of high data rates is not important. This is machine-centric use case.

- **Ultra-reliable and low-latency communication (uRLLC):** services that require very low latency and very high reliability and availability. Some examples are traffic safety, factory automation, e-health services, self-driving car, etc. It covers human and machine-centric communications.

Even though these are the three distinctive use cases, there are scenarios where use cases may be combined, due to the wide range of possibilities for specific services that this technology brings.

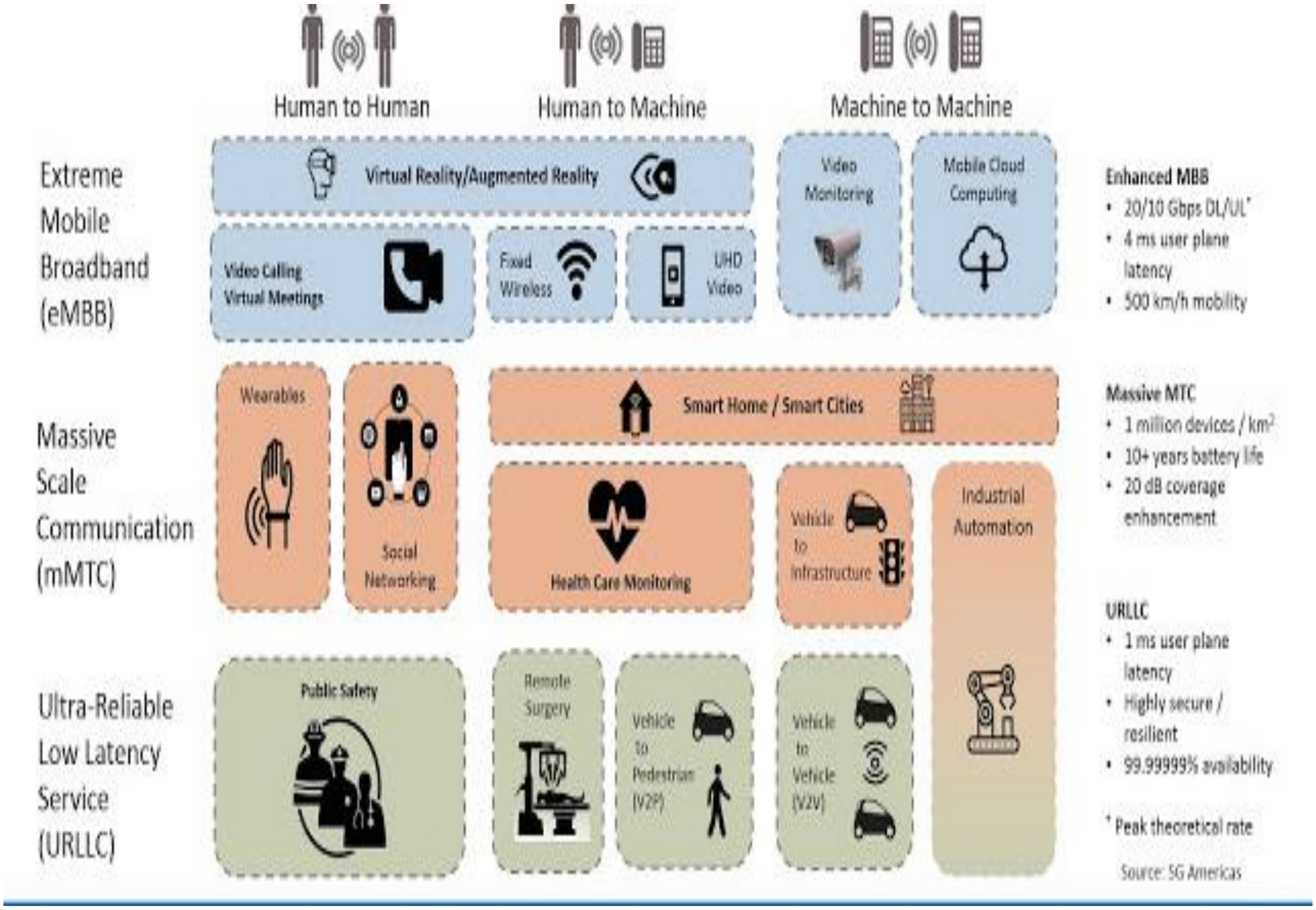


Figure 2.6 5G uses cases

2.3.6.4 Technical requirements and frequency bands:

As part of the standardization process of 5G, the ITU-R, the radio communication sector of the International Telecommunication Union (ITU), responsible for ensuring efficient use of the RF spectrum, issued the International Mobile Telecommunications-2020 (IMT-2020), a series of requirements for the 5G networks.

The following table summarizes the minimum requirements related to technical performance for IMT-2020 radio interfaces, which are based on a set of capabilities needed to support the 5G use cases and usages scenarios.

Table 2.1 Minimum Technical Performance Requirements for IMT-2020

Parameter	Minimum Technical Performance Requirement
Peak data rate	Downlink: 20 Gbps Uplink: 10 Gbps
Peak spectral efficiency	Downlink: 30 bit/s/Hz Uplink: 15 bit/s/Hz
User-experienced data rate	Downlink: 100 Mbps Uplink: 50 Mbps
Area traffic capacity	10 Mbps/m^2 (indoor hotspot for eMBB)
User plane latency	4 ms for eMBB 1 ms for uRLLC
Control plane latency	20 ms
Connection density	1,000,000 devices per km^2
Energy efficiency	Efficient data transmission in a loaded case Low energy consumption when there is no data High sleep ratio Long sleep duration
Mobility	1.5 bit/s/Hz at 10 km/h for indoor hotspot eMBB 1.12 bit/s/Hz at 30 km/h for dense urban eMBB 0.8 bit/s/Hz at 120 km/h for rural eMBB 0.45 bit/s/Hz at 500 km/h for rural eMBB
Mobility interruption time	0 ms
Bandwidth	At least 100 MHz and up to 1 GHz in higher frequency bands. Scalable bandwidth shall be supported

NR can be deployed in different frequency bands, which were defined by 3GPP on the Release 15 work. Because of different RF requirements (e.g. maximum transmission power), these bands were divided into two frequency ranges:

- **Frequency range 1 (FR1)** that includes all existing and new bands below 6GHz.
- **Frequency range 2 (FR2)** that includes new bands in the range of 24.25 – 52.6 GHz.

At the same time, 3GPP defined the operating bands, corresponding to different frequency ranges for downlink and uplink.

Table 2.2 NR Operating Bands

NR Operating Band	Uplink Range (MHz)	Downlink Range (MHz) Duplex Mode	Duplex Mode
Frequency Range 1 (FR1)			
n1	1920 – 1980	2110 – 2170	FDD
n2	1850 – 1910	1930 – 1990	FDD
n3	1710 – 1785	1805 – 1880	FDD
n5	824 – 849	869 – 894	FDD
n7	2500 – 2570	2620 – 2690	FDD
n8	880 – 915	925 – 960	FDD
n12	699 – 716	729 – 746	FDD
n20	832 – 862	791 – 821	FDD
n25	1850 – 1915	1930 – 1995	FDD
n28	703 – 748	758 – 803	FDD
n34	2010 – 2025	2010 – 2025	TDD
n38	2570 – 2620	2570 – 2620	TDD
n39	1880 – 1920	1880 – 1920	TDD
n40	2300 – 2400	2300 – 2400	TDD
n41	2496 – 2690	2496 – 2690	TDD
n50	1432 – 1517	1432 – 1517	TDD
n51	1427 – 1432	1427 – 1432	TDD
n66	1710 – 1780	2110 – 2200	FDD

n70	1695 – 1710	1995 – 2020	FDD
n71	663 – 698	617 – 652	FDD
n74	1427 – 1470	1475 – 1518	FDD
n75	N/A	1432 – 1517	SDL
n76	N/A	1427 – 1432	SDL
n77	3300 – 4200	3300 – 4200	TDD
n78	3300 – 3800	3300 – 3800	TDD
n79	4400 – 5000	4400 – 5000	TDD
n80	1710 – 1785	N/A	SUL
n81	880 – 915	N/A	SUL
n82	832 – 862	N/A	SUL
n83	703 – 748	N/A	SUL
n84	1920 – 1980	N/A	SUL
n86	1710 – 1780	N/A	SUL
Frequency Range 2 (FR2)			
n257	26500 – 29500	26500 – 29500	TDD
n258	24250 – 27500	24250 – 27500	TDD
n260	37000 – 40000	37000 – 40000	TDD
n261	27500 – 28350	27500 – 28350	TDD

2.3.6.5 Waveform, numerology and frame structure:

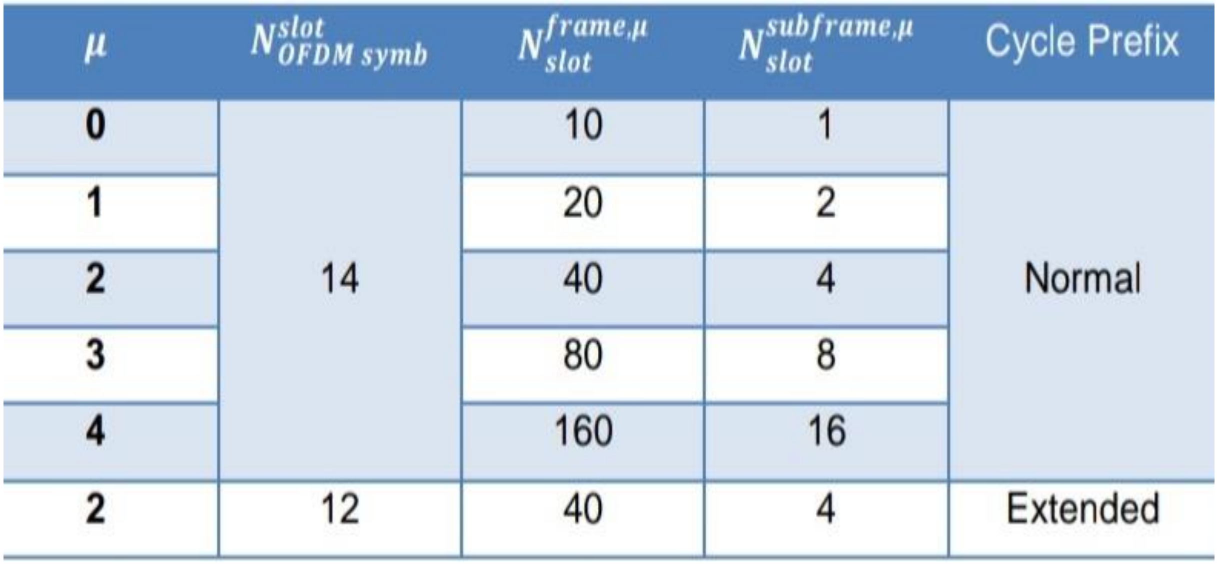
5G NR uses orthogonal frequency division multiplexing (OFDM) with cyclic prefix (CP) for both downlink and uplink.

One of the key features of 5G NR is its scalable OFDM numerology (μ=0, 1, 2, 3, 4), which adopts flexible subcarrier spacing of **$2^{\mu} \cdot 15$ kHz** (from 15 kHz up to 240 kHz). Accordingly, the CP is also proportionally scalable. This allows a wide range of deployment scenarios, from frequency bands bellow 1 GHz up to millimeter wave bands.

The NR time-domain structure consists on a 10ms frame divided into ten 1ms subframes. In turn, a subframe is divided into slots of 14 OFDM symbols each, and its duration in milliseconds depends on the numerology.

On the frequency domain, the resource block (RB) consists of 12 consecutive subcarriers. A NR radio carrier is limited to 3300 active subcarriers (275 RB) which results in carrier bandwidths of 50, 100, 200 and 400 MHz for subcarrier spacing of 15, 30, 60 and 120 kHz, respectively. If even larger bandwidths are to be supported, carrier aggregation can be used, where multiple NR carriers can be aggregated and transmitted in parallel to or from the same device. Up to 16 carriers, can be aggregated allowing bandwidths up to 6.4 GHz.

Table 2.3. Characteristics for a set of numerologies



μ	$N_{OFDM\,symb}^{slot}$	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$	Cycle Prefix
0	14	10	1	Normal
1		20	2	
2		40	4	
3		80	8	
4		160	16	
2	12	40	4	Extended

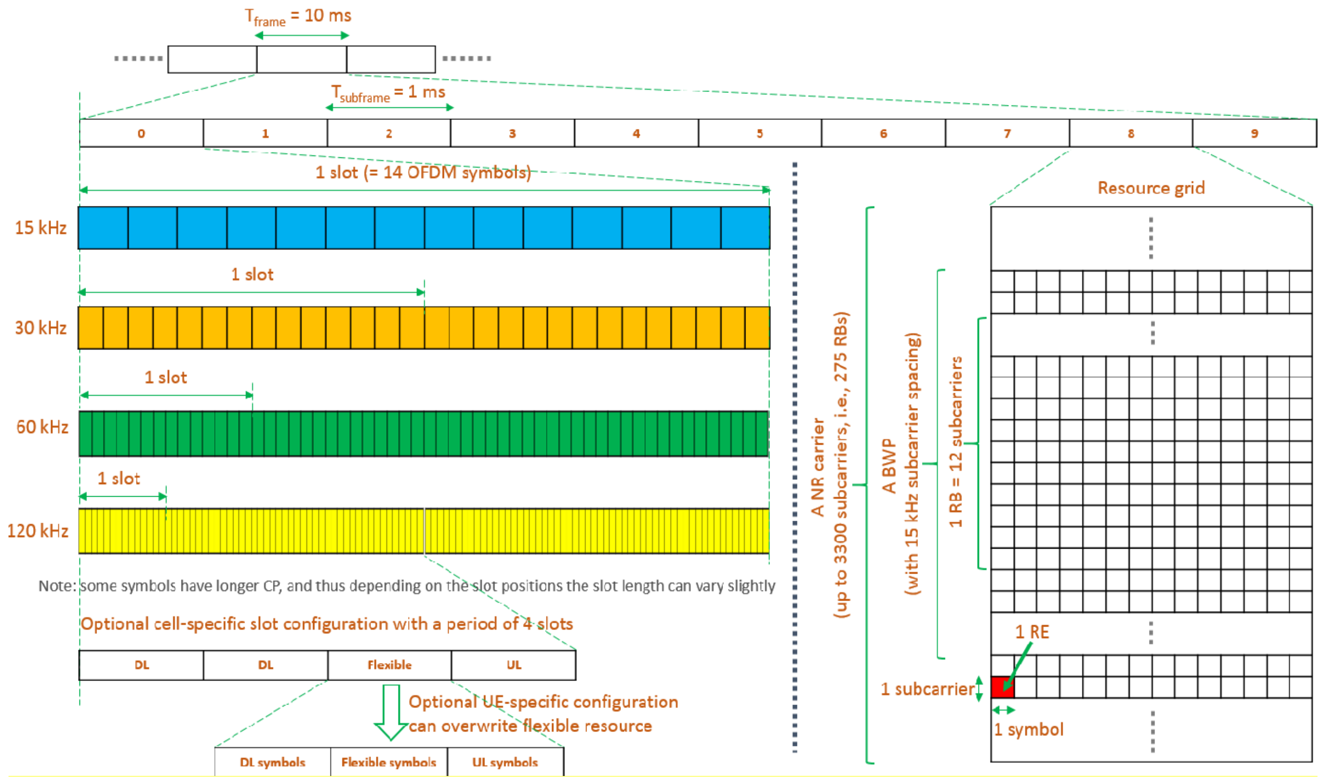


Figure 2.7 5G NR frame structure

2.3.6.6 Duplex schemes:

5G NR supports both frequency-division duplex (FDD) for lower frequency bands and time-division duplex (TDD) for higher frequency bands, subject to either half-duplex or full duplex.

In the case of TDD operation, a single carrier frequency is used for separated downlink and uplink transmissions. NR uses dynamic TDD where a slot can be dynamically allocated to either uplink or downlink as part of the scheduler decision. TDD systems provide a neither large guard time where neither downlink nor uplink transmissions occur, which allows switching the transmission direction and to avoid interference at the base station.

On the other hand, for FDD operation, uplink and downlink transmissions occur simultaneously but use different carrier frequencies. There is also possible a half-duplex mode, where transmissions are separated in frequency and in time.

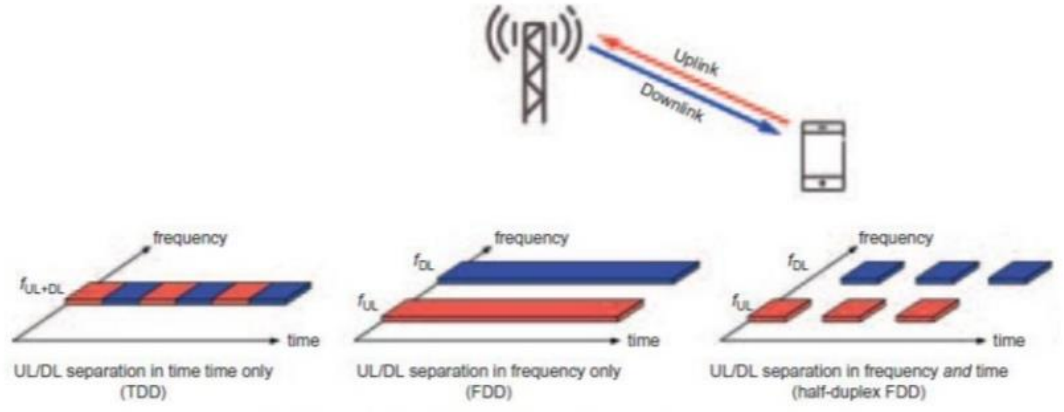


Figure 2.8 5G NR duplex scheme

2.3.6.7 NR physical layer:

5G NR protocol architecture is separated into control-plane and data-plane. The user plane is in charge of user data and the control plane is responsible for connection setup, mobility and security.

The user-plane protocol stack is split into the following layers: physical layer (PHY), medium access control layer (MAC), radio link control layer (RLC), packet data convergence protocol layer (PDCP) and service data adaption protocol (SDAP) layer. The functionalities of these layers. In particular, the PHY layer handles coding/decoding, modulation/demodulation, multi-antenna processing and mapping of signals to physical time-frequency resources.

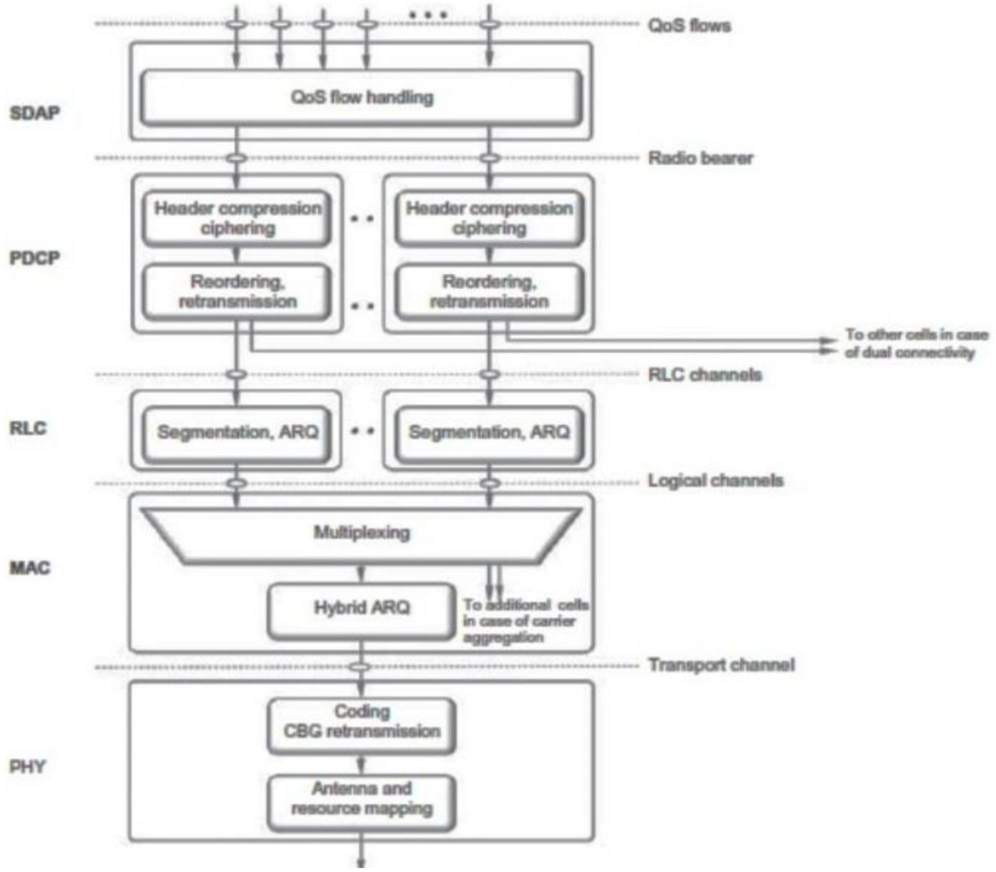


Figure 2.9 5G NR user-plane protocol stack

The time-frequency resources carrying information from higher layers (above PHY) are termed physical channels.

The physical channels defined for NR are the following:

- **Physical Downlink Shared Channel (PDSCH):** main physical channel used for unicast data transmission. It also used for transmission of paging information and delivery of part of the system information.
- **Physical Broadcast Channel (PBCH):** carries part of the system information, required by the device to access the network.
- **Physical Downlink Control Channel (PDCCH):** used for downlink control information, mainly scheduling decisions, required for reception of PDSCH and for scheduling grants enabling transmission on the PUSCH.

- **Physical Uplink Shared Channel (PUSCH):** is the uplink counterpart to the PDSCH.
- **Physical Uplink Control Channel (PUCCH):** used by the device to send hybrid-ARQ acknowledgements, to send channel-state reports and for requesting resources to transmit uplink data upon.
- **Physical Random-Access Channel (PRACH):** used by the UE to request connection setup referred to as random access.

The downlink and uplink transmission between gNB (the radio access network node) and the UE work as follows.

In the downlink, the UE monitors the PDCCH, typically once per slot. After detecting a valid PDCCH, the UE receives one unit of data (transport block) on the PDSCH following the scheduling decision of the gNB. Afterwards, the UE responds with a hybrid ARQ acknowledgment indicating if data was successfully decoded or not.

In the uplink, the UE requests the gNB for physical time-frequency resources to transmit data (scheduling request) and this request is sent over the PUCCH. In response, the gNB sends a scheduling grant over the PDCCH, which gives permission to a UE to use certain resources for transmission. Following the scheduling grant, the UE schedules its data transmission over the PUSCH, data that is received by the gNB and sends hybrid ARQ acknowledgement indicating if the data was decoded correctly or not.

On the other hand, the physical signals correspond to a set of time-frequency resources used by the PHY layer but do not carry information originating from higher layers. These signals are reference signals used for purposes such as demodulation, channel estimation, synchronization and channel-state information.

The downlink physical signals are:

- Demodulation Reference Signal (DM-RS).
- Phase Tracking Reference Signal (PT-RS).

- Channel State Information Reference Signal (CSI-RS).
- Primary Synchronization Signal (PSS).
- Secondary Synchronization Signal (SSS).

Furthermore, the uplink physical signals are:

- Demodulation Reference Signal (DM-RS).
- Phase Tracking Reference Signal (PT-RS).
- Sounding Reference Signal (SRS).

In particular, the PSS and the SSS are signals used in the cell search process, used by UE to find a new cell. The PSS is the first signal that the UE search for and the SSS is a signal transmitted to enable detection of the physical cell ID, an identifier of a cell at physical layer.

Also, 3GPP define some physical layer measurements. One of these measurements is the SS reference signal received power (SS-RSRP), which is defined as the linear average over the power contributions (in Watts) of the resource elements that carry secondary synchronization signals (SSS). This measurement is relevant in the next chapters for understanding the performance of the cell.

2.3.7 Multi-antenna transmission:

Multi-antenna transmission, through the use of massive Multiple Input Multiple Output (MIMO) and beam forming, is a key feature of 5G NR and its use can improve the mobile communication system performance.

It is possible to use multiple antennas on the transmitter to provide diversity against fading by utilizing the fact that different antennas may be at least partly uncorrelated, due to the inter-antenna spacing or due to different polarization between antennas.

Moreover, by adjusting the phase of each antenna element, multiple antennas on the transmitter can be used to provide directivity, that is, to focus the transmitted power in a certain direction. This corresponds to the concept of beam forming, which actually it is just a special implementation of MIMO. This directivity can increase the data rate and range due to higher power reaching a specific location in space, and also reduces interference, which improves the spectrum efficiency.

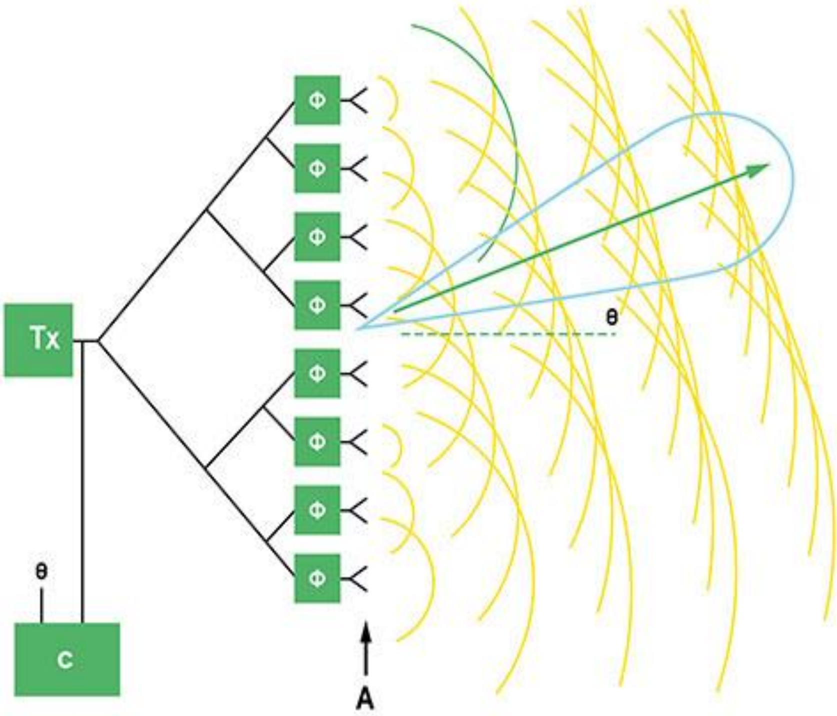


Figure 2.10 5G NR phased array antenna

Similarly, multiple antennas on the receiver can provide diversity, limiting the reception only in the direction of a target signal, while suppressing interference arriving from other directions.

Multiple antennas can be both used at the transmitter and the receiver, with which spatial multiplexing is achieved. This corresponds to the transmission of multiple layers of information in parallel using the same time and frequency resources.

Antenna panels, such as the one illustrated on Figure 2.10, consisting on a large number of small antennas can be used to change the beam direction by adjusting individually the phase of the signals applied to each antenna element. This can be done both in the transmitter side and in the receiver side. The use of focused beams maximizes the user equipment (UE) SNR, consequently improving the communication link for higher modulation and coding schemes.

Since the antenna elements separation is proportional to the wavelength, these antenna panels can have a small reduced size at high frequencies. The antenna panel shown on Figure 2.11 consists of 64 dual-polarized antenna elements, targeting the 28 GHz band. In order to have a reference of the size of the antenna panel, an AAA battery was placed next to it.

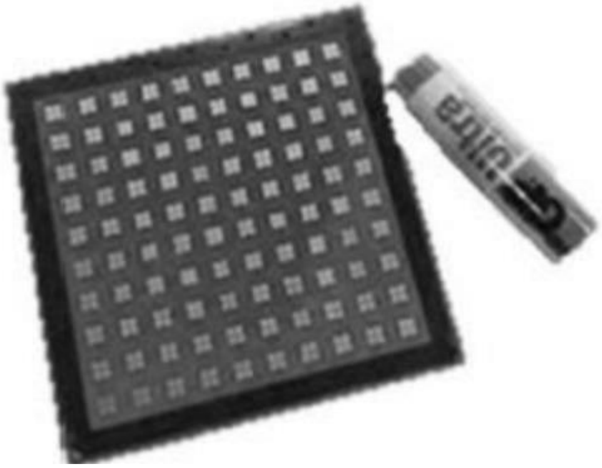


Figure 2.11 Antenna panel with 64 dual-polarized antenna elements

On the other hand, depending on the number of users, different multi-antenna schemes can be considered: single-user MIMO (SU-MIMO) or spatial multiplexing and multi-user MIMO (MU-MIMO).

In SU-MIMO, a single user is scheduled within a given time/frequency resource with transmission of a large number of layers in parallel (up to 8 layers). In other words, a UE can receive at most 8 different streams from the base station in the downlink. This scheme is mainly targeted at cell centered users with sufficient carrier-to-interference-and-noise C(I+N) conditions, in order to improve the data rate.

In MU-MIMO, multiple users are scheduled simultaneously within the same time/frequency resource but with a limited number of spatial layers per scheduled device, in this case, a maximum of 4 layers. In contrast with SU-MIMO, where the spatial multiplexing gain is confined to a single user, MU-MIMO allows multiple co-scheduled users to exploit this gain among two or more UE.

One important benefit of using MU-MIMO is the possibility of reducing the circuitry complexity on the UEs, since UEs would only require a single antenna to benefit from the gains. This is contrary to SU-MIMO which only provides considerable gains with more than one antenna at the user equipment.

In 5G NR, all these benefits of the MIMO schemes can be taken to a larger scale with the use of hundreds to thousands of antennas at the base station. This is referred as Massive MIMO, as seen on Figure 2.12. A larger number of antennas provide the advantages of increased gain, signal to noise ratio, coverage, capacity, data rates and decreased latency, compared to the conventional MIMO systems with fewer antennas.

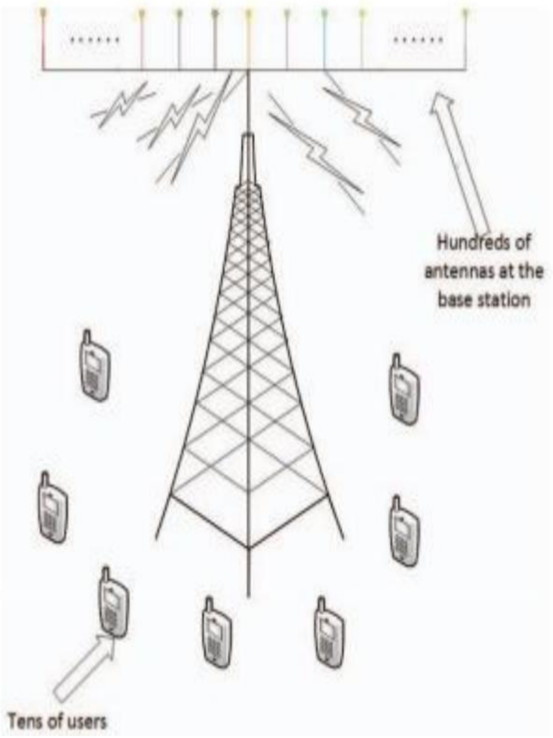


Figure 2.12 Massive MIMO scheme

2.3.8 Millimeter wave communications:

NR can operate in frequencies above 24.25 GHz, corresponding to the frequency range 2 (FR2). This range of frequencies is also known as millimeter wave (mmWave) frequencies.

The main reason of interest behind the use of mmWave is the huge amount of spectrum available in these higher bands. While bands below 6 GHz offer channel bandwidths of up to 100 MHz, the mmWave band offers much larger bandwidths of 500 MHz or even 1 GHz.

These frequencies are expected to support data rates in the order of the Gbps, however, due to high frequencies; mmWave presents major impediments, such as high path loss, increased effect of blockage as a result of weaker non-line-of-sight paths and attenuation due to rain and atmospheric absorption.

It is known that the free space path loss is dependent on the squared of the carrier frequency fc^2 and therefore, for example, increasing the frequency from 3 GHz to 30 GHz, will add a power loss of 20 dB, regardless the distance between the transmitter and the receiver.

With the small wavelengths, mmWave band is sensitive to blockage by obstacles with a significantly larger size than the wavelength (e.g. human body). Studies have shown that human body can attenuate mmWave signals up to 35 dB.

Also, mmWaves signals are affected by many atmospheric factors such as precipitation due to rain, since raindrops are approximately of the same size as the wavelengths; interaction with gas molecules like oxygen, nitrogen dioxide and water vapor present in the atmosphere; and power loss due to foliage obstruction caused by vegetation and the effects of multipath dispersion, diffraction and reflection.

Nevertheless, technologies such as massive MIMO and beam forming that make use of hundreds of antenna elements, consequently, offering high gains help overcome the high path losses and blockages.

CHAPTER 3:

ANALYSIS THE PROJECT

3.1 Introduction:

This chapter contains a preliminary work on 5G-NR planning, Also the functional requirements as the block diagrams that will be applied later using coverage, capacity, and quality calculations and the result will be shown in chapter 5 using atoll program. Also this chapter will mention the methodology that we used through the project in whole as collection information methods and research methodology.

3.2 collection information methods:

The 5G-NR is a new term that is ongoing, so there is a lack of resources about such topic, yet there are some trustworthy resources that mentioned the 5G-NR. We researched and found out some common information that were beneficial, also there was many research in the area of studying. We have visited the ministry of telecommunication many times in order to get the digital map which is necessary for the radio planning.

3.3 Planning steps:

1) Data collections
2) Dimensioning
    - Coverage
    - Capacity
3) Simulation and prediction
4) Sit location
5) Nominal planning (pre-configuration)
6) Site survey
    - Legal
    - installation
7) Detailed planning (code_ neighbor list……)
8) Site acceptance

3.4 Radio planning Block Diagrams:

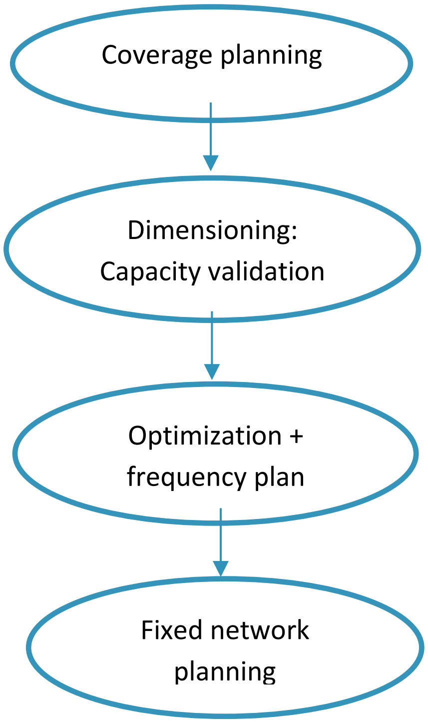


Figure 3.1 Coverage oriented area

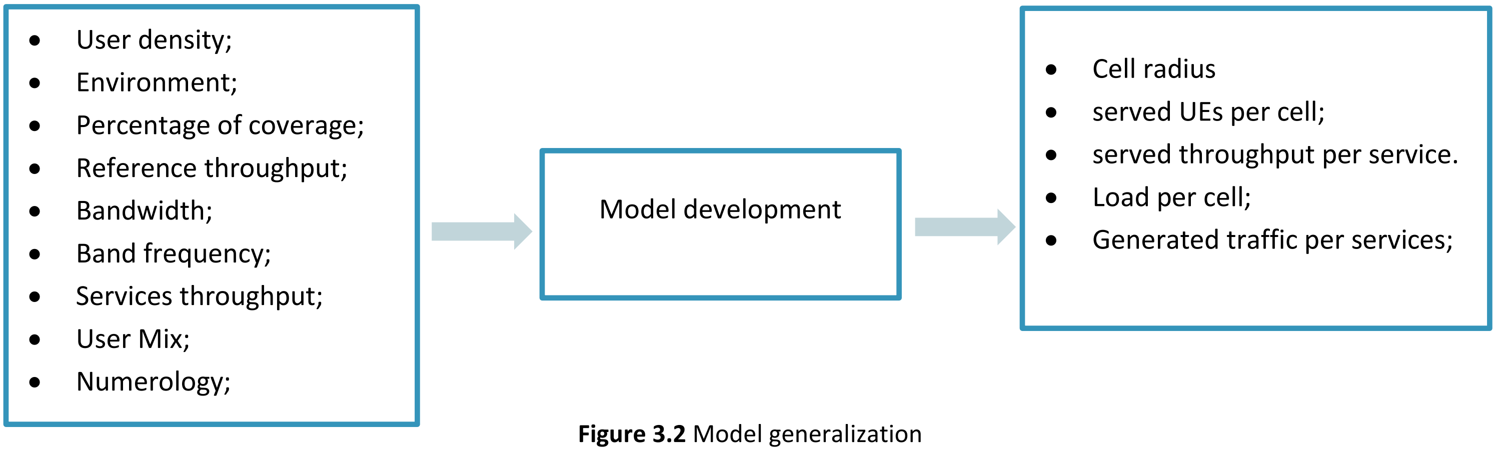


Figure 3.2 Model generalization

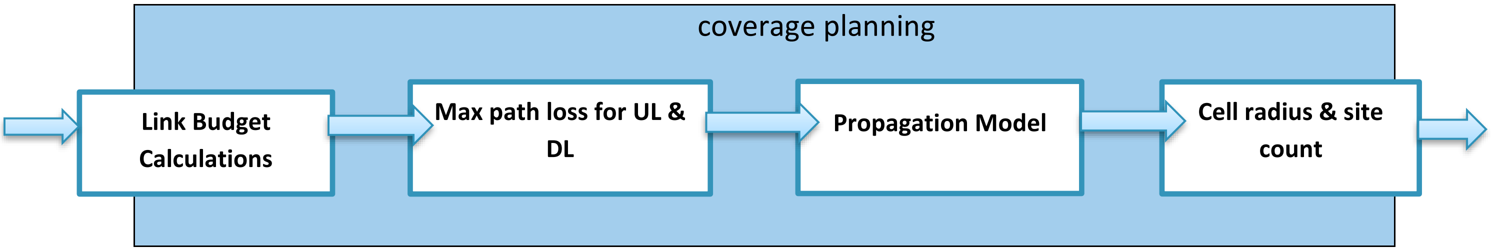


Figure 3.3 General coverage planning process

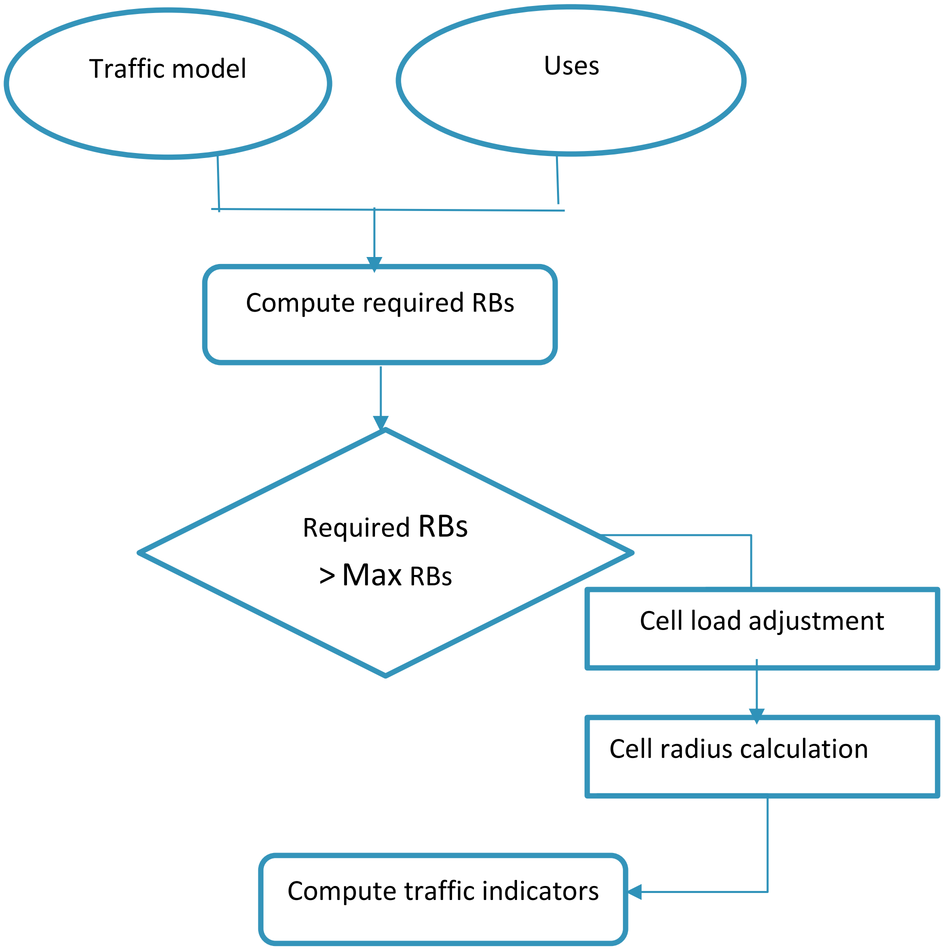


Figure 3.4 Workflow of the capacity planning

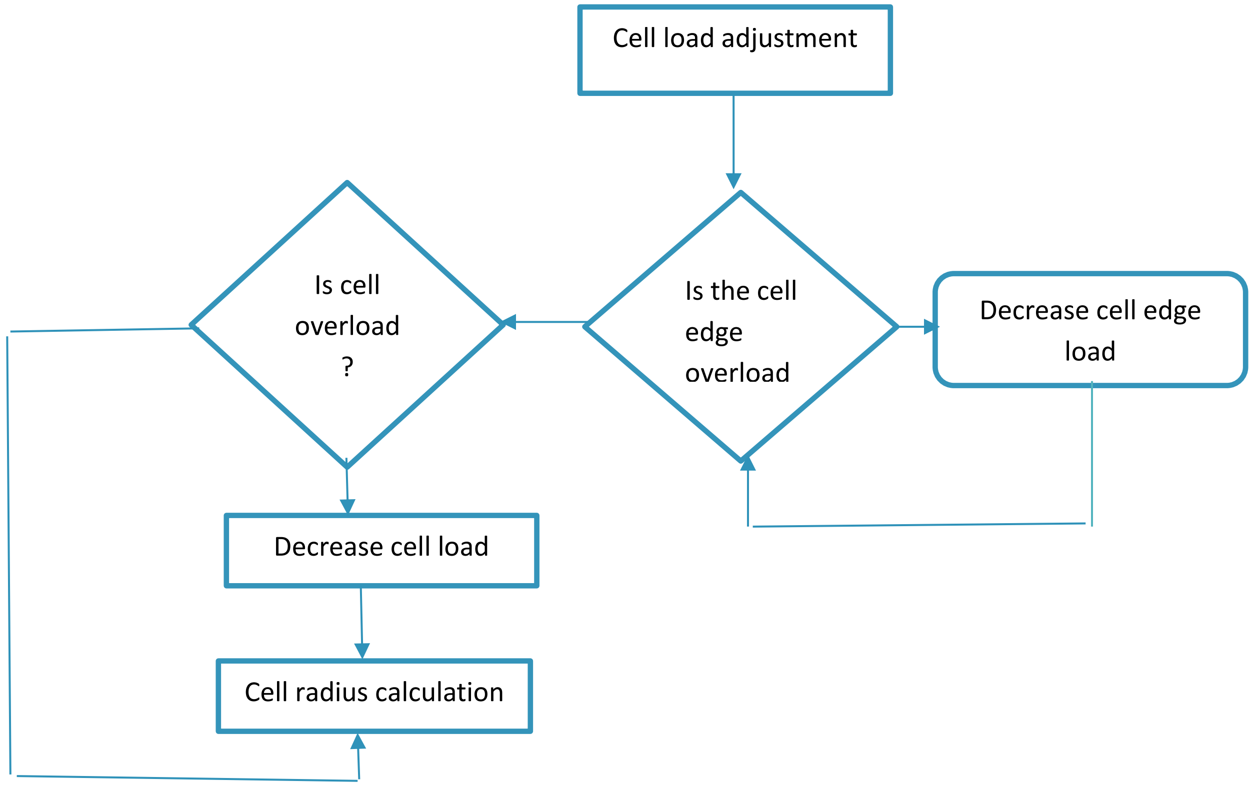


Figure 3.5 Workflow of Cell Load Adjustment

CHAPTER 4:

NETWORK PLANNING

4.1 Introduction:

Fifth generation (5G) mobile communication is expected to enormously expand the capabilities of mobile networks. New technologies and functionalities are being introduced for 5G systems in various domains—wireless access, transport, cloud, application, and management systems. These advancements are targeting traditional mobile broadband users as well as emerging machine-type users, so that new and superior services can be enabled for both consumers and industries at large, unleashing the potential of the internet of things (IoT), and virtual and augmented reality.

The backbone of any mobile communication system is its wireless access technology, which connects devices with radio base stations. As almost every society and industry is looking forward to the 5G revolution with its specific set of requirements, the design of the 5G wireless access is challenging. A 5G wireless access technology is expected to provide extreme data rates, ubiquitous coverage, ultra-reliability, very low latency, high energy efficiency, and a massive number of heterogeneous connections. The human-centric emerging applications are augmented reality, virtual reality, and online gaming—these demand extreme throughput and low latency. For machine-type communication there are two main segments: massive IoT and critical IoT. Massive IoT is characterized by a high number of low cost device connections, supporting small volumes of data per device with long battery life and deep coverage (for example, for underground and remote areas). The applications are in smart buildings, utilities, transport logistics, agriculture, and fleet management. The critical IoT is characterized by ultra-reliability and very low-latency connectivity, for example, to support autonomous vehicles, smart power grids, robotic surgery, traffic safety, and industrial control.

4.2 Scenarios Development:

This section provides the characteristics of the scenarios to be considered in this project, focusing primarily on the spectrum bands and propagation scenarios. A considerable number of spectrum regions for 5G are currently being considered, at both the cm-wave (e.g., 700, 3500 MHz) and the mm-wave spectra (e.g., 28 GHz) in terms of technical and economic feasibility. Due to the very different and complex nature of mm-wave propagation and economic implications in terms of operator network configuration, such as with the need for much denser base station scheme, mm-waves are unlikely to be the first choice in early 5G deployment phases. The main objective is to study the coverage and capacity implications in different scenarios for the cm-wave spectrum, the most likely spectrum to be considered in first network deployments, more specifically in the 0.7 and 3.5 GHz bands. The former will provide MTs general access to the network, while the latter will be able to provide MTs with higher data rates from larger bandwidth allocation or higher MIMO orders. Regarding the possibility of using MIMO at these frequencies, from (4.1) where the number of antennae is the rounding to the closest multiple of 2.

$$N_{antenna} = \left[d \, / \frac{c}{f} \right] \tag{4.1}$$

Where:

- d: device distance (length or width);
- c: speed of light;

4.3 Model Development:

This part provides the description of the models developed during this project, focusing primarily on their mathematical formulation. The main objectives are to describe the model generically, define the model inputs and outputs and which propagation models are to be used.

The model dimensioning should be as objective and detailed as possible, while also permitting changes in input parameters for different network deployment configurations. This process can be seen as a high-level approach to network dimensioning, where by the use of propagation models and specific algorithms it is possible to produce an output solution with an acceptable degree of accuracy.

The input and output parameters are generically described in the next section, as well as the propagation models used for coverage planning. The most relevant models for coverage and capacity are defined in the next section. Besides these essential elements for cellular network planning there is the traffic density/volume and share/mix profile throughout a typical load day.

From the input parameters the first step is to compute the maximum cell distance through link budget and propagation models, given the reference throughput, then to define the maximum network load, from the traffic profile, which produces an estimation cell radius for the different propagation scenarios from which the cell density configurations are retrieved, as seen in Figure 4.1.

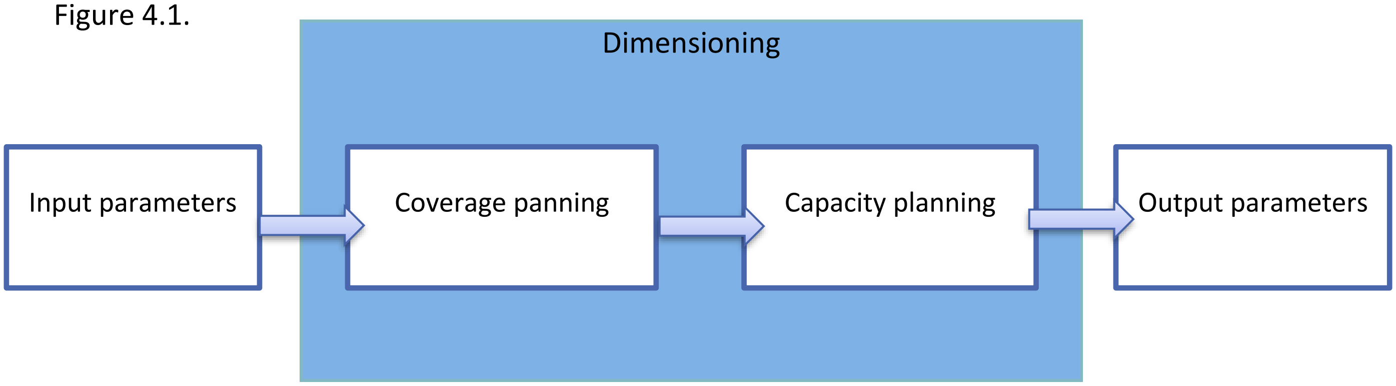


Figure 4.1 Generic network dimensioning

The main parameters considered in this project are segmented both in the capacity/coverage metrics and in the network/MTs perspective [Table 4.1].

Table 4.1 Capacity and coverage metrics for network and UE perspective.

Metrics	Parameters	
Capacity	**Network**	**MTs**
	Device/connection density, throughput, cell size, latency	Throughput, latency, traffic volume profile
Coverage	Propagation scenario, penetration losses, cell size, obstructions	Signal strength, mobility

While there may exist the same parameter in the capacity and coverage field, its meaning is not necessarily the same. For example, a macro-cell could be a suitable solution for coverage purpose while femto-cells could be the most adequate solution to support or increase network capacity in the same coverage area. On the other hand, it is the received power at the MTs that will define their access to the network, but it is through network capacity that MTs can achieve certain parameters.

The fundamental model inputs and outputs are defined in Figure 4.2. Besides these, there are others specifically relevant to 5G-NR network deployments, such as the numerology configuration and the maximum supported MIMO order. Although not considered in the early model development in this project, latency requirements could be added at a later stage.

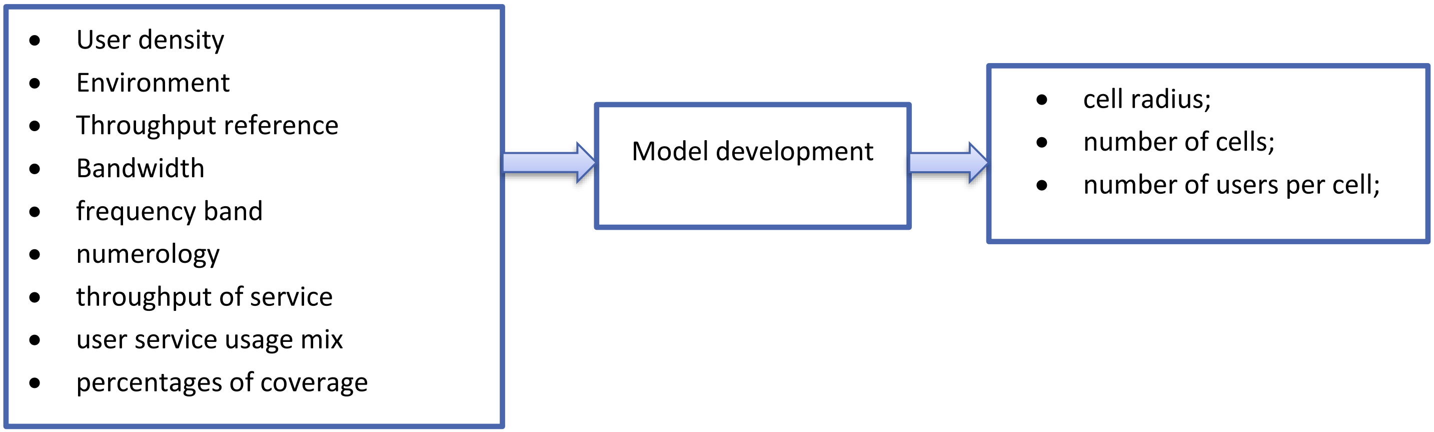


Figure 4.2 Model development Input/output dimensioning

The main output will be the number of base stations in the target area, given by the cell radius computed at the level of coverage and/or capacity evaluation. The former has predominance in terms of network planning over the latter, except for when network capacity is exceeded – then the predominant value is the capacity computed cell radius. Nevertheless, it is from capacity evaluation that the metrics of throughput and maximum number of users are determined.

The fundamental aspects on the propagation model characteristics are presented Table 4.2. The goal is to, essentially, have an outdoors propagation model for both frequency bands (Okumura-Hata for the 0.7 GHz and WINNER II for the 3.5 GHz frequency band) and an indoors model that accepts both frequency bands. The outdoors models are valid for the three propagation scenarios (urban, suburban, rural) while the indoors one is an empirical and site-generic model, meaning it is an abstraction based only on the fact if the main wall to be crossed represents a high or low-loss material.

Table 4.2 General description of considered propagation models.

Environment	**Propagation Mode**	**Propagation Scenario**			**Band [GHz]**	
		U	**SU**	**R**	**0.7**	**3.5**
Indoors	Okumura-Hata	✓	✓	✓	✓	*x*
	WINNER II	✓	✓	✓	*X*	✓
Outdoors	Experimental Indoors	✓	✓	✓	✓	✓

4.4 Dimensioning Process:

The goal of this section is to describe the complete dimensioning process of the cellular network that outputs the estimation for the total number of cells required to cover the target area from a given traffic profile load. This dimensioning process is split into coverage, capacity and cellular levels.

4.4.1 Coverage Planning:

Coverage planning is defined by the radio link budget evaluation for both channels, DL and UL, with no specific concern on the capacity or QoS. From the link budget evaluation, the maximum allowed path loss (MAPL) can be computed based on the required SNR value at the MT, which depends on the reference throughput at the cell edge. With the appropriate propagation model, it is then possible to compute the cell radius and area, and for each municipality, the total number of cells is generated and computed for the global geographical target area.

In the link budget, the essential parameters are related to power (transmission), gains (transmission, reception) and other elements, such as cable or user losses. In the outdoors propagation models the core parameters are the frequency band (0.7 or 3.5 GHz), the propagation scenario (urban, suburban, and rural) and the BS/MT antenna heights.

The cell radius is given by the distance parameter in the MAPL formulation, which is dependent on the propagation scenario (urban, suburban, rural), frequency band and other characteristics, such as the BS and MT heights. The generic formulation is defined:

$$d_{max\,[\mathrm{km}]} = 10^{\frac{L_{p,max}[\mathrm{dB}] - L'_{p}[\mathrm{dB}]}{10\,\alpha_{PD}}} \tag{4.2}$$

Where:

- $L_{p,max}$: maximum path loss (MAPL) given by the link budget computation;
- L'_{p}: path loss given by the sum of the outdoors and indoors path loss;
- α_{PD}: average power decay (model and configuration dependent);

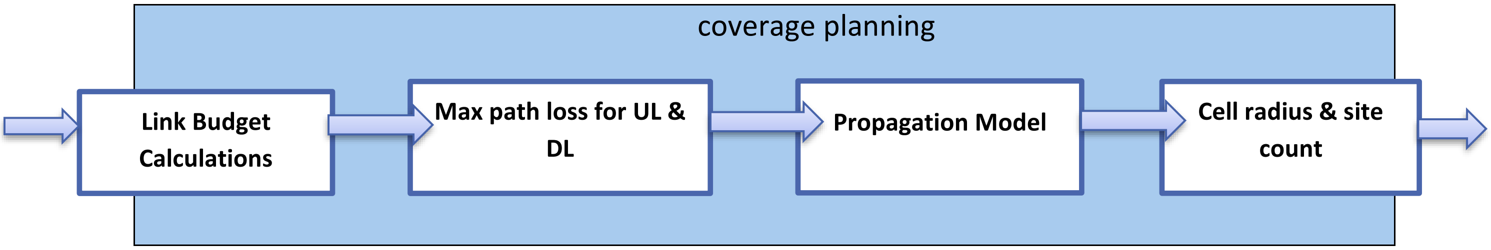


Figure 4.3 General coverage planning process

The different propagation models for the urban, suburban and rural areas and the general radio link budget formulations are defined in appendix ii. Radio Link Budget. Despite the extensive model description in the appendixes, the most relevant equations are described in this section. The main formulation of the radio link budget can be expressed as a function of the maximum path loss from the transmitting power, transmitter and receiver gains as well as the receiver power in (4.2). Besides the link budget computation, the received power for coverage estimation is mainly defined by the receiver sensitivity power, which is given by (4.3) having the specific 5G-NR numerology present in the bandwidth per RB so, the sensitivity is computed by the following expression:

$$P_{Rx,\,min\,[\mathrm{dBm}]} = -174 + 10 \cdot \log\left(B_{RB\,[\mathrm{Hz}]}\right) + F_{N\,[\mathrm{dB}]} + \rho_{N,\,min\,[\mathrm{dB}]} \tag{4.3}$$

Where:

- B_{RB}: bandwidth per RB, which depends on the SCS;
- F_N: noise figure of gNB receiver;
- $\rho_{N,min}$: SNR requirement for a given throughput;

Assuming a constant noise figure and SNR, the effect on changing the numerology bandwidth is represented by a variation in the sensitivity power, which in turn changes the MAPL, that is to say, as the SCS increases the required minimum sensitivity power increases. Therefore, the numerology that offers the maximum coverage distance is the one that minimizes the sensitivity power, which can be achieved with the subcarrier spacing value of 15 kHz (numerology 0).

This is especially important in the throughput at the cell edge evaluation, where a maximum percentage of RBs allocated to the cell edge is defined to ensure that there is always a nominal throughput available at this region. Since in 5G-NR there can be mixed numerologies within the cell and that each numerology will have a maximum, different, coverage distance (due to the higher sensitivity value), the model assumes the numerology with higher coverage distance to compute the share of RBs, and then estimates if the available throughput level matches the throughput requirement at the cell edge. After selecting the suitable SCS configuration for coverage purposes, the MAPL is computed, and from the appropriate propagation models, the distance from the BS to the cell edge can be obtained from the relationship between the distances, maximum path loss (MAPL) and the propagation model parameters/values.

The propagation model equations and the general formulation of the radio link budget with its parameters are described in appendixes ii.

4.4.2 Capacity Planning:

The main objective of capacity estimation is to compute the number of required resources, defined in 5G-NR as resource blocks (RBs), which support the traffic profile in consideration within a certain quality of service (QoS), such as, for example, defining the maximum acceptable service throughput reduction of 10% in the case of capacity overload in the cell.

The initial, and maximum, number of users is given by the coverage estimation, from which the capacity estimation indicates if such users can be served with the required traffic profile. If there is cell capacity overload, the number of users is reduced through cell radius reduction, until or if there is possibility of the cell withstanding the required number of RBs. After this estimation, the final number of users in the cell and in the network can be computed. The throughput per user can be given by:

$$R_{b,\text{user[kbps]}} = N_{RB/U} \cdot N_{SC/RB} \cdot N_{streams} \cdot N_{sym/SF} \cdot N_{bits/sym} \cdot \frac{1}{\tau} \tag{4.4}$$

Where:

- $N_{RB/U}$: number of RBs per user;
- $N_{SC/RB}$: number of subcarriers per RB (12 in 5G-NR);
- $N_{streams}$: order of MIMO configuration;
- $N_{sym/SF}$: number of symbols per subframe;
- $N_{bits/sym} = \log_2 M$: number of bits per symbol;
- τ : time of subframe;

After calculating the coverage of a certain cell, an analysis is made of its capacity. If this analysis represents positive results, no changes are made to the initial plan. Otherwise, the radius of the cell is reduced to reach the required capacity levels. After calculating the cell range, the number of users within each cell can be calculated with the following expression:

$$N_{users,\ cell} = (\eta_{\ [\text{users/km2}]} \cdot S_{\ [\text{km2}]}) \tag{4.5}$$

Where:

- η: user density in the target area;
- S : total area of coverage;

Capacity dimensioning considers the typical hexagonal shape, but for illustration purposes a uniform circular distribution of users is shown in Figure 4.4. The total number of users in a cell is given by the sum of users served by each modulation (from QPSK to 256-QAM), which fits right if the traffic profile consists strongly of mobile broadband services:

$$N_{users,cell} = \sum_{k=1}^{4} N_{users,area}^{4^k-QAM}$$

where:

- $N_{users,area}^{4^k-QAM} = \left\lfloor N_{users,cell} \cdot \frac{A_{4^k-QAM}}{A_{Cell}} \right\rfloor = \left\lfloor N_{users,cell} \cdot \frac{R^2_{4^k-QAM} - R^2_{4^{k+1}-QAM}}{R^2_{QPSK}} \right\rfloor$

(4.6)

The different radii for the different modulations are given by the minimum and maximum SINR values associated to each MCS region through the SNR/throughput relationship, which is discussed in Appendix I. From these radii the number of users per MCS region is computed through the percentage of area each region has, in relation to the total cell area. By taking user traffic profile requirements into account, some cells are prone to saturate more easily than others. Besides, the traffic profile throughout the day can fluctuate and this is represented in the different mix share for each service based on three environment types, Residential, Office and Mixed (ROM). The capacity planning process estimates then the number of necessary RBs to support the traffic profile with a certain level of QoS.

A novelty factor in 5G-NR capacity planning, relative to LTE, is the concept of numerology, which is related to different SCS configurations. The available numerologies for the spectrum considered in this project are shown in Table 4.3, where the bandwidth is computed in (4.7).

Table 4.3 Numerology distribution and associated bandwidth

Band [GHz]	μ	RBs		SCS [kHz] (12/carrier)	Bandwidth [MHz]	
		Min	**Max**		**Min**	**Max**
< 6	**0**	**20**	**275**	**15**	**3.6**	**49.5**
	1			**30**	**7.2**	**99**
	2			**60**	**14.4**	**198**

Also, 5G-NR networks are expected to support a mixed numerology configuration in order to present a more efficient RB allocation. However, if one considers a single numerology in the cell, the global cell bandwidth can be defined by (4.7)

$$BW_{[\text{MHz}]} = N_{RBs} \cdot N_{C} \cdot N_{SCS} \cdot BW_{,SCS\,[\text{MHz}]} \qquad (4.7)$$

where:

- N_{RBs}: number of resource blocks for a given numerology;
- N_{C} : number of carriers being served to the MT (typically one);
- N_{SCS} : number of subcarriers in 5G-NR (12);
- $BW_{,SCS}$: subcarrier bandwidth for a given numerology;

It is important to clarify some effects on using different numerologies. Table 4.4 presents a concise description of the main metrics regarding the SCS considered in this thesis, but it is in the throughput that the most important metric is found and used throughout the work. In Annex I, the throughput per RB is computed and defined for the different modulation schemes (from QPSK to 256-QAM) for the 15 kHz configuration (numerology 0).

Table 4.4 SCS network and propagation main characteristics

Metrics	**Subcarrier Spacing [kHz]**		
	15	**30**	**60**
Noise tolerance	**Low**	**Medium**	**High**
Range/distance	**Large/wide**		**Small/short**
Spectral efficiency	**Higher**		**Lower**
Throughput	**Small**		**High**
Latency	**Higher**		**Lower**

Regarding the throughput per RB for the 30 and 60 kHz options, the increase in throughput is assumed to be theoretically 2, although in practice as the SCS increases the band guards increase, hence it is very much possible the multiplying factor from the 15 to 30 is higher than for the 30 to 60.

The concept of MCS region is linked to a region with a minimum and maximum SNR value in which the maximum throughput curve is given by a certain MCS, but where users in this region can also be served with lower order MCS, seeking to maximize the number of allocated users in an efficient manner, e.g., $N_{U,\,cell\_64QAM}$ means the total number of users in a region in which the maximum throughput is given by the 64-QAM modulation, but users can be served with lower order MCS, such as QPSK.

The cell capacity depends on the available bandwidth and on the bandwidth required to serve the MTs. The higher the available bandwidth, the higher the traffic level the cell can support. Besides, the average throughput per resource block is higher for higher order modulation schemes. This means that 256QAM requires less RBs than QPSK, for example for the same service and throughput, and thus less bandwidth. The average number of required resource blocks per user, for each service and modulation, is defined in (4.8).

$$N_{RB,\,user,\,k} = R_{b,\,user,\,k} / R^{m}{}_{b,\,RB} \tag{4.8}$$

Where:

- $N_{RB,\,user,\,k}$: The average number of required resource block per user;
- $R_{b,\,user,\,k[\text{Mbit/s}]}$: The average throughput per user, per service k;
- $R^{m}{}_{b,\,RB[\text{Mbit/s}]}$: The average throughput per RB, per modulation m;

The number of required RBs per MCS region is naturally different, since both the average throughput per RB and the number of users in each one is different. The number of resource blocks necessary per modulation scheme for a cluster of services can be defined as:

$$N_{RB,required} = \sum\nolimits_{service\ i}^{N} [\, N_{RB\,,user,k} \cdot N_{u,cell}^{m} \cdot p_u^s \,] \tag{4.9}$$

Where:

- $N_{RB,\,required}$: The number of resource blocks required per modulation scheme for a cluster of services;
- $N_{RB\,,user,k}$: The average number of required resource block per user;
- $N_{u,cell}^{m}$: number of users served by modulation m;
- p_u^s : percentage of users using/subscribing service s;

For a single cell, the total number of resource blocks is simply the sum of RBs of each MCS region, defined as in:

$$N_{RB,required} = \sum_{i=1}^{4} N_{RB}^{u^4-QAM} \tag{4.10}$$

Where:

- $N_{RB}^{u^4-QAM}$: number of RBs required for a given MCS region (QPSK to 256-QAM);

With the variable $N_{RB,required}$ it is possible to determine if the system is coverage- or capacity-limited. If $N_{RB,\,required}$ is bigger than the total number of RBs available in a single cell, the system is capacity limited, and the average throughput is decreased, meaning that each user will have less resources available. On the opposite, the system is coverage-limited and in this case, there is no need to change the resources of the BS for QoS purposes. On the other hand, from an economical point of view the resources might be reduced.

To summarize the overload of a cell, it can be broadly defined with the expression (4.11), where the required amount of resources to satisfy the requested traffic is divided by the total number of resources available in a cell. If this value is greater than 100 %, the existence of overload is indicated, on the other hand, if the value is less than 100 % then there is no overload, thus, the load ratio a cell is determined as follows

The total number of required RBs to serve a given traffic profile determines if the cell is coverage or capacity-limited, by comparison to the available RBs at the cell. This cell-capacity ratio is defined in (4.11)

$$\eta_{cell}=\frac{\mathrm{N}_{\mathrm{RB,cell}}}{\mathrm{N}_{\mathrm{RB,required}}} \tag{4.11}$$

Where:

- η_{cell}: cell-capacity ratio;
- $\mathrm{N}_{\mathrm{RB,cell}}$: number of available RBs in the cell;
- $\mathrm{N}_{\mathrm{RB,required}}$: average number of required RBs in the cell;

The implications at the network capacity level is given by (4.11) and in Table 4.5

Table 4.5 Cell-capacity ratio implications

$\eta_{cell} = 0$	$\eta_{cell} < 1$	$\eta_{cell} = 1$	$\eta_{cell} > 1$
No capacity provided in cell	Cell capacity overload	Resource Block balance in cell	Cell capacity in not-overload

The total average throughput per service in the cell can be defined from (4.12) and the percentage of traffic service per cell in (4.13)

$$R_{b,cell[\text{Mbit/s}]} = \sum_{\text{serivice i}}^{\text{N}} \text{R}_{\text{b,user,s}} \,.\, \eta_{cell} \,.\, \text{N}_{\text{u}}^{\text{s}} \qquad (4.12)$$

Where:

- $R_{b,cell[\text{Mbit/s}]}$: The total average throughput per service in the cell;
- $\text{R}_{\text{b,user,s}}$: Average throughput per user, per service;
- η_{cell} : cell-capacity ratio;
- $\text{N}_{\text{u}}^{\text{s}}$: number of active users of the service s;

$$\rho_{traffic\,[\%]} = [\text{R}_{\text{b,user,s}} \,.\, \eta_{cell} \,.\, \text{N}_{\text{u}}^{\text{s}}] \,/\, R_{b,cell[\text{Mbit/s}]} \qquad (4.13)$$

4.4.2.1 Subscriber Traffic Profile from Traffic Model

Traffic forecast should be done by analyzing the offered Busy Hour traffic per subscriber for different services in each area. The traffic model defines an application as shown in Figure 4.6 which consisting of the following services (VoIP, Video, Streaming, interactive gaming, Web browsing &FTP).The main purpose of traffic model is to describe the average subscriber behavior during the most loaded day period (the Busy Hour) .

Traffic data:

- **Voice:**
  1) Erlang per subscriber during busy hour of the network
  2) Codec bit rate, Voice activity
- **Video call:**
  1) Erlang per subscriber during busy hour of the network
  2) Service bit rates
- **Non Real-Time (NRT) data:**
  1) Average throughput (kbps) per subscriber during busy hour of the network
  2) Target bit rates

4.4.3 Cellular Planning:

The main goal of this section is to discuss higher level aspects within the scope of cellular planning, in order to measure and validate the approach taken at this level. To start, a key assumption is that within the coverage area with a specific parameter configuration the cell size is the same, that is to say, it does not take into account two frequencies in use at the same BS site, which could yield different cell radii, nor the existence of other types of antennas other than macro-cells, which could yield additional coverage area in some specific scenarios, such as pico-cells in shopping malls.

The cell structure is assumed to be hexagonal following the concept of tri-sector BSs in use in real-life network cell configuration. This is the optimal geometrical shape, since it minimizes any overlap or gap given, and on top of this assumption a generic value for handover ratio is defined for any cell size, which finds its limitations if the cell size is too large and thus an approach for absolute handover distance could be considered in a future implementation. The hexagonal cell area can then be computed.

$$A_{cell\ [km2]} = \frac{3}{2} \cdot \sqrt{3} \cdot r^2_{max\ [km]} \tag{4.14}$$

- $r^2_{max\ [km]}$: cell max radius (from coverage or capacity estimation);

The number of sites to be deployed can be easily calculated from the Cell Area and the input value of the deployment area (Deployment Area).

$$N_{site} = \frac{A_D}{A_{cell}} \tag{4.15}$$

Where:

- N_{site}: number of sites;
- $A_{D[km^2]}$: development area;
- $A_{cell\ [km^2]}$: site area;

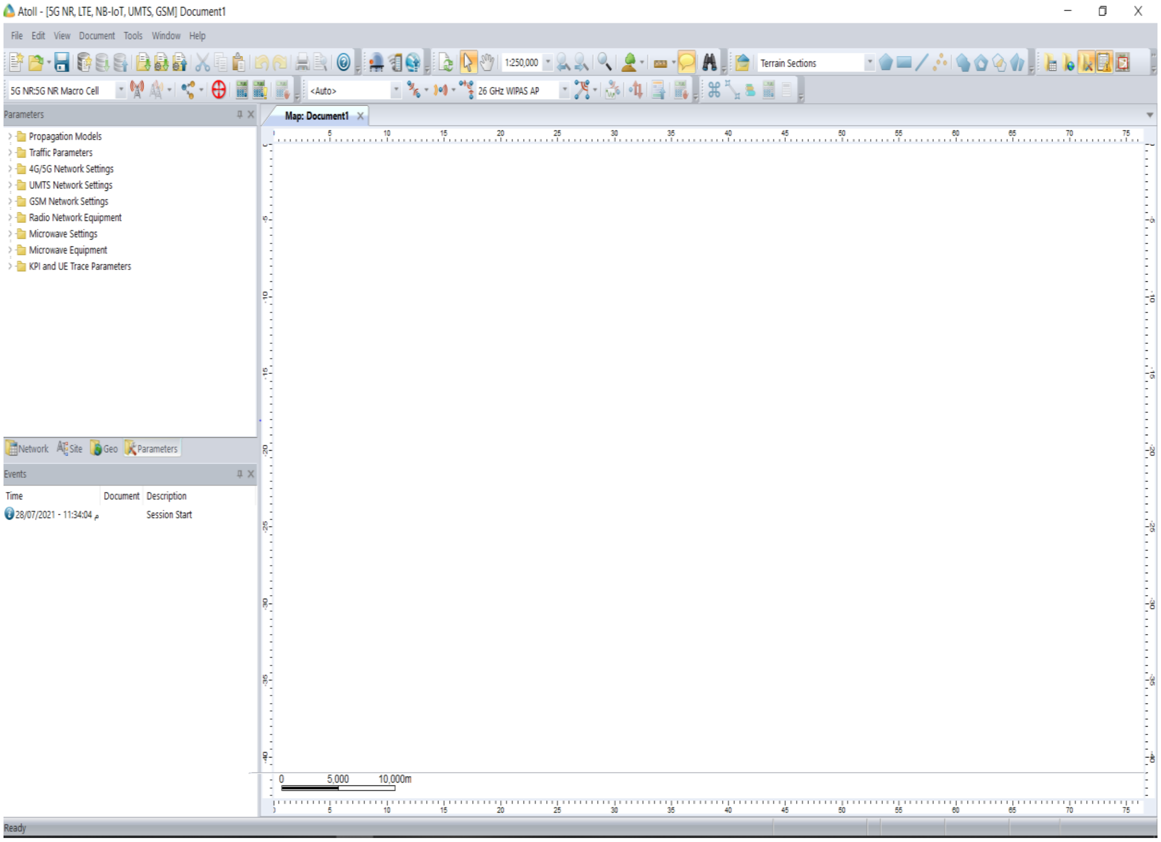
CHAPTER 5:

SIMULATION

5.1 ATOLL Radio Planning Tool:

ATOLL is a multi-technology wireless network design tool that offers unique capabilities of using both predictions and live network data throughout the network planning and optimization process. ATOLL supports the latest technology advances such as massive MIMO, 3D beamforming, and mmWave propagation for the design of 5G networks.

In this chapter, some of the most relevant parameters related to the radio planning using ATOLL are described. They will be used to develop the coverage and capacity analysis for 5G NR networks.



Time	Document	Description
28/07/2021 - 11:34:04		Session Start

Figure 5.1 Atoll working environment

In this chapter, some of the key features of Atoll and parameters configured related to the radio calculation, propagation models, the traffic and capacity planning for 5G NR networks are presented. The configurations mentioned in this chapter are used for the studies carried out on the upcoming chapters, so they should be considered all the time, unless specified differently.

5.1.1 site survey:

The process of site survey is to identify the different environmental factors that directly or indirectly effect on the radio network planning process and as well to list out them as planning parameters. For this project Sana'a City was considered as the area of planning and in this section, we are listing its environmental factors.

5.2 Coverage and Capacity Planning:

As we mentioned earlier the coverage and capacity dimensioning is an important step in deploying a cellular network. In general, the output of coverage and capacity dimensioning is to determine the minimum number of sites needed to satisfy better coverage, capacity and quality of service in a certain area.

Atoll allows to model the different equipment and parameters necessary to design a network, which include BS, the transmitter equipment and the cell parameters. After collecting the information about the area of planning.

5.2.1 Planning Parameters:

The site is defined as the geographical point where the base station and its transmitters are located. Transmitters consist of all the all the equipment used to generate the radio waves in order to transmit or receive data with the use of an antenna. Finally, a cell is the RF channel configured on a transmitter.

The base station subsystem consists of three elements and their properties are taken into account to calculate the downlink and uplink losses:

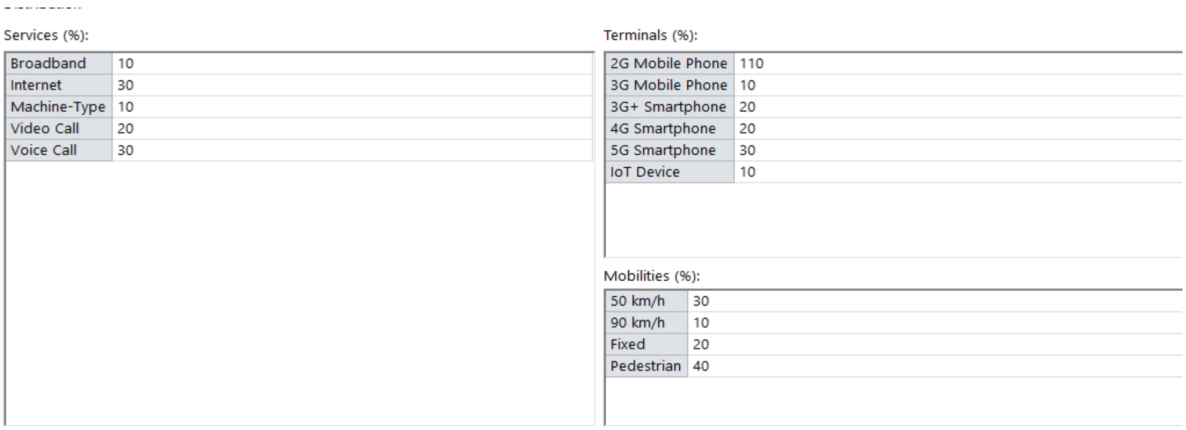
- **Tower-mounted amplifier (TMA):** are used to reduce the composite noise figure of the base station.

- **Feeder cables:** connect the TMA with the antenna.
- **Transmitter equipment.**

Table 5.2 Planning Parameters

Parameter Description	Value
System Frequency[GHz]	3.5
System Bandwidth [MHz]	100
Duplex Mode	TDD
Propagation model	Okumura_Hata WINNER II
Frequency reuse	1
Scheduling	Proportional Fair
Cyclic Prefix (CP)	Normal
Modulation	QPSK, 16-QAM,64-QAM, 256-QAM
F_N : Noise figure [dB]	5 (UL) / 8 (DL)
P_{TX} : BS transmitter output power [dBm]	42
$G_{r,\text{ antenna},}$: **UE antenna gain [dBi]**	0
$G_{t,\text{antenna}}$: BS maximum antenna gain [dBi]	17.8
G_{TMA} : Tower Mounted Amplifier “MIMO order “ **[dBi]**	2
I_m : interference margin **[dB]**	3
G_{Tx}: diversity gain [dBi]	3
Body loss	0 for data Services ,3dB for voice services
Indoor Mean Attenuation Average [dB]	11.7

Table 5.3 Traffic distribution



Services (%):

Broadband	10
Internet	30
Machine-Type	10
Video Call	20
Voice Call	30

Terminals (%):

2G Mobile Phone	110
3G Mobile Phone	10
3G+ Smartphone	20
4G Smartphone	20
5G Smartphone	30
IoT Device	10

Mobilities (%):

50 km/h	30
90 km/h	10
Fixed	20
Pedestrian	40

5.2.2 Propagation Model:

As we mentioned earlier in chapter 4 that propagation model is very critical for computing cell range in 5G_NR planning they are many different propagation models can be used including, Okumura-Hata model, WINNER II model, and Aster model which was developed recently, here we chose Okumura-Hata model for planning urban area in Sana'a city.

Table 5.4 Propagation Model Inputs

$\mathbf{h}_{BS}$: Height of the BS antennas [m]	50
$\mathbf{h}_{MT}$: UE height [m]	1.5
Frequency [MHZ]	3500
Penetration Loss [dB]	17 (Urban area)

5.3 Geographical area of study and data:

This section shows and discusses the coverage and capacity simulation of the Planned Area, but before we starting, must be illustrate the reasons that make us chose this region, we summery this reasons in this points:

- This study region includes the most famous district in Sana’a City
- The high population intensity in this study region.
- The huge usage for the services especially web browsing service in this study region.

5.3.1 Clutter classes:

Clutter height maps describe the altitude of a clutter over the DTM with one altitude defined by pixel. This map can offer more precise information than defining an altitude per clutter class because, in a clutter height file, it is possible to have different heights within a single clutter class. When the clutter altitude is defined in both clutter class map and clutter height map, the clutter altitude is taken from the clutter height map. The map used for the study includes buildings and vegetated areas.

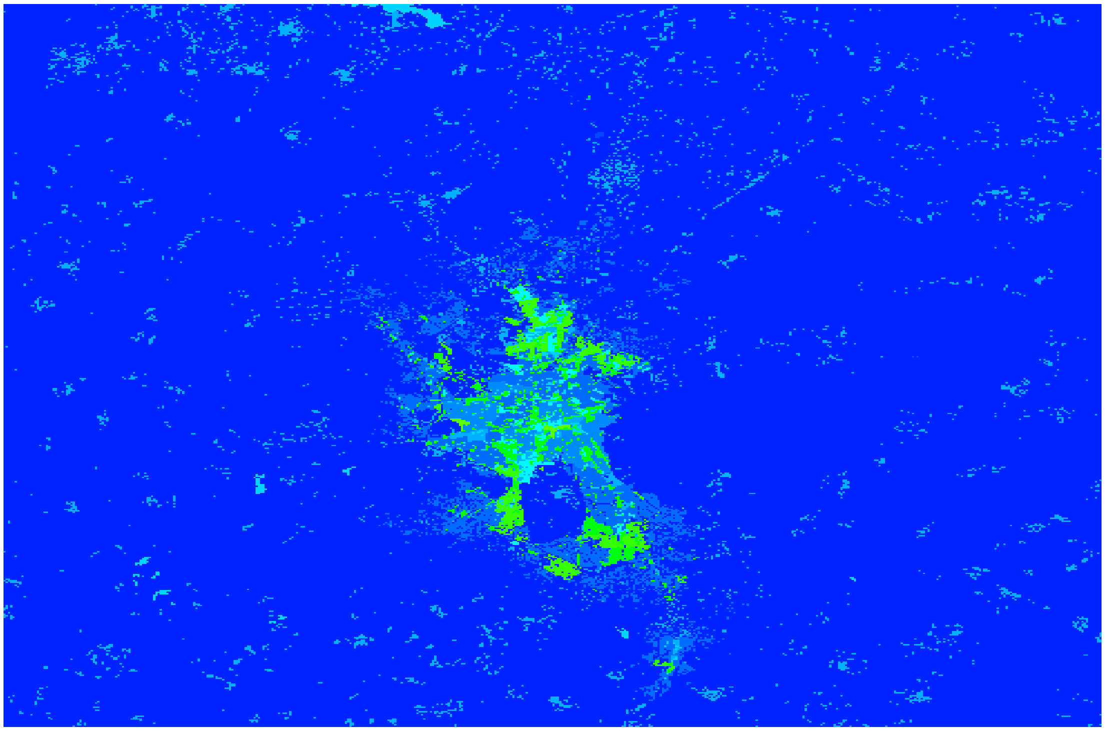


Figure 5.2 Sana’a Clutter Classes Map

5.3.2 Vector layers:

Atoll program supports contours, lines, and points to represent polygons such as regions, or lines such as roads or coastlines, or points. The vectors map involves Vectors: such as:

- Highway
- Inland water
- Main road
- River
- Runway
- Secondary road
- Street

Figure 5.3 Sana'a Vectors Map

5.3.3 Traffic Map of Planning Area:

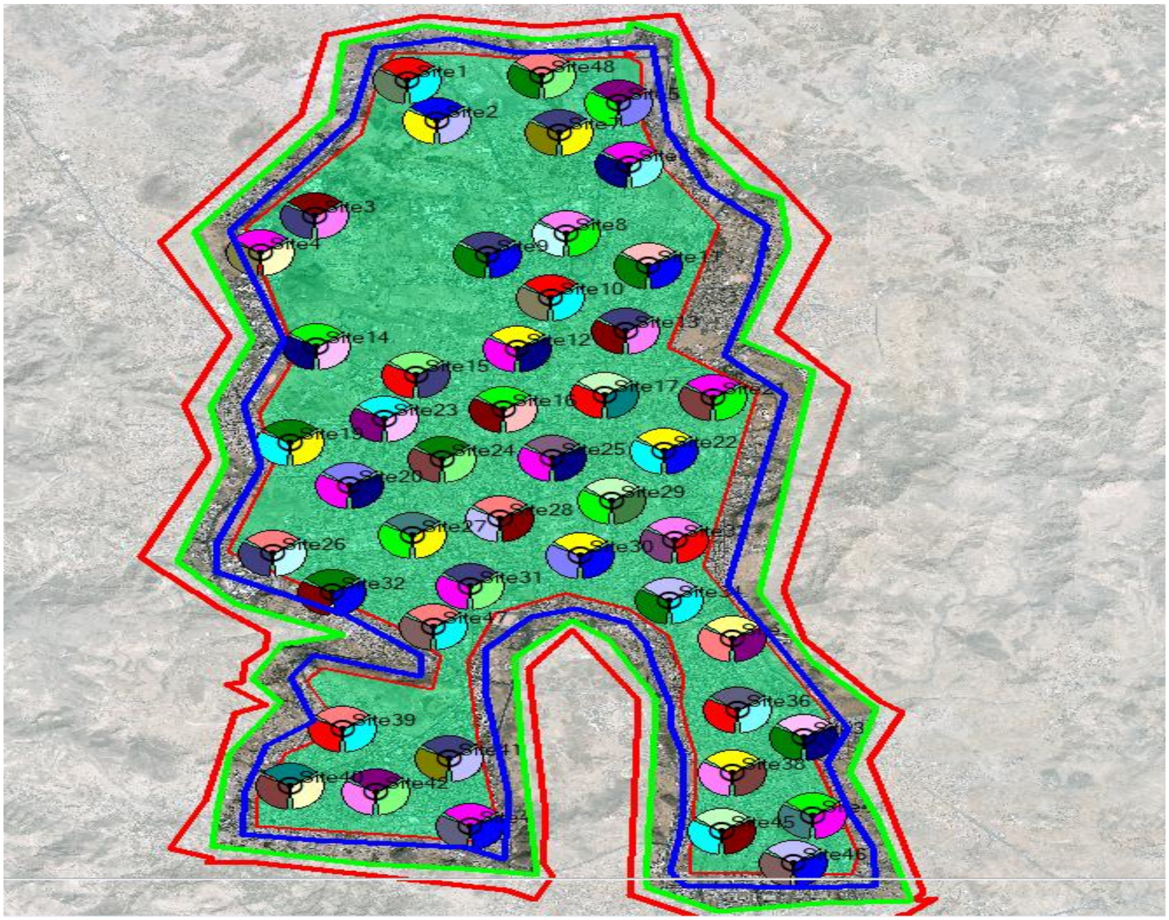
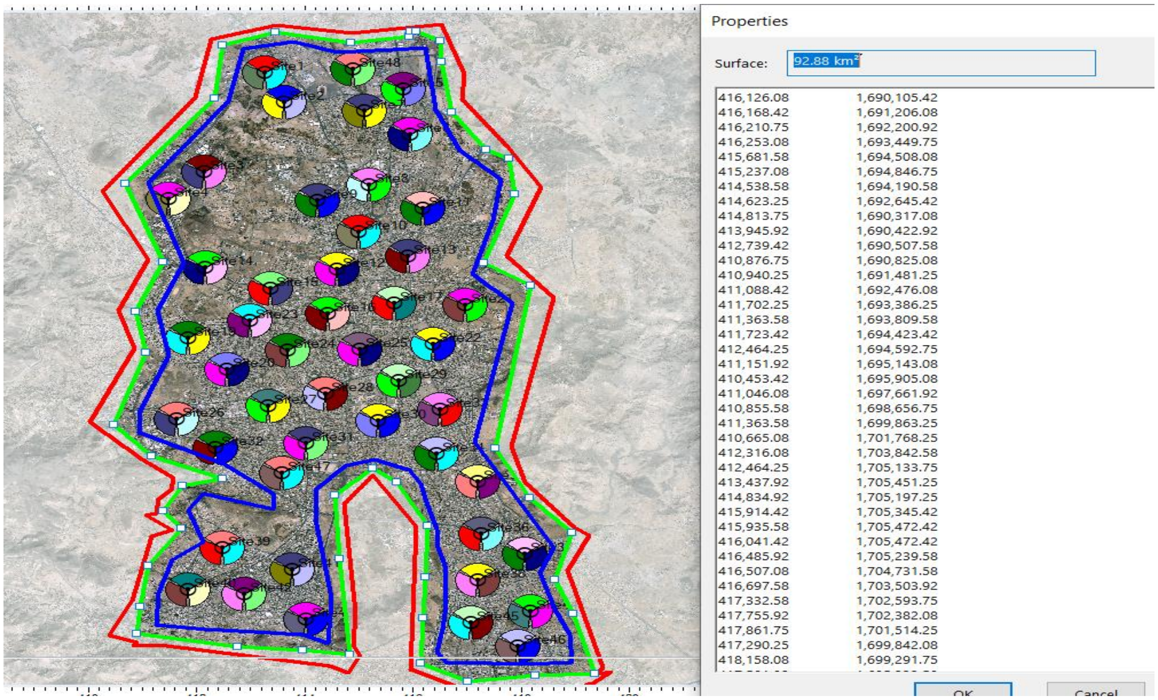


Figure 5.4. Traffic Map of Planning Are

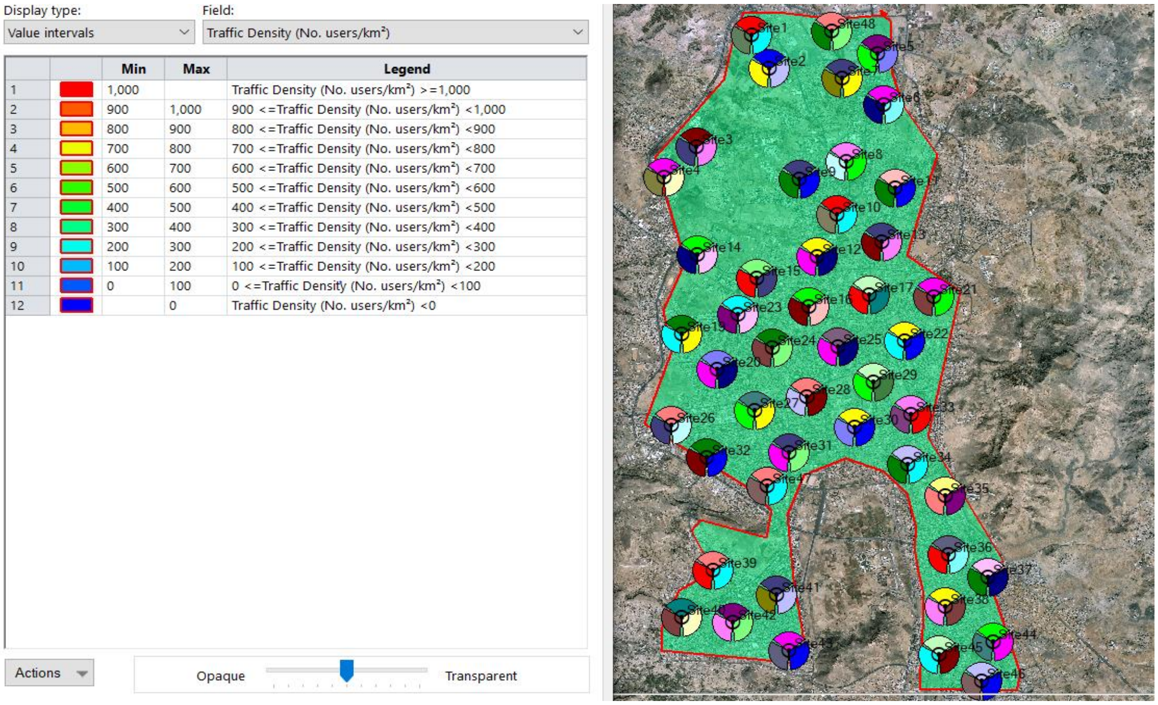


Properties

Surface: 92.88 km²

416,126.08	1,690,105.42
416,168.42	1,691,206.08
416,210.75	1,692,200.92
416,253.08	1,693,449.75
415,681.58	1,694,508.08
415,237.08	1,694,846.75
414,538.58	1,694,190.58
414,623.25	1,692,645.42
414,813.75	1,690,317.08
413,945.92	1,690,422.92
412,739.42	1,690,507.58
410,876.75	1,690,825.08
410,940.25	1,691,481.25
411,088.42	1,692,476.08
411,702.25	1,693,386.25
411,363.58	1,693,809.58
411,723.42	1,694,423.42
412,464.25	1,694,592.75
411,151.92	1,695,143.08
410,453.42	1,695,905.08
411,046.08	1,697,661.92
410,855.58	1,698,656.75
411,363.58	1,699,863.25
410,665.08	1,701,768.25
412,316.08	1,703,842.58
412,464.25	1,705,133.75
413,437.92	1,705,451.25
414,834.92	1,705,197.25
415,914.42	1,705,345.42
415,935.58	1,705,472.42
416,041.42	1,705,472.42
416,485.92	1,705,239.58
416,507.08	1,704,731.58
416,697.58	1,703,503.92
417,332.58	1,702,593.75
417,755.92	1,702,382.08
417,861.75	1,701,514.25
417,290.25	1,699,842.08
418,158.08	1,699,291.75

Figure 5.5 Sites Location on Map of Sana'a city



Display type: Value intervals

Field: Traffic Density (No. users/km²)

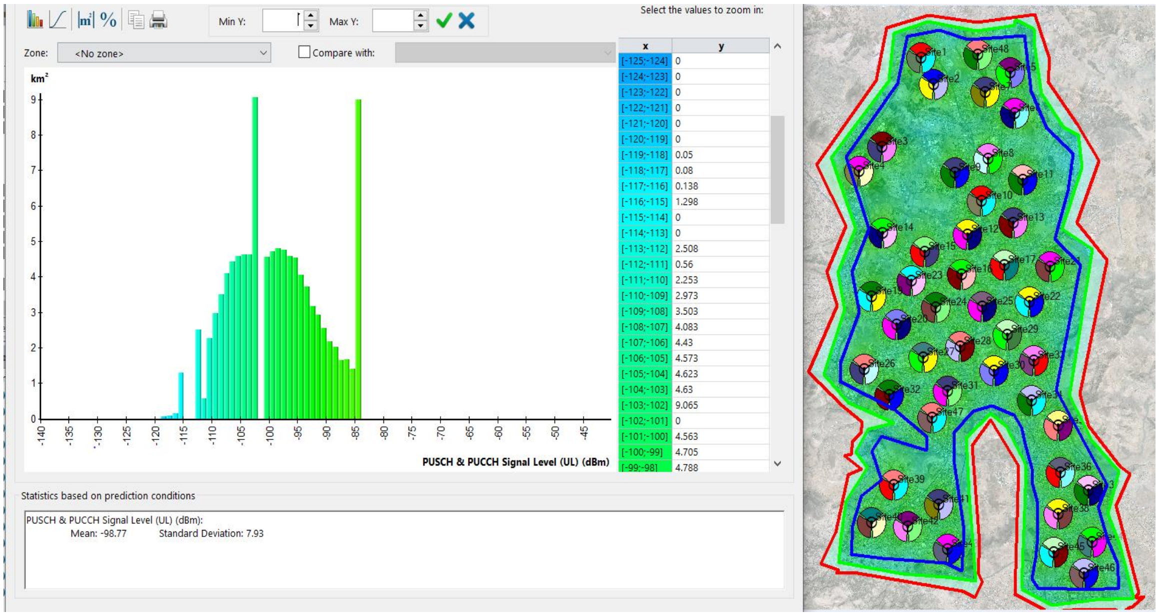
		Min	Max	Legend
1	🟥	1,000		Traffic Density (No. users/km²) >=1,000
2	🟧	900	1,000	900 <=Traffic Density (No. users/km²) <1,000
3	🟧	800	900	800 <=Traffic Density (No. users/km²) <900
4	🟨	700	800	700 <=Traffic Density (No. users/km²) <800
5	🟩	600	700	600 <=Traffic Density (No. users/km²) <700
6	🟩	500	600	500 <=Traffic Density (No. users/km²) <600
7	🟩	400	500	400 <=Traffic Density (No. users/km²) <500
8	🟩	300	400	300 <=Traffic Density (No. users/km²) <400
9	🟦	200	300	200 <=Traffic Density (No. users/km²) <300
10	🟦	100	200	100 <=Traffic Density (No. users/km²) <200
11	🟦	0	100	0 <=Traffic Density (No. users/km²) <100
12	🟦		0	Traffic Density (No. users/km²) <0

Figure 5.6 User density traffic map

5.3.4 Coverage and Capacity Prediction Study:

Coverage by signal level is used to demonstrate the power level of each site. As the signal is near the site the signal will be strong also if the signal is far from the site, it gets weaker. The signal strength also depends on other factors such as power received from transmitter, antenna height, antenna tilt roads, islands, clutter classes and environments. As a result, the color of the coverage used in Atoll changes.

- UL coverage prediction

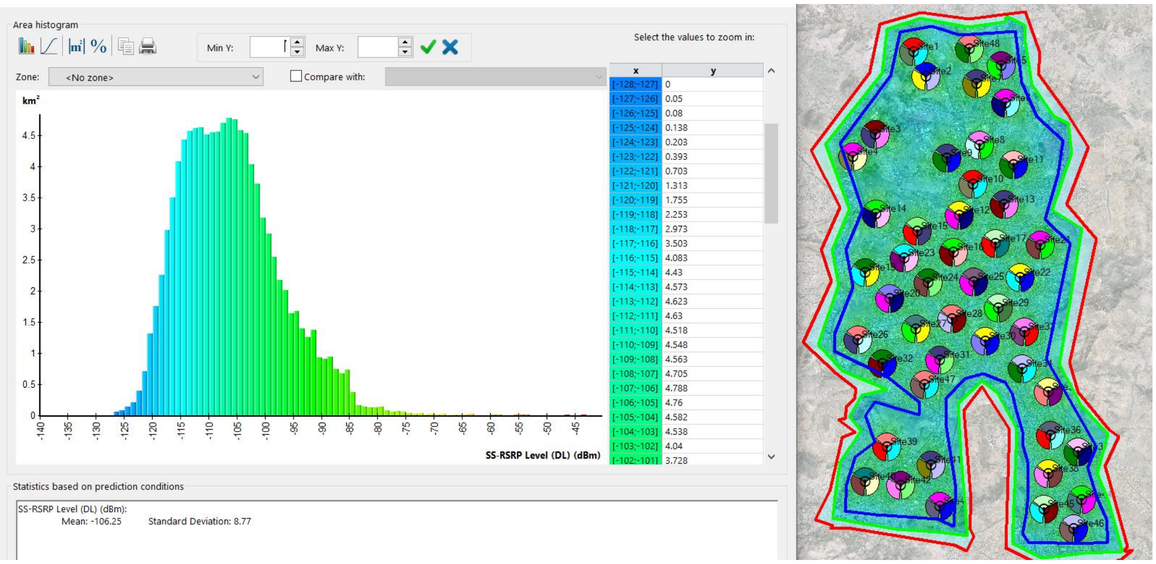


x	y
[-125;-124]	0
[-124;-123]	0
[-123;-122]	0
[-122;-121]	0
[-121;-120]	0
[-120;-119]	0
[-119;-118]	0.05
[-118;-117]	0.08
[-117;-116]	0.138
[-116;-115]	1.298
[-115;-114]	0
[-114;-113]	0
[-113;-112]	2.508
[-112;-111]	0.56
[-111;-110]	2.253
[-110;-109]	2.973
[-109;-108]	3.503
[-108;-107]	4.083
[-107;-106]	4.43
[-106;-105]	4.573
[-105;-104]	4.623
[-104;-103]	4.63
[-103;-102]	9.065
[-102;-101]	0
[-101;-100]	4.563
[-100;-99]	4.705
[-99;-98]	4.788

PUSCH & PUCCH Signal Level (UL) (dBm):
Mean: -98.77 Standard Deviation: 7.93

Figure 5.7 UL coverage prediction

- DL coverage prediction

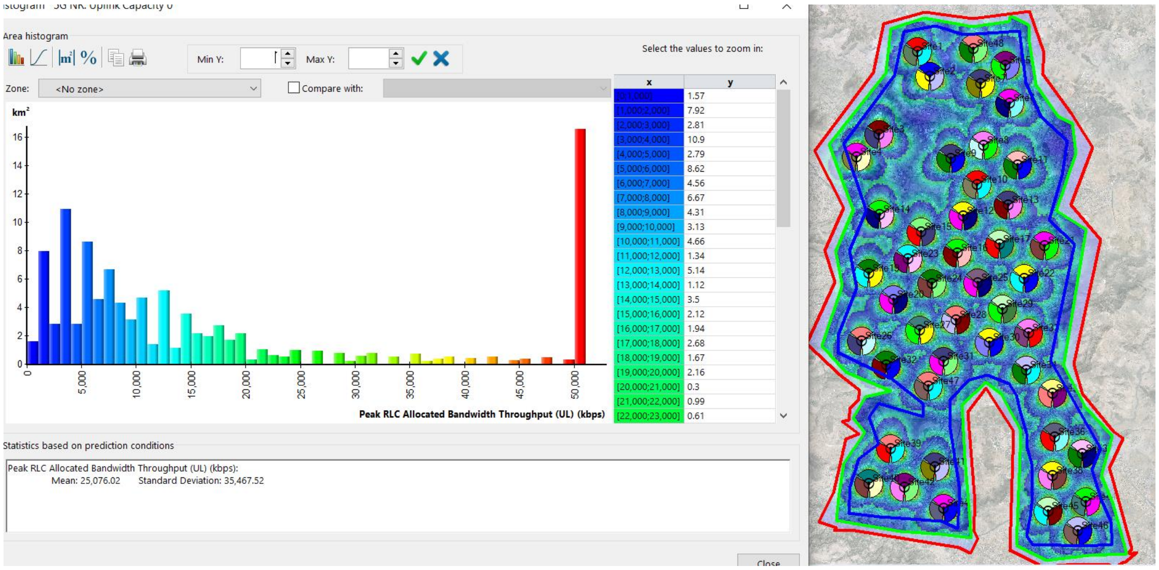


x	y
[-128;-127]	0
[-127;-126]	0.05
[-126;-125]	0.08
[-125;-124]	0.138
[-124;-123]	0.203
[-123;-122]	0.393
[-122;-121]	0.703
[-121;-120]	1.313
[-120;-119]	1.755
[-119;-118]	2.253
[-118;-117]	2.973
[-117;-116]	3.503
[-116;-115]	4.083
[-115;-114]	4.43
[-114;-113]	4.573
[-113;-112]	4.623
[-112;-111]	4.63
[-111;-110]	4.518
[-110;-109]	4.548
[-109;-108]	4.563
[-108;-107]	4.705
[-107;-106]	4.788
[-106;-105]	4.76
[-105;-104]	4.582
[-104;-103]	4.538
[-103;-102]	4.04
[-102;-101]	3.728

SS-RSRP Level (DL) (dBm):
Mean: -106.25 Standard Deviation: 8.77

Figure 5.8 DL coverage prediction

- UL capacity prediction

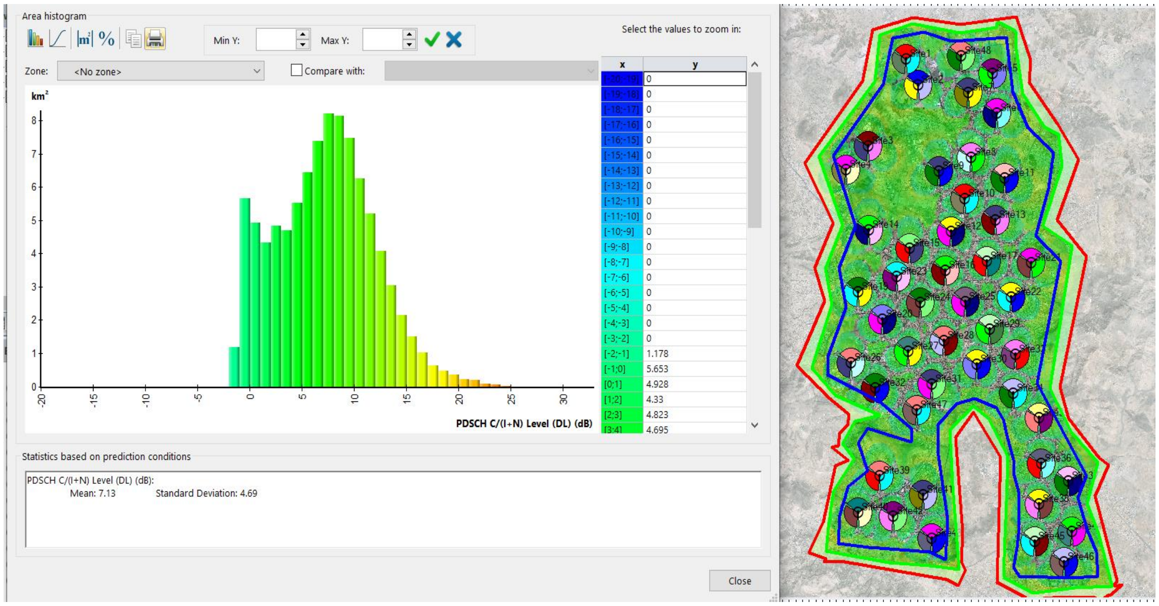


x	y
[0;1,000]	1.57
[1,000;2,000]	7.92
[2,000;3,000]	2.81
[3,000;4,000]	10.9
[4,000;5,000]	2.79
[5,000;6,000]	8.62
[6,000;7,000]	4.56
[7,000;8,000]	6.67
[8,000;9,000]	4.31
[9,000;10,000]	3.13
[10,000;11,000]	4.66
[11,000;12,000]	1.34
[12,000;13,000]	5.14
[13,000;14,000]	1.12
[14,000;15,000]	3.5
[15,000;16,000]	2.12
[16,000;17,000]	1.94
[17,000;18,000]	2.68
[18,000;19,000]	1.67
[19,000;20,000]	2.16
[20,000;21,000]	0.3
[21,000;22,000]	0.99
[22,000;23,000]	0.61

Peak RLC Allocated Bandwidth Throughput (UL) (kbps):
Mean: 25,076.02 Standard Deviation: 35,467.52

Figure 5.9 UL Capacity prediction

- DL capacity prediction



Zone: <No zone>

☐ Compare with:

x	y
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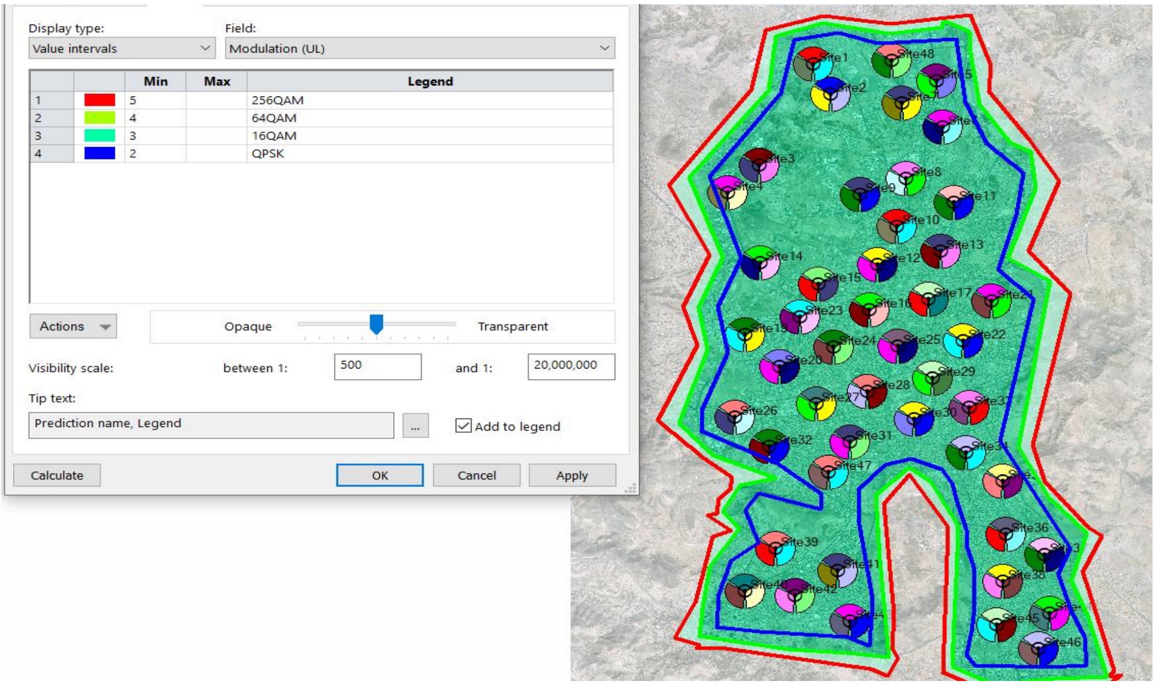
[-19;-18]	0
[-18;-17]	0
[-17;-16]	0
[-16;-15]	0
[-15;-14]	0
[-14;-13]	0
[-13;-12]	0
[-12;-11]	0
[-11;-10]	0
[-10;-9]	0
[-9;-8]	0
[-8;-7]	0
[-7;-6]	0
[-6;-5]	0
[-5;-4]	0
[-4;-3]	0
[-3;-2]	0
[-2;-1]	1.178
[-1;0]	5.653
[0;1]	4.928
[1;2]	4.33
[2;3]	4.823
[3;4]	4.695

Statistics based on prediction conditions

PDSCH C/(I+N) Level (DL) (dB):
Mean: 7.13 Standard Deviation: 4.69

Figure 5.10 DL Capacity prediction

- DL service area



Display type: Value intervals

Field: Modulation (UL)

		Min	Max	Legend
1	🟥	5		256QAM
2	🟩	4		64QAM
3	🟩	3		16QAM
4	🟦	2		QPSK

Visibility scale: between 1: 500 and 1: 20,000,000

Tip text: Prediction name, Legend

☑ Add to legend

Figure 5.11 DL Service Area

5.4 5G-NR Simulation:

Atoll is a multi-technology wireless network design and optimizations platform that supports wireless operators throughout the network lifecycle, from initial design to densification and optimization. Atoll offers unique capabilities of using both predictions and live network data throughout the network planning and optimization process.

Atoll includes integrated single RAN–multiple RAT network design capabilities for both 3GPP and 3GPP2 radio access technologies including 5G NR, LTE, NB-IoT, UMTS, GSM, and CDMA. It provides operators and vendors with a powerful framework for designing and optimizing current and future integrated multi-technology networks. Atoll supports the latest technology advances such as massive MIMO, 3D beamforming, and mmWave propagation for the design and roll-out of 5G networks.

Atoll Microwave is a state-of-the-art point-to-point and point-to-multipoint backhaul planning and optimization software. It allows designing large microwave link networks, according to ITU recommendations, industry standards, and operator guidelines.

Atoll’s integration and customization features help operators smoothly streamline planning and optimization processes. Atoll supports a wide range of implementation scenarios, from standalone to enterprise-wide server based configurations. Atoll has become the industry standard for radio network planning and optimization.

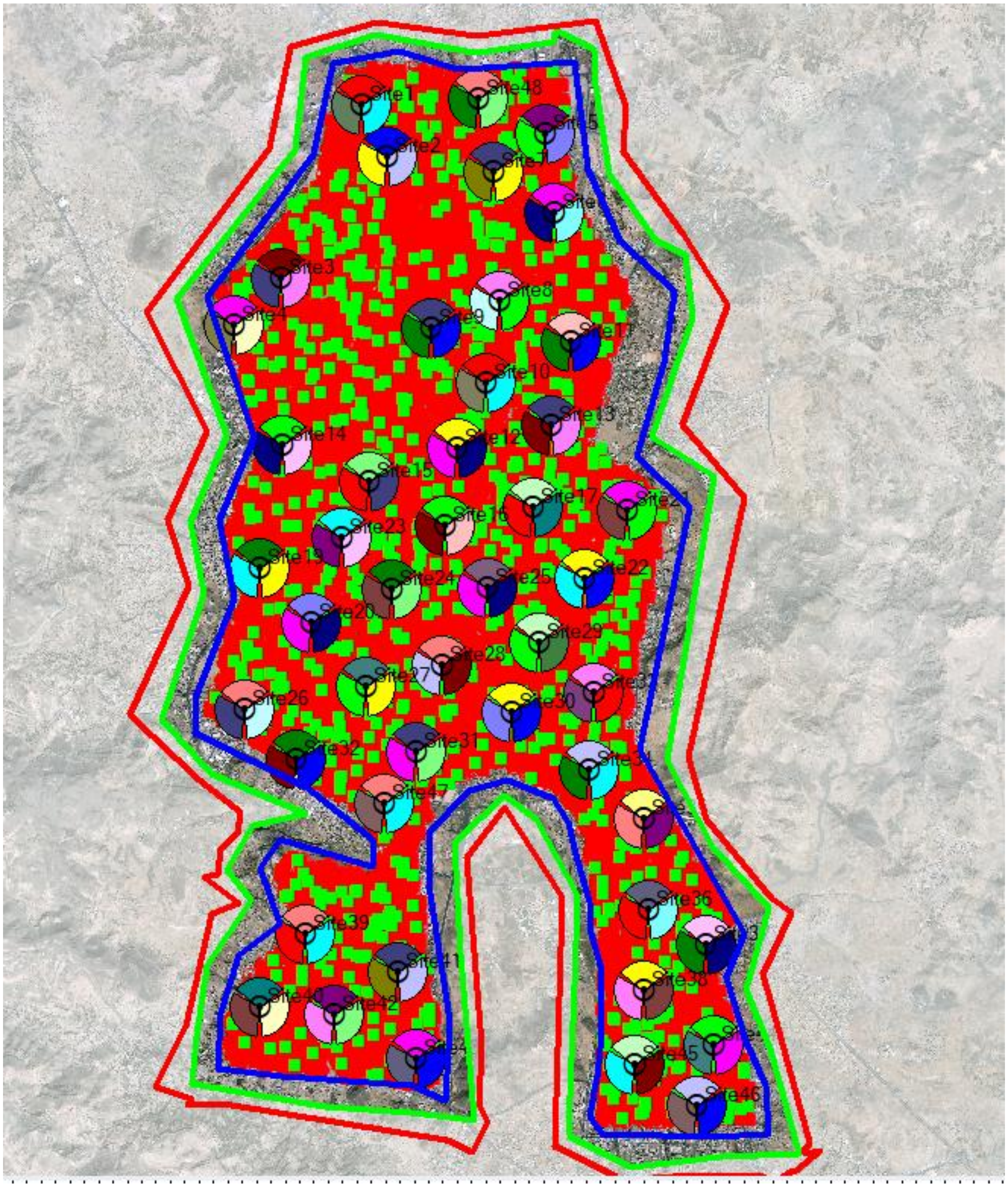


Figure 5.12 5G-NR Simulation map

APPENDIX I :

SNR and Throughput

This annex provides a description and overview on the formulas related to SINR and throughput in 5G for a given set of system configurations.

The relationship between SINR and throughput is established in this Appendix for different modulation scheme configurations. For QPSK, 16-QAM and 64-QAM, each one is associated with the median value of the coding rates (CRs) obtained from the Channel Quality Indicator (CQI) reported by the MT.

Regarding 256-QAM, the experimental relationship from [LLRP2014] defines a 256/64-QAM gain of 23.1%, which is in a good level of agreement with gain of 4/3 due to a different inferior to 10%. Hence, the 256-QAM expression is extrapolated from the 64-QAM in [Alco2017] with the lower gain value of 23.1% from [LLRP2014]. The coding rates and channel models for these MCS are defined in Table A.1

Table A.1 MCS related parameters

Parameters	Modulation Scheme			
Coding Rate	QPSK	16- QAM	64-QAM	256-QAM
	1/3	**1/2**	**3/4**	**[0.7; 0.9]**
Channel Model	EPA5			EPA10

The relationship between the throughput per RB and its SINR, on a MIMO 2x2 configuration and with the coding rates of Table A.1 is defined by the equations:

For QPSK:

$$R_{b,QPSK[\text{bit/s}]} = \frac{2.34201 \cdot 10^{6}}{14.0051 + e^{-0.577897 \cdot \rho_{IN[\text{dB}]}}} \qquad \text{(A.1)}$$

$$\rho_{IN,QPSK[\text{dB}]} = -\frac{1}{0.577897} \cdot \ln\left(\frac{2.34201 \cdot 10^{6}}{R_{b[\text{bit/s}]}} - 14.0051\right) \qquad \text{(A.2)}$$

For 16-QAM:

$$R_{b,16QAM[\text{bit/s}]} = \frac{47613.1}{0.0926275 + e^{-0.295838 \cdot \rho_{IN[\text{dB}]}}} \qquad \text{(A.3)}$$

$$\rho_{IN,16QAM[\text{dB}]} = -\frac{1}{0.295838} \cdot \ln\left(\frac{47613.1}{R_{b[\text{bit/s}]}} - 0.0926275\right) \qquad \text{(A.4)}$$

For 64-QAM:

$$R_{b,64QAM[\text{bit/s}]} = \frac{26405.8}{0.0220186 + e^{-0.24491 \cdot \rho_{IN[\text{dB}]}}} \qquad \text{(A.5)}$$

$$\rho_{IN,64QAM[\text{dB}]} = -\frac{1}{0.24491} \cdot \ln\left(\frac{26405.8}{R_{b[\text{bit/s}]}} - 0.0220186\right) \qquad \text{(A.6)}$$

For 256-QAM:

$$R_{b,256QAM[\text{bit/s}]} = \frac{26407.1}{0.0178868 + e^{-0.198952 \cdot \rho_{IN[\text{dB}]}}} \qquad \text{(A.7)}$$

$$\rho_{IN,256QAM[\text{dB}]} = -\frac{1}{0.198952} \cdot \mathit{ln}\left(\frac{26407.1}{R_{b[\text{bit/s}]}} - 0.0178868\right) \qquad \text{(A.8)}$$

The equations are defined for MIMO 2x2 configuration. However, it may be useful to analyze the throughput-per-RB variation as the MIMO order increases due to it being a likely case for future 5G deployments. The SINR versus throughput relationship per RB in this annex is given for the numerology 0 configuration, with a subcarrier spacing of 15 kHz on a total RB bandwidth of 180 kHz. For other numerology configurations the relationship should be at maximum the same value as the ratio between the higher SCS and the standard of 15 kHz.

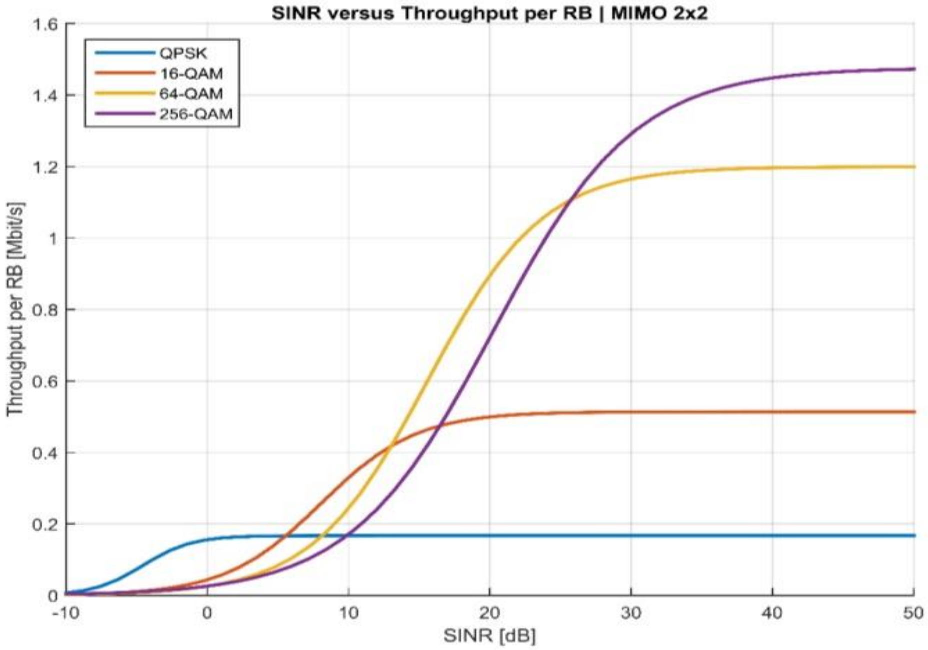


Figure A.1. SINR versus throughput per RB for MIMO 2x2

For the Coverage Planning, a general formula has to be computed comprising the best modulation for each ρ_{IN}:

$$R_{b,max[\mathrm{bit/s}]} = \begin{cases} \dfrac{2.34201 \cdot 10^{6}}{14.0051 + e^{-0.577897 \cdot \rho_{IN[\mathrm{dB}]}}}, & \rho_{IN} < 5.5\ \mathrm{dB} \\ \dfrac{47613.1}{0.0926275 + e^{-0.295838 \cdot \rho_{IN[\mathrm{dB}]}}}, & 5.5\ dB \leq \rho_{IN} < 12.9\ \mathrm{dB} \\ \dfrac{26405.8}{0.0220186 + e^{-0.24491 \cdot \rho_{IN[\mathrm{dB}]}}}, & 12.9\ dB \leq \rho_{IN} < 25.5\ \mathrm{dB} \\ \dfrac{26407.1}{0.0178868 + e^{-0.198952 \cdot \rho_{IN[\mathrm{dB}]}}}, & 25.5\ dB \leq \rho_{IN} \end{cases} \tag{A.9}$$

The average SINR value per modulation scheme region is defined in Table A.2.

Table A.2 Average throughput per RB per modulation and SCS

	QPSK	16-QAM	64-QAM	256-QAM
ρ_{min} [dB]	-10	5.5	12.9	25.5
ρ_{max} [dB]	5.5	12.9	25.5	45
ρ [dB]	-1.3	9.2	19.2	35.3

APPENDIX II:

Propagation Models calculation

B.1 Radio Link Budget:

The general formulation of the radio link budget and its parameters are described in this appendix.

The transmission power is given by the system along with the gains of antennas, transmitter and receptor. So, having all gains and powers of the link, to determine the maximum distance in the next phase, with the Link Budget the maximum path loss that each link in DL and UL can have is calculated with (B.1). The power available at the receiving antenna can be expressed by:

$$P_{r\,[\mathrm{dBm}]} = P_{t\,[\mathrm{dBm}]} + G_{r\,[\mathrm{dBi}]} + G_{t[\mathrm{dBi}]} - L_{p,\,max[\mathrm{dB}]} \qquad \text{(B.1)}$$

Where:

- P_r : power available at the receiving antenna;
- P_t : power fed to the transmitting antenna;
- G_r : gain of the receiving antenna ;
- G_t : gain of the transmitting antenna ;
- $L_{p,max}$: total path loss;

The antenna gains of the BS depend essentially on the antenna type and the number of sectors, while the UE one depends on the type of device. The expressions for the power transmitted in DL and UL can are (B.2) and (B.3) respectively.

$$P_t^{DL}\,_{[\mathrm{dBm}]} = P_{Tx\,[\mathrm{dBm}]} - L_{t\,[\mathrm{dB}]} \qquad \text{(B.2)}$$

Where:

- P_t^{DL}: power fed to the antenna in the DL;
- P_{Tx}: transmitter output power;
- L_t : losses in the cable between the transmitter and the antenna;

P_t^{UL} [dBm] = P_{Tx} [dBm] – L_r [dB] (B.3)

Where:

- P_t^{UL} : power fed to the antenna in the UL;
- P_{Tx}: transmitter output power;
- L_r : losses due to the user's body.

For the losses due to the user's body, the services being used need to be considered. If the service being used is voice, then head attenuation is considered, while for other services like data, where the user is using the phone in their hand, the attenuation considered must be only from their hand.

The power at the receiver in DL and UL can be expressed in (B.4) and (B.5) respectively.

P_{Rx}^{DL} [dBm] = P_{Tx} [dBm] – L_t [dB] (B.4)

P_{Rx}^{DL}: Receiver input power at DL;

P_{Rx}^{UL} [dBm] = P_{Tx} [dBm] – L_r [dB] (B.5)

P_{Rx}^{UL} : Receiver input power at UL;

Therefore, the radio link budget RLB equation can be expressed as:

$$L_{p,\,max[\mathrm{dB}]} = P_{Tx[\mathrm{dBm}]} - L_{t[\mathrm{dB}]} - P_{Rx,min[\mathrm{dBm}]} - L_{r[\mathrm{dB}]} + G_{r[\mathrm{dBi}]} + G_{t[\mathrm{dBi}]} - I_{m[\mathrm{dB}]} + G_{t[\mathrm{dBi}]} + G_{Tx[\mathrm{dBi}]} + G_{TMA[\mathrm{dBi}]} \quad \text{(B.6)}$$

Where:

- I_m: interference margin;
- G_{Tx}: diversity gain (MIMO order);
- G_{TMA}: Tower Mounted Amplifier;

Regarding interference, the parameter that is taken in coverage estimation is the interference margin (I_m), which has a range between 2 dB and 4 dB for coverage limited cells, and between 4 dB and 7 dB for capacity limited ones. A TMA reduces the BS noise figure (FN) and therefore improves its overall sensitivity; it compensates for cable losses, typically 3 dB, but introduces an insertion loss in DL (typically 0.5 dB).

Through the calculation of maximum allowed propagation path MAPL loss for DL and UL and the use of appropriate propagation models, along with the SNR-throughput relationship, it is possible to calculate the maximum distance between the BS and the MT having a given throughput reference. Then, this distance (*cell radius*) is used to determine the number of required cells to cover the desired coverage area. The mean cell-radius is defined as dependent on the share of indoors and outdoors users in B.7:

$$r_{cell} = p_{indoor} \cdot r_{indoor} + p_{outdoor} \cdot r_{outdoor} \quad \text{(B.7)}$$

Where:

- $r_{cell\,[\mathrm{km}]}$: mean cell-radius;
- $p_{indoor\,[\%]}$: percentage of users in indoors;
- $r_{indoor[\mathrm{km}]}$: maximum/mean indoor radius;
- $p_{outdoor[\%]}$: percentage of users in outdoors;
- $r_{outdoor[\mathrm{km}]}$: maximum/mean outdoor radius;

B.2 Propagation Models:

In outdoors propagation a heavy dependence on the signal frequency is expected. From literature research, a description for the models in use is done:

- **Okumura-Hata model:** the standard model is an urban flat environment from which correction factors are considered. It takes urban, suburban and open area scenarios into account from 1 to 20 km, with a BS height between 30 and 100 m and UE terminal height between 1 and 10 m. Its frequency range goes from 150 to 1500 MHz, being a suitable model for the 700 MHz band.

- **WINNER II model:** it presents a variety of distinct propagation. For macro-cells it outputs valid results for urban, suburban and rural areas. It considers distances from 0.05 to 5 km and is based on having a BS height around 25 m and UE terminal height around 1.5 m.

Taking outdoors-indoors attenuation environments, studies have been performed to estimate typical penetration values in a wide range of frequencies, path loss that can then be added to the outdoors one into variable L'_p from (4.2), such as:

- **Experimental Indoors Path Loss Model:** the work is based on field tests from Samsung and Nokia, consisting of an approximate for estimating this penetration loss on the premise of low and high-loss buildings, essentially given by the presence of strongly reflective surfaces, such as glass walls, including both 0.7 and 3.5 GHz bands.

Table B.1. Model equations for indoors scenarios (0.7 and 3.5 GHz).

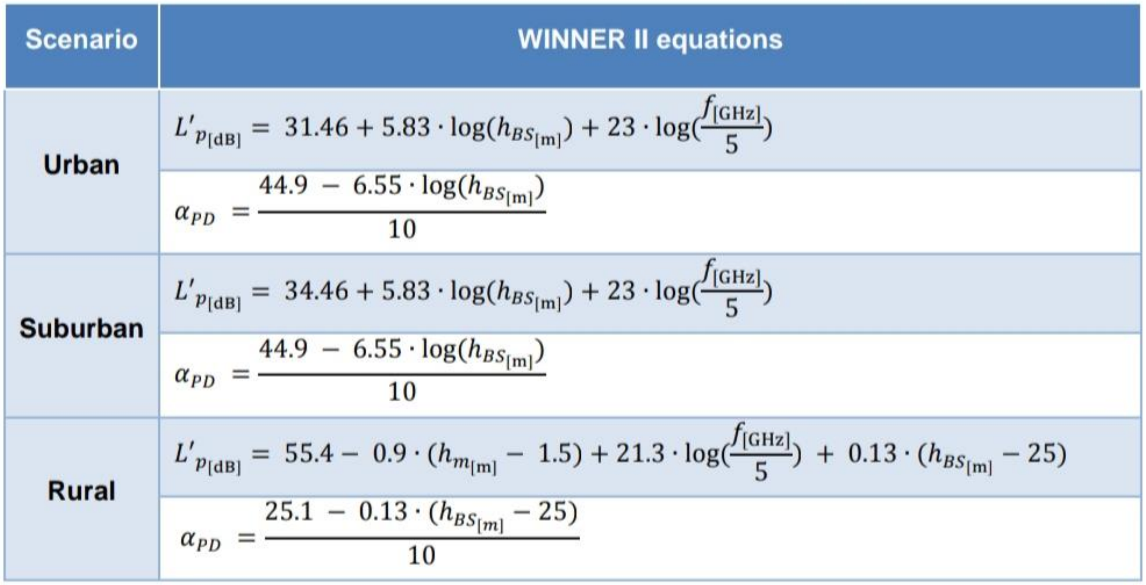
Scenario	Experimental Indoors Path Loss
All	$\Delta L_{p_{[\mathrm{dB}]}} = 10\log(A + B \cdot f_{[\mathrm{GHz}]}^{2})$

The distance formulation provided by the propagation models concerning outdoors propagation are defined in Table B.2 and Table B.3. It should be noted that every distance and path loss equation for every model has its standard deviation and limited range of values, on antenna heights, minimum distances (breakpoint) or others, which are considered later.

Table B.2. Model equations for different scenarios for the 0.7 GHz frequency band (outdoors).

Scenario	Okumura-Hata equations
Urban	$L'_{p_{[\mathrm{dB}]}} = 69.55 + 26.16 \cdot \log(f_{[\mathrm{MHz}]}) - 13.83 \cdot \log(h_{BS_{[\mathrm{m}]}}) - \alpha(h_{mt_{[\mathrm{m}]}})$
	$\alpha(h_{m_{[\mathrm{m}]}}) = [1.1 \cdot \log(f_{[\mathrm{MHz}]}) - 0.7] \cdot h_{m_{[\mathrm{m}]}} - [1.56 \cdot \log(f_{[\mathrm{MHz}]}) - 0.8]$
Suburban	$L'_{p_{[\mathrm{dB}]}} = 69.55 + 26.16 \cdot \log(f_{[\mathrm{MHz}]}) - 13.83 \cdot \log(h_{BS_{[\mathrm{m}]}}) - \alpha(h_{mt_{[\mathrm{m}]}}) - 2 \cdot \log\left(\frac{f_{[\mathrm{MHz}]}}{28}\right)^{2} - 5.4$
	$\alpha(h_{m_{[\mathrm{m}]}}) = [1.1 \cdot \log(f_{[\mathrm{MHz}]}) - 0.7] \cdot h_{m_{[\mathrm{m}]}} - [1.56 \cdot \log(f_{[\mathrm{MHz}]}) - 0.8]$
Rural	$L'_{p_{[\mathrm{dB}]}} = 69.55 + 26.16 \cdot \log(f_{[\mathrm{MHz}]}) - 13.83 \cdot \log(h_{BS_{[\mathrm{m}]}}) - \alpha(h_{mt_{[\mathrm{m}]}}) - 4.78 \cdot \log(f_{[\mathrm{MHz}]})^{2} + 18.33 \cdot \log(f_{[\mathrm{MHz}]}) - 40.98$
	$\alpha(h_{m_{[\mathrm{m}]}}) = [1.1 \cdot \log(f_{[\mathrm{MHz}]}) - 0.7] \cdot h_{m_{[\mathrm{m}]}} - [1.56 \cdot \log(f_{[\mathrm{MHz}]}) - 0.8]$
All	$\alpha_{PD} = \frac{44.90 - 6.55 \cdot \log\left(h_{BS_{[\mathrm{m}]}}\right)}{10}$

Table B.3. Model equations for different scenarios for the 3.5 GHz frequency band (outdoors).



Scenario	WINNER II equations
Urban	$L'_{p[\text{dB}]} = 31.46 + 5.83 \cdot \log(h_{BS_{[\text{m}]}}) + 23 \cdot \log(\frac{f_{[\text{GHz}]}}{5})$
	$\alpha_{PD} = \frac{44.9 - 6.55 \cdot \log(h_{BS_{[\text{m}]}})}{10}$
Suburban	$L'_{p[\text{dB}]} = 34.46 + 5.83 \cdot \log(h_{BS_{[\text{m}]}}) + 23 \cdot \log(\frac{f_{[\text{GHz}]}}{5})$
	$\alpha_{PD} = \frac{44.9 - 6.55 \cdot \log(h_{BS_{[\text{m}]}})}{10}$
Rural	$L'_{p[\text{dB}]} = 55.4 - 0.9 \cdot (h_{m_{[\text{m}]}} - 1.5) + 21.3 \cdot \log(\frac{f_{[\text{GHz}]}}{5}) + 0.13 \cdot (h_{BS_{[\text{m}]}} - 25)$
	$\alpha_{PD} = \frac{25.1 - 0.13 \cdot (h_{BS_{[\text{m}]}} - 25)}{10}$

- L'_p: path loss given by the sum of the outdoors and indoors path loss;
- $L_{p,\,max}$: maximum path loss (MAPL) given by the link budget computation;
- α_{PD}: average power decay (model and configuration dependent);
- h_{BS}: height of base-station;
- h_m: height of mobile terminal;
- f: carrier frequency;

B.3 Propagation Model - Okumura-Hata:

The path-loss experienced by a signal between the BS and the MT in urban, suburban and rural scenarios at the 700 MHz band can be described by Okumura's original experimentation values.

$$L_{p[\text{dB}]} = L_{A[\text{dB}]} + L_{B[\text{dB}]} \cdot \log(d_{[\text{km}]}) + L_{C[\text{dB}]} \quad \text{(B.8)}$$

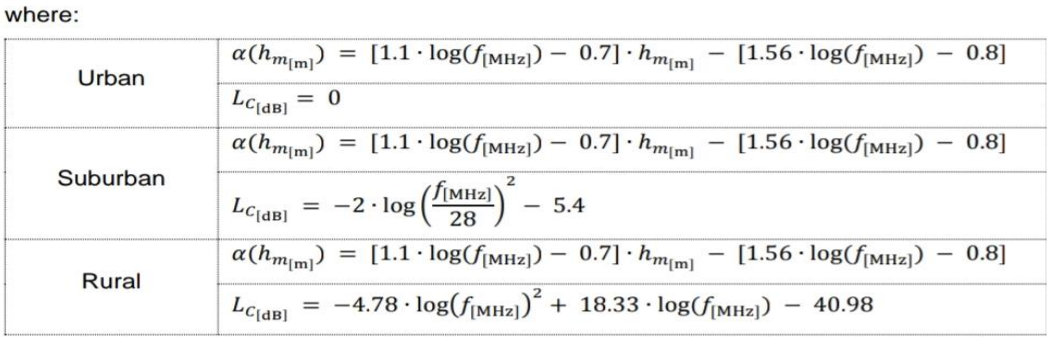
$$d_{max,[\text{km}]} = 10^{\text{Lp,max[dB]} - \text{LA[dB]} - \text{LC[dB]} / \text{LB[dB]}} \quad \text{(B.9)}$$

where:

- L_A : correction factor related to the frequency, BS and UE antenna height, dependent on the propagation scenario;
- L_B : correction factor related to the BS antenna height;
- L_C : propagation scenario correction factor;

In which:

- $L_{A[\text{dB}]} = 69.55 + 26.16 \cdot \log(f_{[\text{MHz}]}) - 13.83 \cdot \log(h_{BS[\text{m}]}) - \alpha(h_{mt[\text{m}]})$ (B.10)
- $L_{B[\text{dB}]} = 44.90 - 6.55 \cdot \log(h_{BS[\text{m}]})$ (B.11)



where:

Urban	$\alpha(h_{m_{[\text{m}]}}) = [1.1 \cdot \log(f_{[\text{MHz}]}) - 0.7] \cdot h_{m_{[\text{m}]}} - [1.56 \cdot \log(f_{[\text{MHz}]}) - 0.8]$
	$L_{C_{[\text{dB}]}} = 0$
Suburban	$\alpha(h_{m_{[\text{m}]}}) = [1.1 \cdot \log(f_{[\text{MHz}]}) - 0.7] \cdot h_{m_{[\text{m}]}} - [1.56 \cdot \log(f_{[\text{MHz}]}) - 0.8]$
	$L_{C_{[\text{dB}]}} = -2 \cdot \log\left(\frac{f_{[\text{MHz}]}}{28}\right)^2 - 5.4$
Rural	$\alpha(h_{m_{[\text{m}]}}) = [1.1 \cdot \log(f_{[\text{MHz}]}) - 0.7] \cdot h_{m_{[\text{m}]}} - [1.56 \cdot \log(f_{[\text{MHz}]}) - 0.8]$
	$L_{C_{[\text{dB}]}} = -4.78 \cdot \log(f_{[\text{MHz}]})^2 + 18.33 \cdot \log(f_{[\text{MHz}]}) - 40.98$

B.4 Propagation Model – WINNER II:

The path-loss experienced by a signal travelling between the BS and the UE can be calculated from the WINNER II model, with a valid frequency from 2 to 6 GHz, according to [WINN07]. The model parameters have been developed from measurements carrier both from WINNER and from open literature results. It is valid for different antenna heights.

$L_{p[\text{dB}]} = \text{A} \log(d_{[\text{m}]}) + B + C \log(f_{[\text{GHz}]} / 5.0)$

where:

- L_p: path loss;
- A : path loss exponent;
- B : intercept parameter;

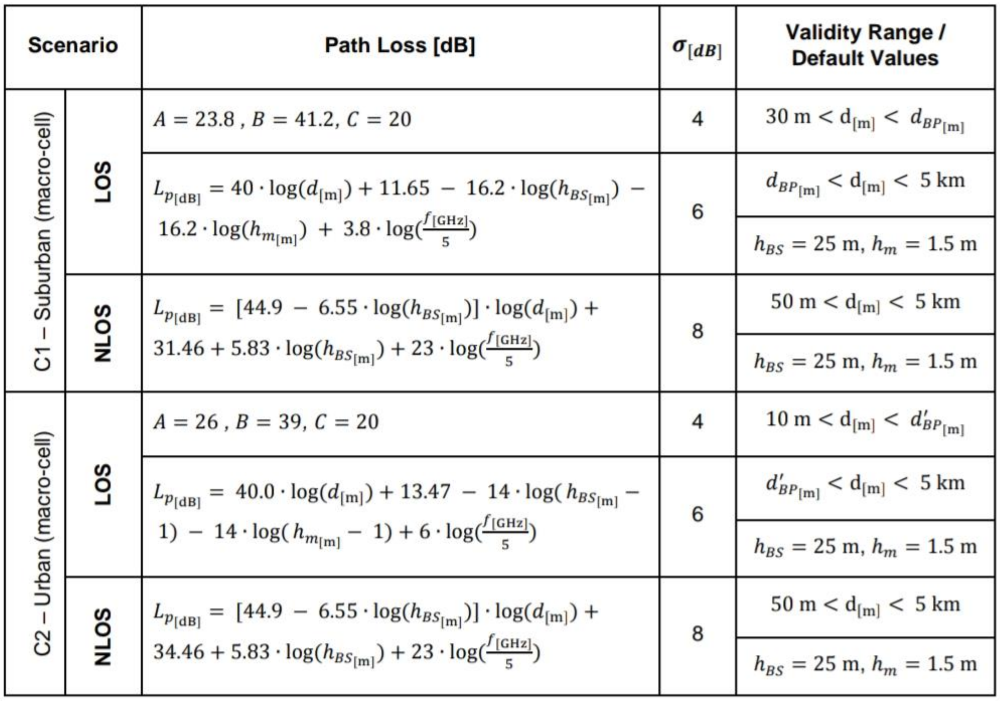
- C : path loss frequency dependence;

This model accounts for penetration losses in some propagation scenarios. The summary table of the WINNER II propagation model parameters is defined in Table B.4 (path-loss), Table B.5 (distance) and Table B.6 (path-loss). The breakpoint distance is defined, which can be formulated by:

$$d_{BP\text{[m]}} = 4 \cdot h_{m\text{[m]}} \cdot h_{BS\text{[m]}} \cdot (f_{\text{[Hz]}} / c_{\text{[m/s]}}) = (40/3) \cdot h_{m\text{[m]}} \cdot h_{BS\text{[m]}} \cdot f_{\text{[GHz]}}$$

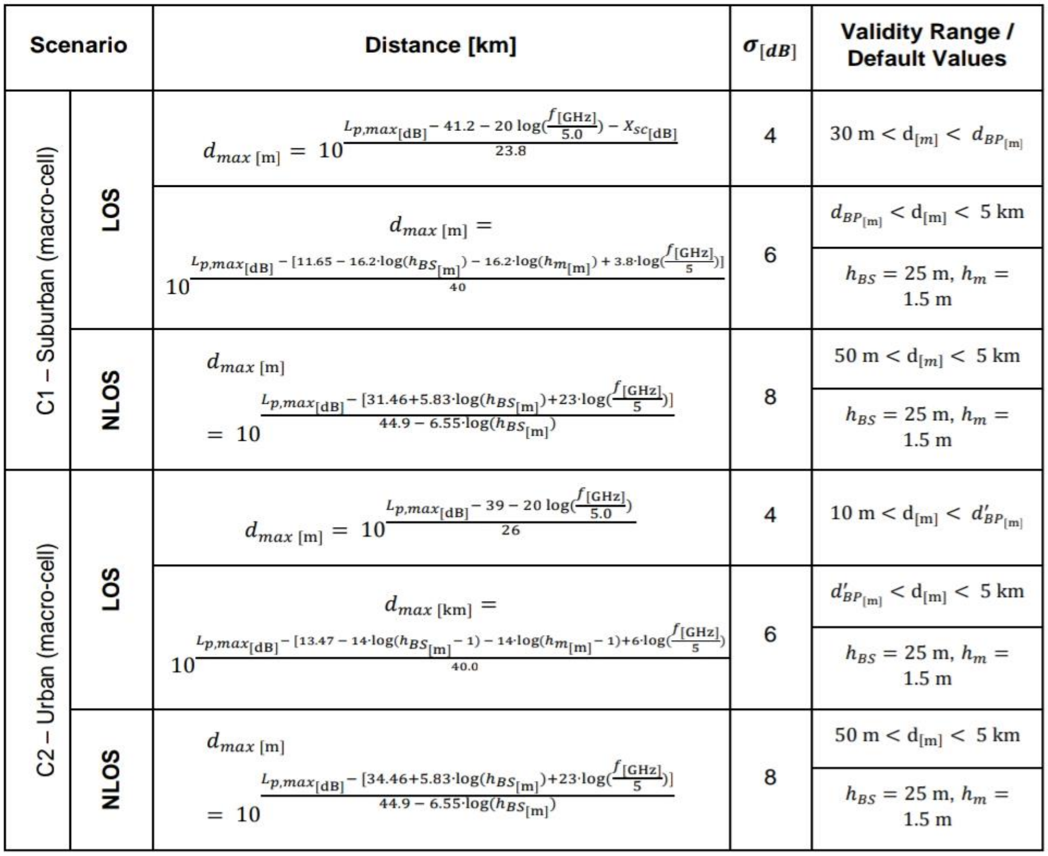
$$d'_{BP\text{[m]}} = 4 \cdot (h_{m\text{[m]}} - 1) \cdot (h_{BS\text{[m]}} - 1) \cdot (f_{\text{[Hz]}} / c_{\text{[m/s]}}) = (40/3).\ (h_{m\text{[m]}} - 1) \cdot (h_{BS\text{[m]}} - 1) \cdot f_{\text{[GHz]}}$$

Table B.4. WINNER II path-loss equations



Scenario		Path Loss [dB]	$\sigma_{[dB]}$	Validity Range / Default Values
C1 – Suburban (macro-cell)	LOS	$A = 23.8\ , B = 41.2,\ C = 20$	4	$30\ \text{m} < \text{d}_{[\text{m}]} < d_{BP_{[\text{m}]}}$
		$L_{P[\text{dB}]} = 40 \cdot \log(d_{[\text{m}]}) + 11.65 - 16.2 \cdot \log(h_{BS_{[\text{m}]}}) - 16.2 \cdot \log(h_{m_{[\text{m}]}}) + 3.8 \cdot \log(\frac{f_{[\text{GHz}]}}{5})$	6	$d_{BP_{[\text{m}]}} < \text{d}_{[\text{m}]} < 5\ \text{km}$
				$h_{BS} = 25\ \text{m},\ h_m = 1.5\ \text{m}$
	NLOS	$L_{P[\text{dB}]} = [44.9 - 6.55 \cdot \log(h_{BS_{[\text{m}]}})] \cdot \log(d_{[\text{m}]}) + 31.46 + 5.83 \cdot \log(h_{BS_{[\text{m}]}}) + 23 \cdot \log(\frac{f_{[\text{GHz}]}}{5})$	8	$50\ \text{m} < \text{d}_{[\text{m}]} < 5\ \text{km}$
				$h_{BS} = 25\ \text{m},\ h_m = 1.5\ \text{m}$
C2 – Urban (macro-cell)	LOS	$A = 26\ , B = 39,\ C = 20$	4	$10\ \text{m} < \text{d}_{[\text{m}]} < d'_{BP_{[\text{m}]}}$
		$L_{P[\text{dB}]} = 40.0 \cdot \log(d_{[\text{m}]}) + 13.47 - 14 \cdot \log(h_{BS_{[\text{m}]}} - 1) - 14 \cdot \log(h_{m_{[\text{m}]}} - 1) + 6 \cdot \log(\frac{f_{[\text{GHz}]}}{5})$	6	$d'_{BP_{[\text{m}]}} < \text{d}_{[\text{m}]} < 5\ \text{km}$
				$h_{BS} = 25\ \text{m},\ h_m = 1.5\ \text{m}$
	NLOS	$L_{P[\text{dB}]} = [44.9 - 6.55 \cdot \log(h_{BS_{[\text{m}]}})] \cdot \log(d_{[\text{m}]}) + 34.46 + 5.83 \cdot \log(h_{BS_{[\text{m}]}}) + 23 \cdot \log(\frac{f_{[\text{GHz}]}}{5})$	8	$50\ \text{m} < \text{d}_{[\text{m}]} < 5\ \text{km}$
				$h_{BS} = 25\ \text{m},\ h_m = 1.5\ \text{m}$

Table B.5. WINNER II distance equations



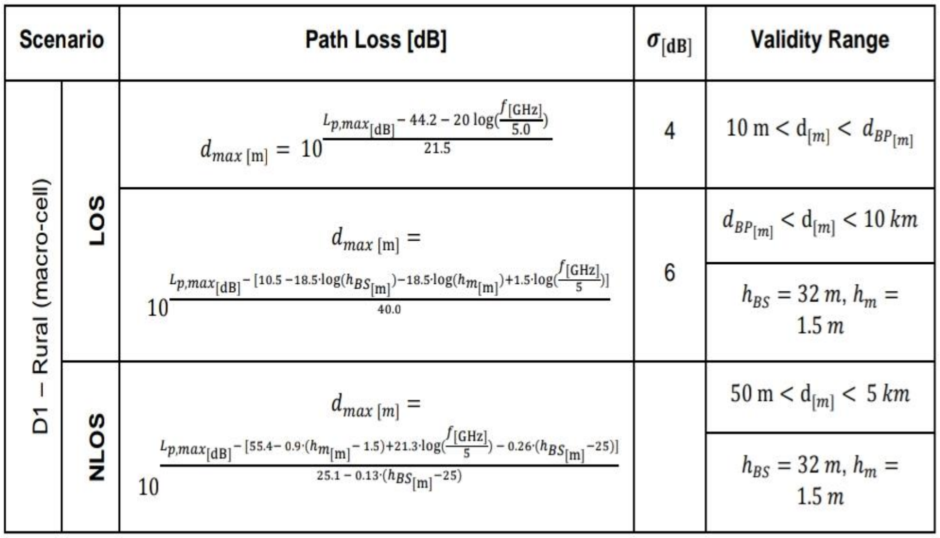
Scenario		Distance [km]	$\sigma_{[dB]}$	Validity Range / Default Values
C1 – Suburban (macro-cell)	LOS	$d_{max\ [\mathrm{m}]} = 10^{\frac{L_{p,max_{[\mathrm{dB}]}} - 41.2 - 20\log(\frac{f_{[\mathrm{GHz}]}}{5.0}) - X_{sc_{[\mathrm{dB}]}}}{23.8}}$	4	$30\ \mathrm{m} < \mathrm{d}_{[m]} < d_{BP_{[\mathrm{m}]}}$
		$d_{max\ [\mathrm{m}]} = 10^{\frac{L_{p,max_{[\mathrm{dB}]}} - [11.65 - 16.2\cdot\log(h_{BS_{[\mathrm{m}]}}) - 16.2\cdot\log(h_{m_{[\mathrm{m}]}}) + 3.8\cdot\log(\frac{f_{[\mathrm{GHz}]}}{5})]}{40}}$	6	$d_{BP_{[\mathrm{m}]}} < \mathrm{d}_{[\mathrm{m}]} < 5\ \mathrm{km}$ $h_{BS} = 25\ \mathrm{m},\ h_m = 1.5\ \mathrm{m}$
	NLOS	$d_{max\ [\mathrm{m}]} = 10^{\frac{L_{p,max_{[\mathrm{dB}]}} - [31.46 + 5.83\cdot\log(h_{BS_{[\mathrm{m}]}}) + 23\cdot\log(\frac{f_{[\mathrm{GHz}]}}{5})]}{44.9 - 6.55\cdot\log(h_{BS_{[\mathrm{m}]}})}}$	8	$50\ \mathrm{m} < \mathrm{d}_{[m]} < 5\ \mathrm{km}$ $h_{BS} = 25\ \mathrm{m},\ h_m = 1.5\ \mathrm{m}$
C2 – Urban (macro-cell)	LOS	$d_{max\ [\mathrm{m}]} = 10^{\frac{L_{p,max_{[\mathrm{dB}]}} - 39 - 20\log(\frac{f_{[\mathrm{GHz}]}}{5.0})}{26}}$	4	$10\ \mathrm{m} < \mathrm{d}_{[\mathrm{m}]} < d'_{BP_{[\mathrm{m}]}}$
		$d_{max\ [\mathrm{km}]} = 10^{\frac{L_{p,max_{[\mathrm{dB}]}} - [13.47 - 14\cdot\log(h_{BS_{[\mathrm{m}]}} - 1) - 14\cdot\log(h_{m_{[\mathrm{m}]}} - 1) + 6\cdot\log(\frac{f_{[\mathrm{GHz}]}}{5})}{40.0}}$	6	$d'_{BP_{[\mathrm{m}]}} < \mathrm{d}_{[\mathrm{m}]} < 5\ \mathrm{km}$ $h_{BS} = 25\ \mathrm{m},\ h_m = 1.5\ \mathrm{m}$
	NLOS	$d_{max\ [\mathrm{m}]} = 10^{\frac{L_{p,max_{[\mathrm{dB}]}} - [34.46 + 5.83\cdot\log(h_{BS_{[\mathrm{m}]}}) + 23\cdot\log(\frac{f_{[\mathrm{GHz}]}}{5})]}{44.9 - 6.55\cdot\log(h_{BS_{[\mathrm{m}]}})}}$	8	$50\ \mathrm{m} < \mathrm{d}_{[\mathrm{m}]} < 5\ \mathrm{km}$ $h_{BS} = 25\ \mathrm{m},\ h_m = 1.5\ \mathrm{m}$

The C1 and C2 model configuration assume macro-cells located above the rooftops to allow a wide coverage area and mobile users to be outdoors at street level:

- The **C1 configuration assume** buildings are typically low residential detached houses top two floors or blocks of flats with a few floors. The environment is moderately open, with open areas such as parks or playgrounds, and vegetation is modest.
- The **C2 Configuration assumes** obstructed line of sight is a common case since street level is often reached by a single diffraction over the rooftop. The building blocks can form either a regular type of grid or have more irregular patterns. Typical building heights are over 4 floors, with height and density mostly homogeneous.

Furthermore, the D1 configuration (rural macro-cell) configuration consists of radio propagation in large areas (up to 10 km) with low building density. The height of the base station is in the range of 20 to 70 m, above the average surrounding building height, leading to good LOS conditions. The model parameters and distance validity range are shown below:

Table B.6. WINNER II path-loss equations



Scenario		Path Loss [dB]	$\sigma_{[dB]}$	Validity Range
D1 – Rural (macro-cell)	LOS	$d_{max\,[m]} = 10^{\frac{L_{p,max_{[dB]}} - 44.2 - 20\log(\frac{f_{[GHz]}}{5.0})}{21.5}}$	4	$10\text{ m} < d_{[m]} < d_{BP_{[m]}}$
		$d_{max\,[m]} = 10^{\frac{L_{p,max_{[dB]}} - [10.5 - 18.5\cdot\log(h_{BS_{[m]}}) - 18.5\cdot\log(h_{m_{[m]}}) + 1.5\cdot\log(\frac{f_{[GHz]}}{5})]}{40.0}}$	6	$d_{BP_{[m]}} < d_{[m]} < 10\,km$
				$h_{BS} = 32\,m,\ h_m = 1.5\,m$
	NLOS	$d_{max\,[m]} = 10^{\frac{L_{p,max_{[dB]}} - [55.4 - 0.9\cdot(h_{m_{[m]}} - 1.5) + 21.3\cdot\log(\frac{f_{[GHz]}}{5}) - 0.26\cdot(h_{BS_{[m]}} - 25)]}{25.1 - 0.13\cdot(h_{BS_{[m]}} - 25)}}$		$50\text{ m} < d_{[m]} < 5\,km$
				$h_{BS} = 32\,m,\ h_m = 1.5\,m$

B.4 Propagation Model – Experimental Indoors:

This model is retrieved from [HTZA16] and it is based on field tests from Samsung and Nokia, consisting on an approximate for estimating this penetration loss on the premise of low and high-loss buildings, given by the presence of strongly reflective surfaces, e.g., glass walls, for both frequency bands. Its path loss is given by:

$L_{p,\ indoor\,[\mathrm{dB}]} = 10\log\left(A + B \cdot f^2_{[\mathrm{GHz}]}\right)$

where:

- A: 5 for low-loss buildings, 10 for high-loss buildings;
- B: 0.03 for low-loss buildings, 5 for high-loss buildings;

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