Next Generation Integrated Sensing and Analytical System for Monitoring and Assessing Radiofrequency Electromagnetic Field Exposure and Health

D2.2: EMF Technologies and new exposure patterns

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Contributors and Peer Reviewers

Contributors
Nikolaos Petroulakis, Marios Chortis, Nikolaos Karamolegkos (FORTH), Myrtill Simkó, Mats-Olof Mattsson (SPi), Eduardo Soudah (CIMNE), Fulvio Schettino, Marco Donald Migliore, Gaetano Panariello, Daniele Pinchera, Mario Lucido (UCAS), John Bolte, Erdal Korkmaz (THUAS), Vasileios Theodorou, Dimitris Laskaratos (ICOM), Andrea Schiavoni (TIM), Marco Spirito (TUD), Francisco Vargas Marcos (MHS), Loek Colussi (AT), Antonios Paragioudakis (SANL), Mathieu Pruppers, Maarten Velghe (RIVM)
Peer Reviewers
John Bolte, Erdal Korkmaz (THUAS), Loek Colussi (AT)

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Glossary of terms and abbreviations used

Abbreviation / Term	**Description**
(G)MSK	(Gaussian) Minimum-Shift Keying
1G-6G	First-Sixth Generation technology standard for broadband cellular networks
3GPP	3rd Generation Partnership Project
5G NR	5G New Radio
AAS	Active Antenna System
AM, ASK	Amplitude Modulation, Amplitude Shift Keying
BER	Bit Error Rate
BPSK, QPSK	Binary/Quadrature Phase-Shift Keying
DL	Downlink
EDGE	Enhanced Data Rates for GSM Evolution
EIRP	Effective Isotropic Radiated Power
EMF	ElectroMagnetic Field
ERP	Envelope Radiation Pattern
FDD	Frequency Division Duplex
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FEM	Finite Element Method
FIT	Finite Integration Technique
FM, FSK	Frequency Modulation, Frequency Shift Keying
FR1	Frequency Range 1
FR2	Frequency Range 2
GO	Geometrical Optics
GPRS	General Packet Radio Service
GSM	Global System for Mobile communication

GTD	Geometrical Theory of Diffraction
HPBW	Half-Power BeamWidth
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEC	International Electrotechnical Commission
IoT	Internet of Things
ITU	International Telecommunication Union
LTE	Long Term Evolution
MaMIMO	Massive Multiple Input Multiple Output
MPE	Maximum Power Extrapolation
OFDMA	Orthogonal Frequency-Division Multiple Access
PAPR	Peak to Average Power Ratio
PAS	Passive Antenna System
PM, PSK	Phase Modulation, Phase Shift Keying
PTD	Physical Theory of Diffraction
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RA	Risk Assessment
RAN	Radio Access Network
RBS	Radio Base Station
RBW	Resolution Bandwidth
RE	Resource Element
RIS	Reconfigurable Intelligent Surface
RRH	Remote Radio Head
SAR	Specific Absorption Rate
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access

UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
VHF	Very High Frequency
W-CDMA	Wideband Code Division Multiple Access

Executive Summary

The deliverable D2.2: "EMF Technologies and new exposure patterns" provides an overview of all the mobile technologies employing digital modulations, with particular focus on the latest generation, which is currently under deployment, in order to pave a technical background for the activities to be carried out during the NextGEM project. For each generation, a description of the technical standard is given, and the main features of base station hardware solutions are reviewed. The purpose is to analyse the evolution of mobile technologies over thirty years, in order to better understand the impact and the characteristics of EMF exposure, and the challenges that new generations (5G and 6G) pose to researchers for the development of new measurements and modelling techniques.

The main contribution of the present document to the entire project is to provide a basic knowledge and requirements for the design of new paradigms and technologies for exposure monitoring and assessment.

1 Introduction

Mobile technologies have dramatically evolved over more than thirty years, leading to a fully connected society and empowering socio-economic transformations, including those for productivity, sustainability, and well-being. A tremendous growth in connectivity and density/volume of traffic has been experienced due to the ever-growing demand for mobile services. An unprecedented step forward is represented by the introduction of 5G New Radio standard, which is expected to provide much greater throughput, much lower latency, ultra-high reliability, much higher connectivity density, and higher mobility range.

However, in order to fully understand the evolution of mobile technologies, an overview of the previous generations of mobile communications systems is useful to take advantage of the developed methods and models, which will represent the basis for the new advancements to be achieved during the NextGEM project. As a matter of fact, 5G NR has introduced new solutions in terms of standard (frame duration, bandwidth, power allocation, etc) and a completely new concept of management of the radiation distribution (beamforming, power control). Consequently, currently adopted approaches for exposure monitoring and assessment, as well as for coverage optimization are not suitable anymore and completely new paradigms have to be introduced. One of the ambitions of the NextGEM project is to accomplish necessary and much sought-after improvements in field level assessment in real scenarios. This document aims at providing a technical background by comparing the main features of past and new mobile technologies.

1.1 Mapping NextGEM Outputs

The purpose of this section is to map NextGEM's Grant Agreement (GA) commitments, both within the formal Task description and Deliverable, against the project's respective outputs and work performed.

Table 1: Adherence to NextGEM's GA Tasks and Deliverables Descriptions

TASKS	
Task Number & Title	**Respective extract from formal Task Description**
Task 2.2 - EMF Technology assessment to establish new exposure patterns, comparison of old and new exposure patterns	5G New Radio (NR) represents a dramatic improvement in wireless technology compared to previous generations. This task is devoted to the comparison of new and existing patterns of mobile phones technologies. In particular, the impact of new technologies - such as, but not limited to, Massive Multiple Input Multiple Output (MaMIMO), beamforming, power control, use of radio resource - on the exposure change over time and space will be addressed. Moreover, a thorough analysis of novel measurement paradigms and statistical models will also be carried out, which are strictly related to the variability of new EMF exposure patterns.
DELIVERABLE	
Deliverable D2.2: EMF Technologies and new exposure patterns This deliverable will cover all levels of EMF technologies focusing on the comparison between 5G exposure patterns and previous technologies.	

1.2 Deliverable overview and report structure

Based on the objectives and work carried out under Task 2.2, the document starts with the Executive Summary followed by the introduction of the document in Section 1.

Section 2 is devoted to the analysis of the second and third generation of mobile communication technologies, with an overview of their evolution, with particular reference to the standards and hardware solutions implemented.

Section 3 provides a description of the key features of the current mainstream mobile network technology, that is the fourth generation, representing the direct predecessor of the 5G NR systems.

The aim of Section 4 is to describe the fifth generation of mobile communication technologies, including an analysis of the social and technological impact of 5G NR.

Section 5 focuses on the antennas currently used in mobile devices.

Section 6 provides some preliminary insights into future sixth generation.

Finally, Section 7 concludes the deliverable.

2 2G and 3G technologies

This section provides a review of the previous mobile technologies, i.e., second and third generation, and their evolution from the frequency allocation, standards and hardware solutions implemented in the downlink radiating systems. This section represents a basis to the reader to understand the complex mobile communication environment of today's network and to understand the different developments that led to the fourth generation (discussed in Section 3) and 5G NR concepts (covered in Sections 4 and 5).

2.1 Overview of first mobile technologies

The second generation cellular network (2G) was commercially launched with the GSM (Global System for Mobile communications) standard in 1991. Succeeding the analogue 1G standard, 2G was the first full digital standard introduced, enabling a significantly more efficient use of the frequency spectrum.

The technology used for 2G systems is time-division multiple access (TDMA), in combination with Frequency Division Duplex (FDD). This means that multiple users share the same frequency channel, which is then divided into different time slots. Separate frequency bands are used simultaneously for uplink (UL) and downlink (DL) traffic. Apart from voice also limited data service is available by means of text messages.

With the introduction of General Packet Radio Service (GPRS) a theoretical maximum transfer speed of 40 kbit/s became possible (2.5G). With EDGE (Enhanced Data Rates for GSM Evolution), the theoretical maximum transfer speed was increased to 384 kbit/s (2.75G). Although newer technologies have been introduced, 2G is still being used as a fallback for (emergency) voice phone calls and to facilitate many installed internet of things (IoT) applications that still rely on it (e.g., smart meters, eCall). 2G is mostly used in the 900 MHz band and the 1800 MHz band.

The request for a more efficient worldwide mobile communication system triggered the introduction of 3rd generation systems. All different proposals were included under the International Telecommunications Union – Radio (ITU-R) umbrella called International Mobile Telecommunications (IMT-2000). Their harmonization led to the foundation of the 3rd Generation Partnership Project (3GPP) and finally to the establishment of the Universal Mobile Telecommunication System (UMTS)[1]. 3G telecommunication networks support services that provide an information transfer rate of at least 384 kbit/s (moving vehicles) up to 2 Mbit/s (stationary or walking). Later 3G releases, often denoted 3.5G and 3.75G, also provide mobile broadband access of several Mbit/s to smartphones and mobile modems in laptop computers. This ensures it can be applied to wireless voice calls, mobile internet access, fixed wireless internet access, video calls and mobile TV technologies. The latest UMTS release, Evolved High Speed Packet Access (HSPA+), can provide peak data rates up to 56 Mbit/s in the downlink in theory (28 Mbit/s in existing services) and 22 Mbit/s in the uplink.

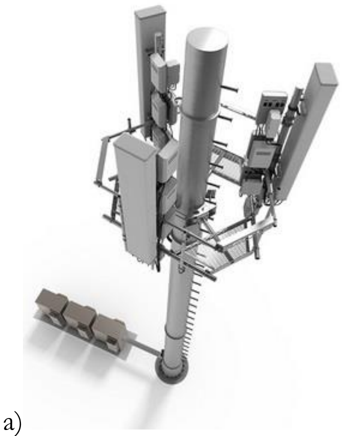
3G employs a technology that is called Wideband Code Division Multiple Access (W-CDMA), in combination with FDD. This means that multiple users share the same frequency channel, each employing an individual coding. Separate frequency bands are used simultaneously for UL and DL traffic. Because, currently, 3G has been outperformed for data traffic by newer standards (4G, 5G), it is expected that 3G will be phased out soon, probably even earlier than operational 2G systems.

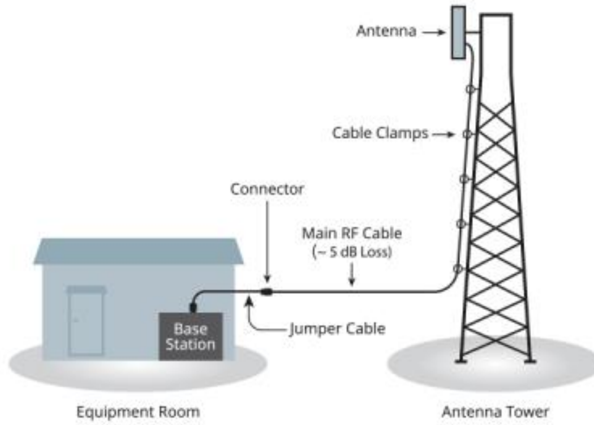
Base stations for 2G and 3G often consist of an equipment cabinet, located at ground level and passive antennas placed in a mast. The connection between the base station equipment and the antennas is done by coaxial cables. The development of the radiating system composing such base stations is discussed in the next Section.

2.2 Radiating systems

Cellular networks that are at the base of our mobile communication infrastructure employ base stations to interface the signal from and to (mobile) users to the core network. Base stations are composed, as shown in Figure 1, by an antenna interface (located on the antenna tower), a connection in the form of RF cables to the RF and baseband circuity and digital interface, which are located in the equipment room. In this section the evolution of the radiating interfaces in previous generation of mobile communication systems (i.e., 2G and 3G) will be presented.

[1] 3GPP TS 25.301 version 17.0.0 Release 17


a)



b)

Figure 1: Base stations installation: (a) rendered image of antenna tower with multiple antennas, (b) schematic view of the sub systems composing a base station[2]

The radiating systems in base station antennas employed in 2G and 3G systems have often resulted in arrays typically of 1 to 2 meters long with gains between 15 and 21 dBi placed in towers between 25 and 75 meters above ground [1].

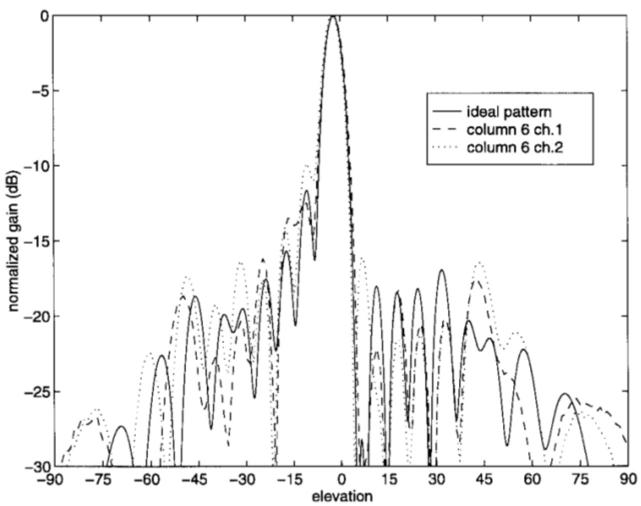


Figure 2: Vertical beam pattern of a BTS antenna (with slanted +/- 45° polarization channels) for mobile communication [2]

2.2.1 Vertical beam shaping

Since the capacity of cellular telecommunication system cells is often limited by interference from the adjacent ones, the radiation pattern of base station antenna systems is designed to provide the following characteristics (Figure 2):

1) a downward tilted beam (i.e., negative elevation angle in Figure 2)
2) a rapid roll-off above the beam pattern peak in order to minimize interference to neighbouring cells
3) a slow roll-off and nulls cancellation below the beam peak to provide coverage in close proximity to the antenna tower.

During the early development of mobile networks, the base station radiating interface was often composed by a limited number of omnidirectional antennas to minimize system complexity. Here we will briefly describe the various developments that have been implemented over the years on the radiating system of the base station to cope with the exponential expanse in mobile usage.

[2] Testing RF Cables in Cellular Networks Combining LTE and 5G Technologies – Application Note available on-line https://dl.cdn-anritsu.com/en-us/test-measurement/files/Application-Notes/Application-Note/11410-02878A.pdf.

2.2.2 Sectorization

With the increase of mobile communications already in 2G, it became necessary to increase the capacity of any single cell. To achieve this, the area covered by the cell was (sub)divided in sectors and multiple antenna systems with reduced beamwidth were employed to provide the cell coverage. In this way by replicating the hardware block behind each antenna element a higher capacity could be provided.

The first attempt to sectorization introduced a split into three antennas providing a beamwidth of 120°. Later, to further increase capacity, narrower beam antennas with half-power beamwidth (HPBW) such as 65° and even 33° where introduced. While solving the capacity issue, this simple scaling approach on the antenna panels increased the mechanical loading of the tower creating a limiting constraint. This limitation was then addressed at the antenna design level by moving to multi-beam panels, where a single panel could provide multiple beams, as shown in Figure 3.

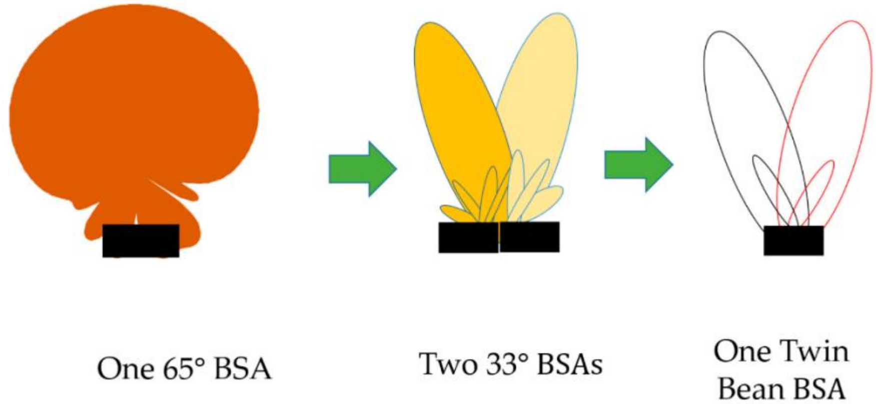


Figure 3: Sketched patterns, from left to right of, single beam base station antenna, two closely spaced base station antennas and a multi (two) beam antenna [3]

2.2.3 Diversity reception techniques

During the various telecommunication generations, it was determined that reliable communication in an environment where the channel characteristics are time-varying, can be achieved by receiving the signal on two or more independent channels. This is based on the concept that in multipath environments by applying diversity to a given parameter of the receiving channels the fades between the multiple signals can be made strongly uncorrelated. In such a way, the separate signals can be further processed by a diversity combiner to either mix them together or select the best one.

The most used method to separate signals has been originally to exploit space diversity, i.e., to receive the signals at two separate locations where the fading due to the environment would be independent. Nevertheless, this approach presented the major drawback of requiring a larger or double housing to accommodate the second receiver (given a spacing requirement of multiple λs). This would result in a higher wind load and an increased cost of the installation.

To overcome this limitation, polarization diversity was adopted as mainstream from 2G onwards. This approach was based on the concept that in multipath environments, such as urban ones, the signal received at the base station has a varying polarization. The two polarizations present different fading because each encounter different reflection coefficients in its path. The main advantage of polarization diversity comes from the fact that the two receiving antennas can be located in the same housing and aligned to two orthogonal polarizations, as shown in Figure 4a.

2.2.4 Multiband antennas

With every new telecommunication generation deployment, additional spectrum is being added for data usage in order to increase both the capacity and the data rates achievable by the newer generation. The added bands while providing benefit to the system performance required innovations to be introduced at the antenna interface of the system. This is because base station antennas have a limited bandwidth and the radiating element topologies cannot operate over multiple bands. For this reason, a common approach became to use multiple (distinct) radiating elements to cover the multiple bands available in a given generation, as shown in Figure 4b.

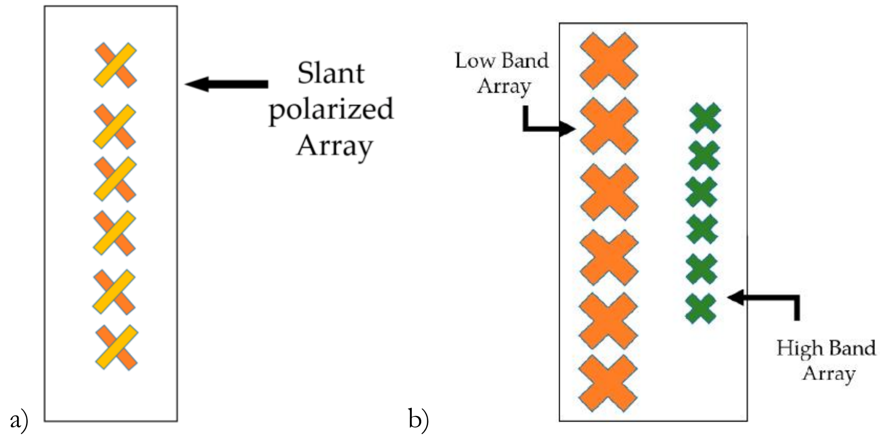


Figure 4: a) Slant polarized dipole array, b) multiband antenna with physically separated arrays [3]

2.3 Signal standards

The different kinds of signals and networking technologies cause antennas and mobile devices to generate profoundly different emission and reception power levels. Mobile phones use low power transmitters that can reach a transmitted power of less than two W peak and are designed to automatically transmit at the lowest possible power to maintain connection quality. This is a feature known as adaptive power control. Obviously, cell phone network technologies affect radiation exposure as much as the phone design itself. Users of the same mobile device may absorb different amounts of radiofrequency emissions, depending on which carrier serves them [4]. When operators shifted from 2G to 3G technologies, mobile devices operating on 3G networks used lower power level for a larger amount of the (transmit) time, and their users experienced lower radiation exposures [5]. Therefore, signal standards applied in any telecommunication scheme are one of the most crucial factors concerning network performance and enhanced services, as well as health and safety compliance.

Wireless communication networks are based on protocols specifying how information must be exchanged between the different nodes. These protocols refer to all levels of networking and primarily to the physical level. Of course, on the physical level, wireless communication protocols are based on the specified signal standards with regards to the modulation and multiplexing techniques used for the generation, transmission, and reception of the signals. The progress of modulation and multiplexing techniques defined the exploitation of the spectrum, as well as the overall evolution of signal standardisation of mobile networks. To facilitate a thorough outlook of the progress of the signal standards, a brief overview of the evolution of the technologies used is reported here.

2.3.1 Background – Digital Modulation schemes

The simplest type of digital modulation involves transmitting a sequence of waveforms ("symbols") $S_i(t)$ of equal duration T where each waveform is chosen from a set of M waves. This allows for transmission of up to $b = \log_2(M)$ bits per symbol. Each possible symbol is a combination of two values and can be plotted as a point in the complex plane. The power transmitted for each symbol of amplitude S_i is $|S_i|^2/2$, and the energy per symbol is the power times the duration of the symbol. If at a given instant all signals achieve maximum power value, the overall output envelope reaches a peak. If the peak power is high, compared to the average power transmitted i.e., the Peak to Average Power Ratio (PAPR) is very high, the system is considered inefficient in terms of energy consumption and adjacent channels robustness. Along with PAPR there are also other key channel performance indicators such as the Signal to Noise Ratio (SNR), and the Bit Error Rate (BER), and the Carrier to Noise density, C/N_0. The BER is the number of bit errors per unit time and the C/N_0 is the ratio of the power level of the whole carrier to the noise power spectral density in a system. For digital communications a direct analogous to SNR, but much more indicative than plain SNR, is the energy per information bit transmitted (redundancy bits for error correction not included) over the noise power density per bandwidth unit received for a certain bandwidth (E_b/N_0). Modulation schemes are usually compared through SNR or BER plots against E_b/N_0.

There are several modern digital modulation techniques which are distinguished in three categories regarding the type of the signal modulated and the signal parameters' variations employed to encode the data:

- Amplitude Modulation techniques (AM), where the amplitude is varied
- Frequency Modulation techniques (FM), where the frequency is varied
- Phase Modulation techniques (PM), where the phase is varied.

The corresponding digital modulation formats are the Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK). A popular version of FSK is the Minimum Shift Keying (MSK), where the modulation index is as minimised as possible, providing fewer sidebands and more robust transmission. To improve spectral efficiency, data rates, carrier frequencies, and shift frequencies are selected in such ways that there are no discontinuities in the carrier waveforms when transitioning from one binary state to another (continuous coherent operation). Another way to improve spectral efficiency is to filter the binary data prior to modulation. Special Gaussian and raised cosine low pass filters are used for this purpose. The modulation scheme used in GSM is Gaussian Minimum Shift Keying (GMSK). Spectral efficiency is also acquired with other techniques such as Binary Phase Shift Keying (BPSK), and Multiple Phase Shift Keying (e.g., Quadrature Phase Shift Keying, QPSK or 4PSK, and 8PSK, 16PSK etc.). In BPSK the modulator produces one wave whose phase is shifted 180° at the zero crossing points of the waveforms, for each change in binary state. In QPSK the modulator produces two waves, 90° apart, whose phase transitions added together produce a total of four signals, shifted by 90° from one another (four symbols). Each final symbol represents two bits of data (two bits/symbol). In 8PSK smaller phase shifts are used so as to produce eight symbols in total, and so on.

Quadrature Amplitude Modulation (QAM) on the other hand, indicates the combination of amplitude and phase variations in order to carry more bits per symbol. Two different signal frequencies, 90° apart, can be transmitted on the same carrier. The so-called baseband signal is separated into in phase (I) and quadrature phase (Q) components. Each carrier is ASK and PSK modulated, hence there are two amplitude levels and two phases for each frequency. Consequently, there are eight different combinations (symbols) carrying 3 bits each. 16QAM has even smaller phase transitions and can modulate symbols into $2^4 = 16$ different waveforms and thus carries four bits per symbol. In the same way 32QAM carries five bits/symbol, 64QAM carries six bits/symbol, etc. Symbols like any other vector quantity can be plotted on the 2D plane. In a phasor diagram the phasor (vector) represents the carrier wave amplitude peak and its position indicates the phase. A constellation diagram shows exactly the same information and represents all the available symbols used to map the information bits as points on the plane (Figure 5).

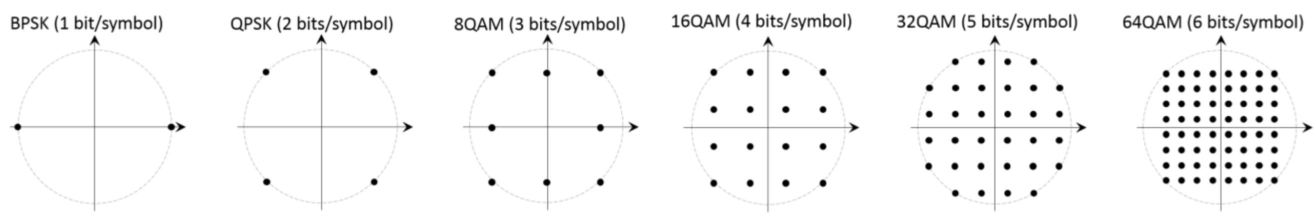


Figure 5: Examples of BPSK, QPSK, 8PSK, 16QAM, 32QAM, 64QAM constellation diagrams[3]

The higher the order of modulation is, the higher the resulting throughput is, but also the more susceptible to errors is the channel, due to the high proximity of symbols' values. Hence, accordingly larger numbers of redundancy bits are required to ensure channel reliability, high data rates, and low BER. The coding schemes applied define the coding rates i.e., the ratio of useful information data. The information herein is usually Grey coded, where the Hamming distance of two neighbours is always 1, which allows for cyclic prefixes and easy error correction. The different combinations of modulation and coding constitute schemes (MCS) that offer a variety of characteristics and are appropriately utilized for each type of channel employed.

In general, the quality of a signal received by a user, is determined by the channel quality of the serving cell, the level of interference from other cells, and the noise level. Thus, the transmitter has to adjust the data rate to the variations of the received signal. This procedure is commonly referred to as link adaptation, and along with adaptive power control, determines the signal profile. The modulation and coding schemes in the physical layer along with the different multiplexing techniques used for multiple access, define the signal standards specified for all types of air interface telecommunications.

[3] http://opticalcloudinfra.com/index.php/2017/03/26/new-modulation-formats/

2.3.2 History

The earliest form of mobile networking technology, which is now referred as **0G** (zero generation) mobile technology, was developed in the previous century and was mostly used for military purposes. Usually vehicle mounted, huge transceivers and dials were utilised, so as to achieve communication among moving units.

1G (first generation) was later developed and mobile phones were realized for commercial use. The key features of 1G, in terms of technology and services were briefly the following:

- The **Cell** concept developed by the Bell Labs in the 70's was utilized and the first commercial use of cellularly structured networks for mobile communications was introduced. Each cell is an area where a base station serves all mobile users in range. When a user moves from one cell to another their service is handed over to the next base station without interruption of communication (handover or handoff).
- Voice was the only type of information transferred in the network.
- The information (sound) signal transfer was made possible with Analogue Frequency Modulation with carrier frequencies in the Very High Frequency (VHF) band.
- The modulation nature defined a single analogue channel for signal transmission and reception.
- The multiplexing technique used was Frequency Division Multiplexing (FDM), in which the entire bandwidth is divided in several sections. Each sub band is assigned to a certain device [6]. It is feasible to apply Time Division Multiplexing (TDM) on each of the sub bands separately.

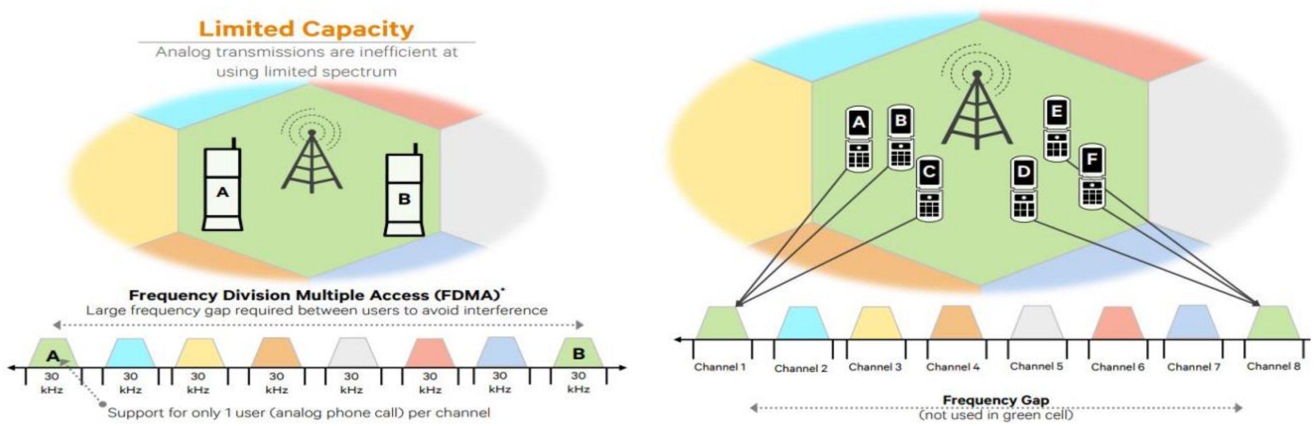


Figure 6: FDMA (left) channel distribution (1G) vs TDMA (right) channel distribution (2G)[4]

The channel access technique used in 1G was the Frequency Division Multiple Access (FDMA), as it was the earliest and most sophisticated channel access method at the time, for transmission of multiple channels of information through a single communication medium. The FDMA scheme is a technique built on the FDM method (Figure 6, left). This technique can be considered the oldest and the simplest form of multiplexing. In this technique the available frequency band is divided into channels of equal bandwidth so that each conversation is carried on a different frequency sub-band [6]. Each sub-band is assigned to a certain device. Users can send data through a subchannel by modulating it on a carrier wave at the subchannel's frequency. It is also feasible to apply TDM on each sub-band separately. Guard bands are used to minimise the crosstalk between the channels, which leads to a waste of capacity. Moreover, if an FDMA channel is not in use, then it is idle as it cannot be used by other users to increase or share capacity.

The advantages of 1G systems were numerous and unprecedented. However, the capacity limitations, the quality issues, and the limitations of national standards of the first analogue mobile communication systems led to the development of a 2nd generation of cellular mobile communication systems.

[4] https://www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/the_evolution_of_mobile_technologies-wireless-networks.pdf

2.3.3 2G Systems

As mentioned before, 2G was the first generation of digital cellular mobile telecommunication systems. There were several systems deployed as part of the second generation. The most successful and universally deployed 2G system, for over three decades, was GSM, upon which all others were applied as enhancements. The main features of GSM technology are listed below:

- **GMSK** modulation: As mentioned before, it is based on MSK, which is itself a form of continuous-phase frequency-shift keying. One of the problems with standard forms of PSK is that sidebands extend out from the carrier [7]. To overcome this, MSK and its derivative GMSK was used. MSK is a spectrally efficient modulation scheme for use in mobile communication systems because of its properties such as constant envelope, spectral efficiency, good BER performance, self-synchronizing capability. GMSK was preferred as it is a filtered version of MSK. GMSK is most notably used in GSM, in Bluetooth, in satellite communications, and Automatic Identification System for maritime navigation. Later on, higher order modulation schemes were used.
- **TDMA** signalling: This allows several users to share the same frequency channel by dividing the signal into different time slots. The users transmit in rapid succession, one after the other, each using its own time slot (
- Figure 6, right). Slots from all subscribers are combined into cyclically repeated super-slots. Synchronization can be performed by periodically sending known service sequences within one or more super-slots.
- **FDD** carriers: FDD is used for establishing a full-duplex communications link by using two different radio frequencies for transmit and receive operations. The transmission and reception frequencies are separated by a defined frequency offset. FDD is a solution to resolve the transmit-receive signal ratio situation, just as power control is a solution to resolve the near-far signal strength ratio problem.
- Channel spacing of 200 kHz.
- Designed for operation in the **900 MHz** band but was adapted also for **1800 MHz** and upon its later introduction in North America, GSM incurred further adaptation to the 800 and 1900 MHz bands, as well as other bands over the years[5].

GSM was designed for digital voice telephony. Later on, the High-Speed Circuit-Switched Data (HSCSD) service was introduced in the GSM Phase 2+. A significant increase in speed could then be obtained by aggregating up to four channels into a single, grouped, circuit-switched connection. HSCSD is an example of multi-slot configuration, in which all channels have the same channel mode. HSCSD has later been replaced by GPRS and EDGE, which offer higher data rates.

GPRS adds packet-switched functionality to GSM, which is essentially circuit switched. It offers faster data rates than plain GSM by aggregating several GSM timeslots into a single bearer, potentially up to eight. The access scheme is still TDMA, with eight basic physical channels per carrier. Therefore, one physical channel (Packet Data Channel-PDCH) is employed for data transfer, upon which several logical channels are mapped, and is defined by a sequence of TDMA frames, a time slot number, and a frequency hopping sequence.

The basic radio resource is a time slot, whose physical content is called burst, and is lasting ≈ 576,9 μs and transmitting information at a modulation rate of ≈ 270,833 ksymbol/s. Each symbol is one to five bits depending on the actual modulation used: GMSK, QPSK, 8-PSK, 16QAM and 32QAM respectively. The overall slot structure in the GPRS physical channel is the same as in GSM and therefore shares the **same power profile**. The RF channel spacing is 200 kHz, allowing for 41 (T-GSM 380), 41 (T-GSM 410), 35 (GSM 450), 35 (GSM 480), 89(GSM 710), 74 (GSM 750), 74 (T-GSM 810), 124 (GSM 850), 209 (ER-GSM 900), 194 (GSM 900), 374 (DCS 1 800) and 299 (PCS 1900) radio frequency channels.

EDGE is an enhancement of the GSM radio access technology to provide faster bit rates for data applications, both circuit- and packet-switched. As such, EDGE is realized via modifications of the existing GSM physical layer, rather than by separate, stand-alone specifications. The increased data rate was accomplished by the 8-PSK modulation technique coupled with new channel coding resulting in improved spectral efficiency. In fact, EDGE uses a combination of 8-PSK and GMSK, which improves the bit rate under virtually all radio conditions (Table 2). The four coding schemes of GPRS increased to nine in EDGE, and new segmentation techniques can radically improve

[5] 2nd Generation (GERAN). (2023/03/31). ETSI. https://www.etsi.org/technologies/mobile/2g

throughput by permitting the coding scheme to be changed on the fly in case of retransmission of a segment in rapidly changing radio conditions. EDGE is transparent to the upper layers, so it is possible to apply EDGE on top of GPRS (Enhanced GPRS), thus increasing the theoretical data rate to 384 kbit/s which is comparable with the early 3G rates. For this reason, EDGE is considered to be the bridge between the 2nd and the 3rd generation of mobile communication systems. GSM network enhanced with HSCSD, GPRS, and EDGE is referred under the umbrella acronym GERAN (GSM/EDGE Radio Access Network).

Table 2: GMSK, 8PSK Comparison

	GSM / GMSK	EDGE / 8PSK
Symbol Rate	270.833 kbps	270.833 kbps
bits/symbol	1	3
Bit rate/time slot	22.8kbps	68.4kbps

2.3.4 3G Systems

As mentioned before, the ever-growing demand for more efficient mobile communication systems led to the foundation of 3GPP, with the purpose of harmonization of the different proposal, and to the establishment of UMTS. One of the most important mobile standards included, was the CDMA2000 standard, which operated in a paired 2x1.25 MHz FDD channel, instead of 2x5 MHz. This narrower channel band allowed for greater spectrum assignment flexibility and cost efficiency.

UMTS[6] offers greater spectral efficiency than GSM and has 2 modes:

- In FDD mode UL and DL streams are separated in the frequency domain via different frequency bands[7]. This mode is also called W-CDMA or Direct Spread CDMA. W-CDMA, as an air interface standard, has been designed for always-on packet-based wireless service, so that computers and entertainment devices may all share the same wireless network and connect to the Internet simultaneously.
- In TDD mode (Time Division Duplex) UL and DL streams are separated in the time domain via different time slots. Both modes use direct sequence to separate the different users, i.e., each symbol of one user is multiplied by a user specific spreading code. With this CDMA technique multiple users can transmit in the same (larger) band and the decoder, knowing one user's spreading code, can pick up the data of this specific user. The data of other users appear as noise in this decoding process. Using a wide frequency band makes the system inherently resistant to many drawbacks of narrow band systems such as interference from other transmissions, multipath reflections, etc.
- W-CDMA supports data rates of up to 2.048 Mbps if the user is stationary, thereby allowing high-quality data, multimedia, streaming, and broadcast services to consumers. With W-CDMA, data rates from as low as 8 kbps to as high as 2 Mbps can be carried simultaneously on a single W-CDMA 5MHz radio channel, with each channel supporting between 100 and 350 simultaneous voice calls at once, depending on antenna sectoring, propagation conditions, user velocity and antenna polarisation.
- Both modes were originally (in the first release: Release 99) defined with a 10ms radio frame divided into 15 slots, a chip rate of 3,84 Mchips/s and a channel spacing of 5MHz. A physical channel is defined as a code or number of codes and complementarily as a sequence of time slots in TDD mode.
- UMTS was originally specified for operation in bands in the 2 GHz range. Subsequently, it was extended to operate in a number of other bands, including those originally reserved for 2G services.
- UMTS was continuously enhanced over several releases with new techniques such as 64QAM, and MIMO, and offered the potential capability for Home NodeBS, Active Antenna Systems, Indoor Positioning, Self-Optimising Networks, and others.

[6] ETSI Technical Specifications, Universal Mobile Telecommunications System (UMTS), Physical layer - general description

[7] 3GPP TS 25.101 version 17.0.0 Release 17

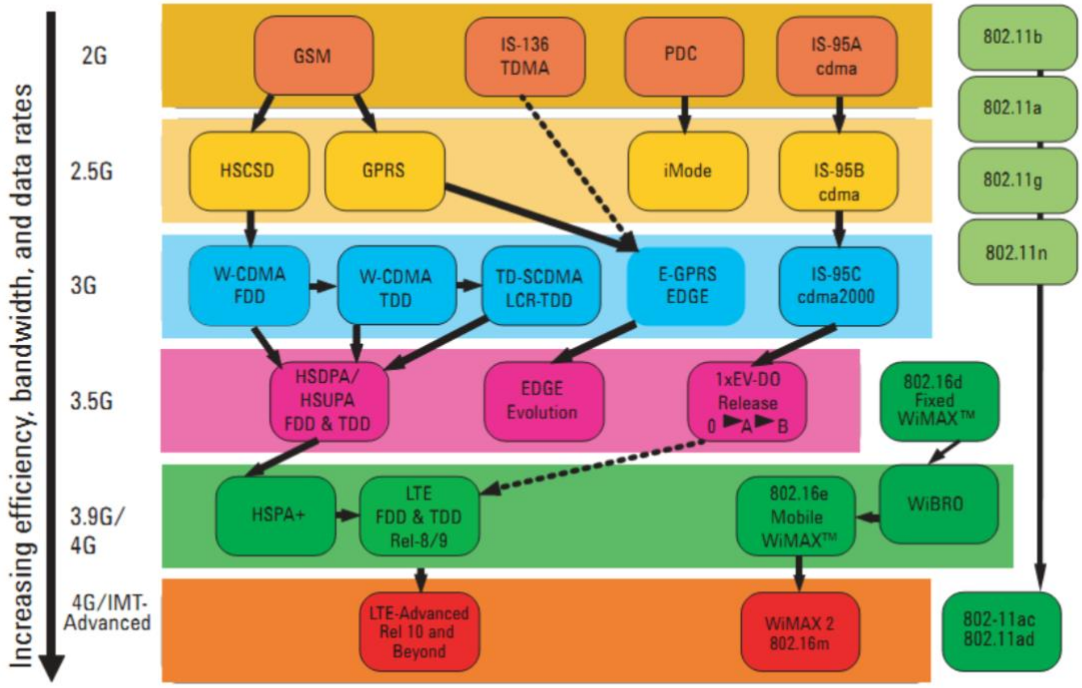


Figure 7: Evolution of Mobile Technologies[8]

Essentially, 3G systems integrated voice and data applications and offered greater end to end security than their predecessors. This paved the way for the implementation of new signalling and networking techniques and combinations. The evolution of mobile telecommunication systems, as shown in Figure 7 has been rapid during the last three decades.

[8] Equipment in the LTE Network, Yang Bo, China Academy of Information and Communications Technology, ITU, CAICT 2016

3 4G Technology

In this section, we focus on describing the key features of the current mainstream mobile network technology, i.e., 4G. The fourth-generation system technology being the direct predecessor of the 5G NR systems (discussed in Section 4) introduces from both the signal coding techniques as well as the radiating system interfaces key technologies that are being conceived for 5G systems.

When comparing technology generations, the two main technological features of 4G, which will be described in this section, are the Orthogonal Frequency-Division Multiple Access (OFDMA) and the usage of Multiple Input Multiple Output (MIMO) concepts. From the signal standard point of view, 4G introduced two key standards, i.e., WiMAX (Worldwide Interoperability for Microwave Access) and LTE (Long Term Evolution). Data rates, as shown in Figure 8, increased dramatically over the years, especially through the passage from 1G to 2G with the deployment of digital radio interfaces, and from 3G to 4G with MIMO. 1G established mobile services, 2G increased voice capacity and introduced internet data exchange, 3G optimized mobile data exchange by enabling mobile broadband service. Undoubtedly, 4G LTE delivered far more capacity and thus faster and better mobile broadband communications. A comparison between 3G and 4G is shown in Table 3.

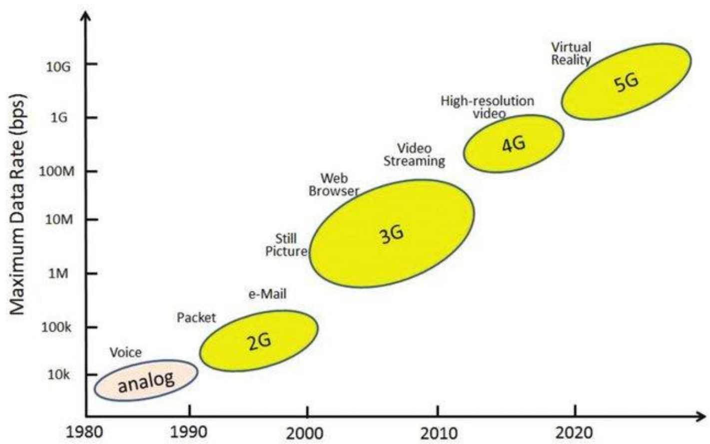


Figure 8: Data Rates & Generations [7]

3.1 Overview of fourth generation mobile technology

The fourth generation of cellular network technology was introduced around 2010, according to the standard IMT Advanced, which consists of an IP-based packet-switched network. 4G uses a broadband technique called LTE, with increased spectral efficiency, offering a significant increase in speed as compared to 3G, up to 100 Mbit/s for high mobility use and 1 Gbit/s for low mobility use (LTE Advanced).

LTE is a spread spectrum technique that can be used with various signal bandwidths (1.4, 3, 5, 10, 15, 20 MHz) in FDD as well as TDD mode. The LTE signal is digitally modulated with OFDMA, consisting of a number of subcarriers that are assigned to different users. Due to its wideband nature OFDMA is very robust against multipath, fading and (narrow band) interference. Since the OFDM coding is a spread-spectrum technique, it causes the RF signal to have a high PAPR of more than 10 dB. Measurement of RF signal power should be done using an averaging detector (RMS), to avoid excessive measurement readings due to (rare) signal peaks.

4G is mostly used in the 800 MHz band, the 1400 MHz band, the 1800 MHz band, the 2600 MHz band in FDD-mode and the 2600 MHz band in TDD-mode.

Base stations for 4G often consist of a Remote Radio Head (RRH), that is placed in the mast close to passive antennas for each frequency band and coverage sector. Signalling up to the RRH is done by Fibre to the Antenna (FTTA) architecture. This implementation offers more reliability, flexibility, and substantial energy savings.

One disadvantage of 4G is the poor capability to handle voice calls. Although Voice-over-LTE (VoLTE) has been introduced for this purpose, it suffers from compatibility and latency issues. For this reason, a fallback scenario to 2G/3G networks is still mandatory.

Table 3: Comparison of Generations[9]

3G Technology	4G Technology
The maximum upload rate is 5 Mbps.	The maximum upload rate is 500 Mbps.
The maximum download rate is 21 Mbps.	The maximum download rate is 1 Gbps.
It uses a packet switching technique.	It uses the packet switching technique as well as the message switching technique.
The frequency range is from 1.8 GHz to 2.5 GHz.	While its frequency range is from 2 GHz to 8 GHz.
It is a wide area cell-based network architecture.	It is the integration of Wireless LAN as well as Wide Area cell-based network architecture.
Turbo codes are used for error correction.	Concatenated codes are used for error correction.
Internet Service is broadband.	Internet Service is ultra-broadband.
Data bandwidth is 2 Mbps – 21 Mbps.	Data bandwidth is 2 Mbps – 1 Gbps.

3.2 Radiating systems

The development of the radiating systems in 2G and 3G systems, as briefly reviewed in Section 2, was mostly driven by the capability to increase the system capacity. In 4G systems, given the increased mobility of end-users and the level of the multimedia content, the main development drivers have been to reduce both the capital expenditures (CAPEX), i.e., manufacturing costs, as well the operating expenses (OPEX) of these systems. These drivers together with the need for a more scalable and sustainable environment for the networks led to the introduction of the RRH and the introduction of the FTTA concepts.

A RRH unit encloses the RF circuitry of the base station in a small outdoor module, performing all RF functionalities like transmit and receive functions, filtering, and amplification. Moreover, it contains analogue-to-digital or digital-to-analogue converters and up/down converters. Given the capabilities of RRH units to be located remotely to the BTS/NodeB/eNodeB it allows to be deployed in a more modular and pervasive way into both rural and urban environments, as can be seen in the sketch shown in Figure 9.

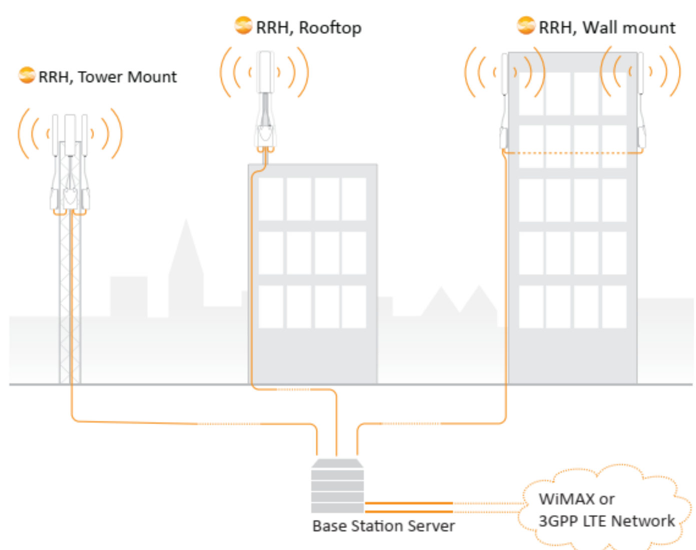


Figure 9: Distributed Wireless Base Station system employing RRH units [8]

[9] Difference between 3g and 4g technology. (2023/02/22). Geeksforgeeks. https://www.geeksforgeeks.org/difference-between-3g-and-4g-technology/

Owing to the capability of RRH unit to perform digital to analogue conversion as well as up and down-conversion to the carrier frequency, the link between the base station unit (BSU) and the RRH unit was developed using a fibre-optic distribution network, sketched in Figure 10. Among other advantages of FTTA architecture is the lower power requirements, distributed antenna sites, and a reduced base station footprint.

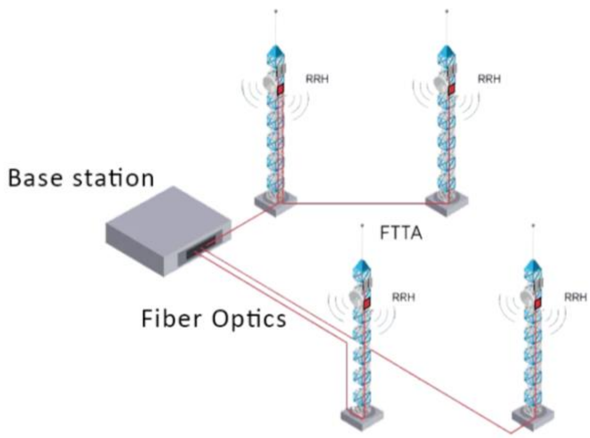


Figure 10: Sketch of a fibre optics-based distribution network between the base station unit and the RRH unit

Another key technology employed in 4G systems is the incorporation of MIMO concepts based on the usage of multiple antennas at the input and/or output, see Figure 11. The transmitter and receiver have more than one antenna and using the processing power available at either end of the link, they are able to employ the different paths existing between the two sides of the channel (i.e., Tx and Rx) to provide improvements in the signal to noise ratio.

There are several ways in which MIMO is implemented in LTE. These vary according to the equipment used, the channel function and the equipment involved in the link. Among these various modes, one is worth to be specifically mentioned here and is referred to as *Beam-forming.* In this mode the radiating system employs the antenna array to focus the radiation onto a particular area. This active energy focusing, reduces interference, and increases capacity as the UE receives a beam formed in its direction. This concept has been further developed in 5G NR and will be explored in Section 4.

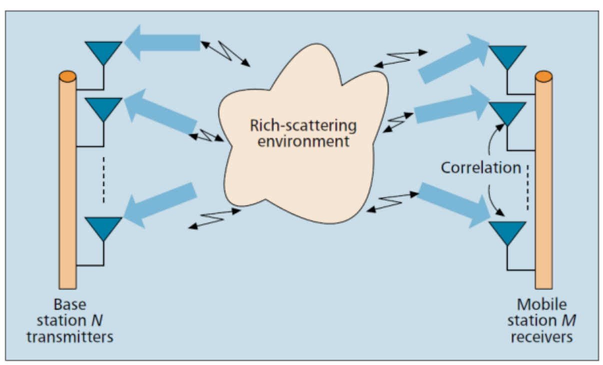


Figure 11: Illustration of multiple input, multiple output (MIMO) system using N base stations and M mobile receivers [9]

3.3 Signal standard

In December 2004, the industry that has developed the 3GPP technologies launched a project called Long Term Evolution to study requirements for a new air interface called E-UTRA (Evolved Universal Terrestrial Radio Access). The results of this study i.e., the E-UTRA/LTE requirements were documented in Rel-7[10]. LTE is the upgrade to both GSM/UMTS networks and CDMA2000 networks. It was developed to increase the speed and capacity of mobile

[10] https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=1342

communication networks using digital signal processing techniques and modulations. Digital interfaces were integrated and used to enable interoperability.

The new characteristics of 4G included:

- significantly increased peak data rates e.g., 100 Mbps in downlink/50 Mbps in uplink,
- increased bitrates at the edge of cells assuming current site locations,
- improved spectrum efficiency,
- reduced latency,
- scalable bandwidth for a greater flexibility in frequency allocations,
- reduced capital and operational expenditure including backhaul,
- acceptable system and terminal complexity,
- ad hoc and multi-hop networks,
- cost and power consumption,
- support for inter-working with existing 3G systems and non-3GPP specified systems,
- efficient support of the various types of services (e.g., Voice over IP, Presence),
- optimisation for low data rates but supporting high mobile speed (up to 500 km/h).

Some of the features of the **LTE** systems are the following:

- While UMTS started with a focus on circuit-switched data that was then more and more enhanced via shared channels and HSPA into the direction of a packet switched system, LTE is a pure **packet-switched system**.
- The multiplexing technique used is **OFDM** and the access method is OFDMA. In brief, OFDMA works by dividing a wireless channel into smaller sub-carriers and separating those sub-carriers into even smaller resource units. The transmitter then can divide those very small parts of bandwidth among multiple users by bundling separate packets into a single simultaneous transmission. OFDM makes use of the concept of orthogonality of signals, as shown in Figure 12, and the properties of Discrete Fourier Transform (DFT) to transmit the signals whose spectrum can overlap with each other avoiding the use of guard band which was needed in traditional frequency division multiplexing technique. Since DFT is a linear combination of orthogonal sinusoids, it essentially correlates its input signal with each sinusoid basis function. So, if the signal has some energy at certain frequency there will be a peak in the correlation of the input signal and the basis sinusoid that is at that corresponding frequency. OFDM with a cyclic prefix is used in the downlink, and Single-Carrier FDMA (SC-FDMA) with a cyclic prefix in the uplink. SC-FDMA is also called DFT-S-OFDM which indicates that it can be understood as a precoding (by Discrete Fourier transform) plus the same OFDMA that is used in downlink. The use of DFTS-OFDM transmission for the uplink, as mentioned before, is motivated by the lower PAPR of the transmitted signal compared to conventional OFDM. This allows for more efficient usage of the power amplifier at the terminal, which translates into an increased coverage and/or reduced terminal power consumption.

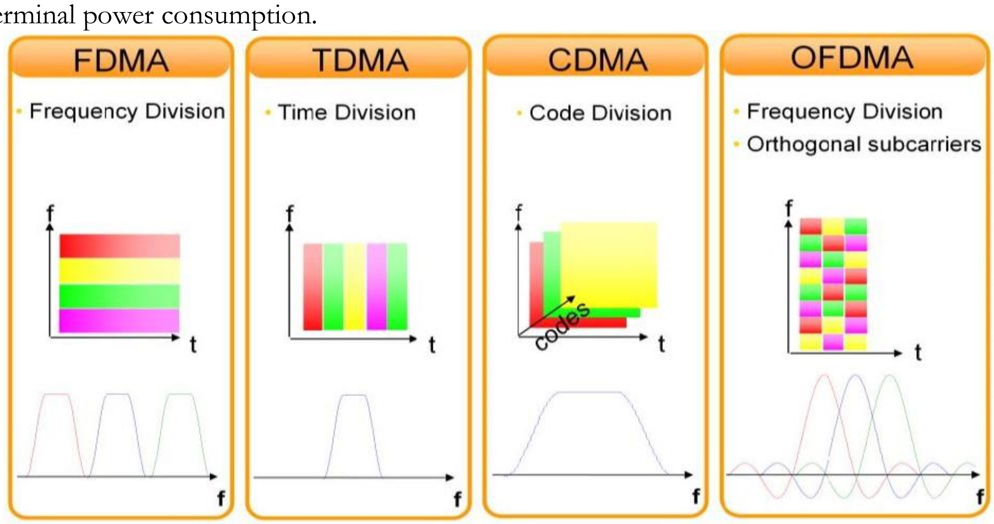


Figure 12: Multiple Access Methods

- To support transmission in paired and unpaired spectrum, two duplex modes are supported: FDD, supporting full duplex and half duplex operation, and TDD. Frequency Division Multiplexing extends the concept of single carrier modulation by using multiple subcarriers within the same single channel. The total data rate is divided between various subcarriers. The data is not needed to be divided evenly nor they have to originate from the same information source. Different modulation schemes can be used for each data, and this is the advantage of FDD over single carrier modulation. The FDD LTE frequency bands are paired to allow simultaneous transmission on two frequencies. The TDD LTE bands are unpaired because the uplink and downlink share the same frequency, being time multiplexed (Figure 13).

- While UMTS (at least FDD and 3,84Mbps TDD) used a channel bandwidth of 5MHz, LTE allows for six different channel bandwidths:1,4/3/5/10/15/20MHz. UMTS/UTRA as well as LTE/E-UTRA use both a 10ms radio frame, both have FDD and TDD modes and LTE/E-UTRA supports full interoperability with UMTS/UTRA and GSM/GERAN/EDGE.
- **Signals** (logical) are defined as reference signals, primary and secondary synchronization signals, resynchronization signals, wake-up signals, and discovery signals. The modulation schemes supported in the uplink, depending on the type of operation are, π/2 BPSK, π/4 QPSK, QPSK, 16QAM, 64QAM and 256QAM, in the downlink, QPSK, 16QAM, 64QAM, 256QAM and 1024QAM, in the sidelink, QPSK, 16QAM and 64QAM[11].
- **MIMO** was introduced into 4G LTE to improve the signal performance. LTE MIMO adds complexity to the system, but it is able to provide significant improvements in performance and spectral efficiency.

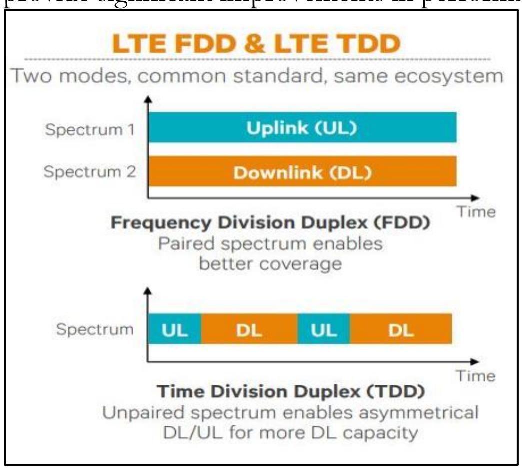


Figure 13: LTE FDD and LTE TDD[4]

Generally, the radio interface is layered into three protocol layers:
- the physical layer
- the data link layer
- network layer

The physical layer performs the following main functions:
- Macrodiversity distribution/combining and soft handover execution
- Error detection on transport channels and indication to higher layers
- FEC encoding/decoding and interleaving/deinterleaving of transport channels
- Multiplexing of transport channels and demultiplexing of coded composite transport channels
- Rate matching
- Mapping of coded composite transport channels on physical channels
- Power weighting and combining of physical channels
- Modulation and spreading/demodulation and despreading of physical channels

[11] 3GPP TS 36.101 version 14.5.0 Release 14

- Frequency and time (chip, bit, slot, frame) synchronization
- Measurements and indication to higher layers (interference power, transmit power, etc.)
- Closed-loop power control
- RF processing
- Support of timing advance on uplink channels (TDD only)
- Support of Uplink Synchronisation (TDD only).

The physical layer in 4G is defined in a bandwidth agnostic way based on resource blocks (Figure 14). This allows adaptation to various spectrum allocations, that are articulately described in 3GPP specifications.
"A resource block spans either 12 sub-carriers with a sub-carrier bandwidth of 15kHz or 24 sub-carriers with a sub-carrier bandwidth of 7.5kHz or 72 sub-carriers with a sub-carrier bandwidth of 2.5kHz, each over a slot duration of 0.5ms, or 144 sub-carriers with a sub-carrier bandwidth of 1.25kHz over a slot duration of 1ms, or 486 sub-carriers with a sub-carrier bandwidth of approximately 0.37kHz over a slot duration of 3ms. Narrowband operation is also defined, whereby certain UE may operate using a maximum transmission and reception bandwidth of 6 contiguous resource blocks within the total system bandwidth; for narrowband operation, sub-resource-block operation may also be used in the uplink, using 2, 3 or 6 sub-carriers"[12].

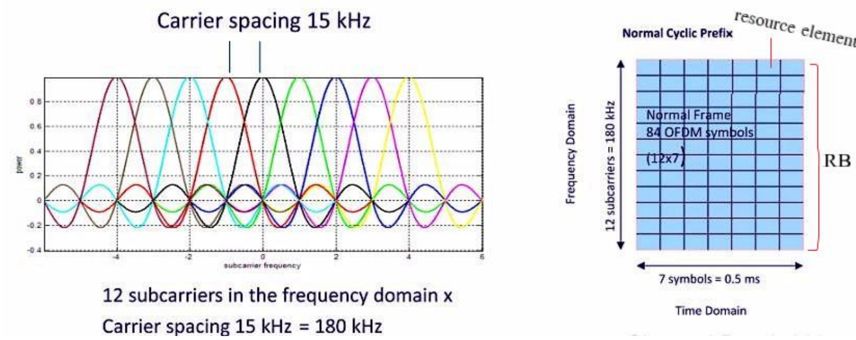


Figure 14: Resource blocks[13]

The proposals for additional spectrum for IMT systems (in 450 MHz band, in UHF band (698-960 MHz), in the 2.3-2.4 GHz band, in C-band (3400-4200 MHz)) and the general request for an advanced radio interface triggered further developments of the 4th generation of mobile communication systems. To support a Multimedia Broadcast and Multicast Service (MBMS), LTE offers the possibility to transmit Multicast/Broadcast over a Single Frequency Network (MBSFN), where a time-synchronized common waveform is transmitted from multiple cells for a given duration.

Finally, transmission with MIMO antennas is supported with configurations which allow for multi-layer downlink transmissions and beamforming in both horizontal and vertical dimensions, where a single code word is transmitted over a single spatial layer. A dedicated reference signal is used for an additional port. The terminal estimates the channel quality from the common reference signals on the antennas. Multi-layer uplink transmissions with up to four streams are supported in the uplink. Multi-user MIMO, i.e., allocation of different spatial streams to different users is supported in both UL and DL.

[12] 3GPP TS 36.201 version 10.0.0 Release 10

[13] LTE Air Interface. (2023/04/02). AIRCOMM. https://www.slideshare.net/AIRCOMmarketing/aircom-lte-webinar-series-lte-air-interface

4 5G technology

This section is devoted to the latest evolution of communication systems: 5G NR. The impact of such a technology will be described, as well as the main features of the signal standard and the new concepts developed in the framework of base stations. As a matter of fact, 5G shares with 4G many technological aspects, with some new features allowing for a much greater flexibility and unprecedented performance and data rates.

4.1 Overview of fifth generation mobile technology

The fifth generation of cellular network technology was introduced late 2018, according to the 5G NR technology standard set by the 3GPP consortium. Like 4G it is an IP-based technology, offering increased bandwidth (download speeds up to 10 Gbit/s), ability to handle a larger number of simultaneous connected devices, lower latency, and improved machine-to-machine support.

5G NR is a spread spectrum technique that can be used with various signal bandwidths in FDD, but usually in TDD application. The 5G NR signal is digitally modulated with OFDMA, consisting of a number of subcarriers that are assigned to different users. Due to its wideband nature OFDMA is very robust against multipath, fading and (narrow band) interference. Since the OFDMA coding is a spread-spectrum technique, the RF signal is characterized by a high PAPR. Therefore, measurement of RF signal power should be done using an averaging detector, to avoid excessive readings caused by measuring signal peaks. Figure 15 shows the typical power distribution of an OFDMA-modulated 5G NR traffic signal, in which a PAPR of more than 10 dB is visible.

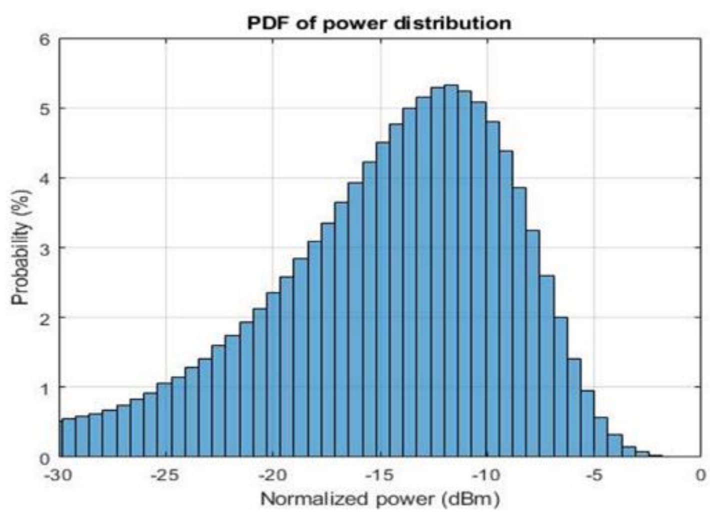


Figure 15: Power distribution of a 5G NR traffic signal

The transmitted power of 5G NR signals depends heavily on the traffic load and user behaviour. This is an important difference with respect to older technologies, which has major consequences for the way EMF measurements are performed. When EMF measurements are done to evaluate the highest possible exposure of a base station at a certain location, one has to consider that the maximum emitted power by the base station will only be available and accurately measurable under the following constraints:

- Full data traffic shall be provoked by UE (e.g., by means of a massive download, using a smartphone).
- A single traffic beam shall be continuously pointed towards the measurement antenna, within a line of sight.
- UE should not be too close to the base station, as to avoid underestimation due to power control reduction.
- In case of TDD one has to take care that the power of the UE is not included in the measurement result.

Alternatively, EMF measurement can also be done, without generating any traffic, by choosing the so-called extrapolation method, as described below and recommended by IEC 62232 [10].

5G NR is applied for FDD in the 700 MHz band (uplink: 703 – 733 MHz; downlink: 758 – 788 MHz) and for TDD in the 3.5 GHz band (3.3 – 3.8 GHz) and the 26 GHz band (26.5 – 29.5 GHz). Frequencies below 7.125 GHz are collectively called Frequency Range 1 (FR1), whereas above 24.250 GHz are named Frequency Range 2 (FR2). For

700 MHz base stations an RRH is used, together with a (traditional) passive sector antenna. For the 3.5 GHz and 26 GHz bands Active Antenna Systems (AAS) are applied, in which RRH and antenna are combined and facilitate electronic beamforming and steering (Figure 16).

Figure 16: 5G NR AAS for use in the 3.5 GHz band

4.2 Radiating systems

Whenever a new mobile communication system is made available it is necessary to review, update and adapt the approaches used for the mobile network design to take advantage of the new opportunities introduced by the technology. This is the case with 5G NR; among all the new opportunities introduced by the technology, the use of AAS has required a step forward in the Radio Access Network (RAN) design.

Radiating systems equipped with AAS (even known as Smart Antennas, Massive MIMO Antennas or Beamforming antennas) have introduced two new concepts in RAN design: payload is delivered where necessary, when required and for the time it is required and interference management.

Radiating systems before 5G NR made use of Passive Antenna Systems (PAS) for delivering the service: PAS have a static and time-invariant radiation pattern on which all what is needed for managing the communication and delivery of information are transmitted, independently where the service is required in the coverage area. The only randomness element was the time dependent radiated power required to guarantee the Quality of Service (QoS) to users. That means the energy is spread all over the coverage area, independently where the users are with a consequent not optimal energy usage and low control of the interference level.

AAS make available some more degrees of freedom in RAN design not available for previous technologies: the antenna is able to generate dedicated radiation pattern(s) (beams) specifically designed in shape and gain for the specific user requirements. This is an important step forward: the radiating system adapts to the specific user by tailoring the coverage and resources to the specific need so optimizing, at the same time, resources management for the user and for the network.

RAN design process involving AAS radiation systems requires to answer the following questions:

1. Which are the radiating systems characteristics that better describe the service to be delivered?
2. When dealing with coverage, performances, and exposure to EMF, what is the metric to be used for evaluating the RAN design performances and compliance to exposure limits?

These questions will be addressed later in this section; summarized here are the major elements to be considered, for each of the previous questions:

Regarding question 1 the three main parameters to be considered are the radiated power, the antenna radiation pattern and the operating frequency. As for technologies before 5G NR, radiating system power control mechanisms make the radiated power at the sufficient level to guarantee the QoS making the power changing randomly in the time. The maximum configured power on the antenna is effective for coverage and performance design. In the reality, radiated power randomly changes during operations, due to users' distribution and activity, so the local field, in general, is lower than the one generated with the maximum configured power; that leads to an overestimation on the EMF exposure.

As previously mentioned, when using PAS all information relevant to the communications are delivered on the same radiation pattern. AAS use a different approach; there are available two classes of radiation patterns, namely broadcast and traffic radiation patterns that could be even completely different from each other. Broadcast radiation patterns manage the coverage area while traffic radiation patterns are used to deliver the service. As will be described later, the use of two such classes of radiation patterns generate a further level of randomness having a heavy impact on methodologies used for RAN and exposure to EMF design. 5G NR can be delivered in FR1 and FR2; since FR1 includes the frequencies traditionally used in mobile communications, design methodologies are well assessed. On the other hand, particular attention is required in FR2. Due to changed characteristics of the propagation, obstacles, and presence of people in the scenario cannot be neglected in FR2 as was the case for FR1. Field distribution and QoS are more and more impacted by the scenario characteristics and changes in FR2.

Question 2 introduces a new element in RAN design due to AAS: randomness. While for coverage and performances it is possible, by using some new concepts, to reconduct the RAN design process to an approach like that used for PAS, the same is not possible for exposure to EMF assessment. Since AAS generates beams according to the distribution of users requiring service over the coverage area, the spatial and time radiation distribution in the coverage area has the same characteristic of randomness as the user distribution has, so not known a priori. Consequently, a statistical approach, that was not used for technologies up to 4G, was included in the EMF exposure process for assessing compliance to exposure limits.

The following sections deal specifically with the topics listed before from the outdoor planning, indoor planning, and exposure to EMF compliance perspective while randomness is specifically discussed in section 4.5.1.

4.2.1 Outdoor coverage and performance planning

One of the major innovations introduced by 5G NR technology is the use of AAS instead of traditional PAS as done in previous technologies.

An AAS generates one or more specific beams capable of directing flows of information towards service requests, manages the interference by spatially decoupling beams towards specific users and/or generates nulls of the radiation pattern towards specific directions, optimizes power management and therefore can provide very high performance even on cell border.

Differently from previous technologies, AAS can use two different classes of radiation patterns:

- broadcast radiation pattern(s) that define the coverage area where UEs can attach
- traffic radiation pattern(s) providing data connection over the coverage area, once the UEs has completed the attachment procedure.

In general broadcast beam performance is different from traffic beam performance.

Coverage area can be managed by two different ways:

- Unlike PAS, broadcast radiation pattern can change over time: by using the sweeping broadcast beams approach, the coverage area is divided into sub-areas each one covered by a specific beam; the set of beams is periodically swept to scan the whole coverage area (ex: up to 8 beams in FR1). The radiating system is then capable of knowing the position of users and then can provide service by generating dedicated traffic beams in the specific direction.
- The attach area can be guaranteed by the coverage of a fixed and stable beam over time, in the same way as PAS, using just one fixed broadcast beam.

Figure 17 shows an example of broadcast beam set, including 3 beams, sweeping the coverage area. The first beam covers the first portion of the coverage area (Figure 17 left panel) then switches to the second beam, covering the second portion, (Figure 17, central panel), then switches to the third beam (Figure 17, right panel). The sweep procedure is then repeated continuously.

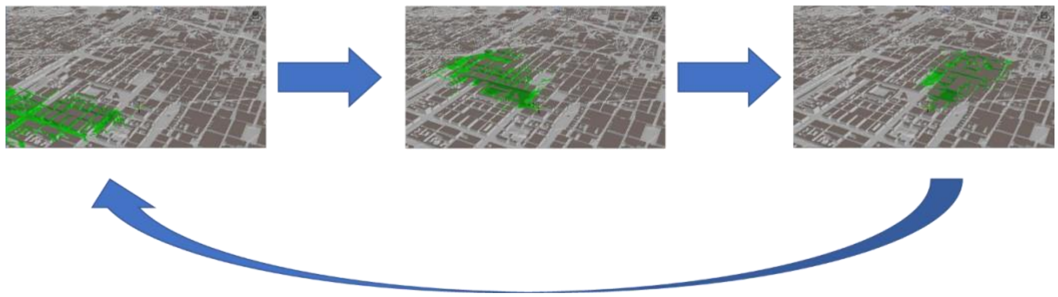


Figure 17: The sweeping broadcast beam set

Once the broadcast beam discovers a UE requiring service, the AAS generates a traffic narrow beam toward the UEs while broadcast beams continue to sweep the coverage area, see Figure 18.

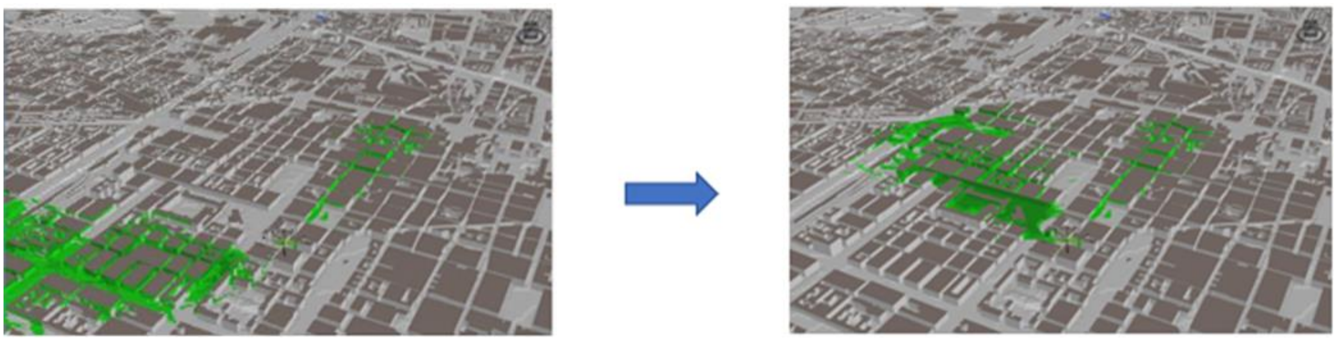


Figure 18: The traffic beam activated (right beam), while the broadcast continues to sweep

The ability to generate service beams based on user's distribution makes the traffic coverage time variant, with variable spatial characteristics and time duration based on service requirements. Therefore, radio traffic coverage is no longer static and stable over time, as for technologies below 5G, but changes with randomness as users' distribution is.

The high performances that 5G services can reach and the use of AAS has required a changing approach in radio coverage planning compared to previous technologies. While for technologies prior to 5G NR the goal of coverage and performance planning was to achieve a minimum performances requirement on the cell boarder, in 5G technology it is possible to have high performances even on the cell border thanks to the radio performance can be obtained by AAS, namely:

- using a (or more) narrow beam directed only in the direction of the user carrying information, limiting interference by spatial decoupling,
- higher antenna gain, with respect to PAS, due to many radiators acting as an antenna array,
- higher system performances and spectrum usage optimization.

The spatial coverage randomness requires the need to change the network coverage design approaches, introducing the traffic envelope radiation pattern concept. Due to the randomness of the radiation direction within the coverage area, the envelope pattern provides the maximum performance that the antenna can give in each direction, reconducting the coverage and performances design to concepts like those used for PAS network design.

The simultaneous presence of the broadcast coverage and traffic coverage, requires duplicate network planning:

- An attach coverage design, defining the UEs' attach area, based on the broadcast beam set.
- A traffic coverage design, defining the performances (e.g., throughput) that can be obtained in the coverage area.

4.2.2 Indoor coverage and performance planning

5G indoor solutions include both Sub-6 GHz (FR1) and millimeter wave (FR2) bands [11], [12]. Radiating systems that use FR1 bands can be equipped with MaMIMO antennas or with passive antennas, like previous technologies, e.g., 4G. Consequently, design methodologies in FR1 are like those used for outdoor deployments.

Different approaches need to be considered for radiating systems working in FR2; traditional propagation models like COST231 [13] are no more suited for the coverage planning in this band and Ray-tracing engines should be used.

While radiating system can be equipped with MaMIMO antennas or with passive antennas, the effect of the scenario on the coverage and performances is more and more stressed. In FR2 details become important and integral part of the time space distribution of the coverage, in particular:

- Wall attenuation in FR2 increases more and more with respect to FR1 as well as isolation of environment; that helps in managing interference and confinement of the electromagnetic field where needed at the cost of a denser distribution of radiating systems to cover the same area.
- Scenario furniture and details become important and integral parts of the coverage as well as the presence of people [14]; that implies the coverage is intrinsically random and follows people movement and distribution; any obstacle can generate shadows with a temporary lack in coverage and connectivity that need to be managed, as an example with space diversity. This effect increases the randomness of the field distribution to be considered in all design stages.

Figure 19 shows two examples (2D and 3D) of a coverage simulation at 26 GHz in which environment isolation is highlighted.

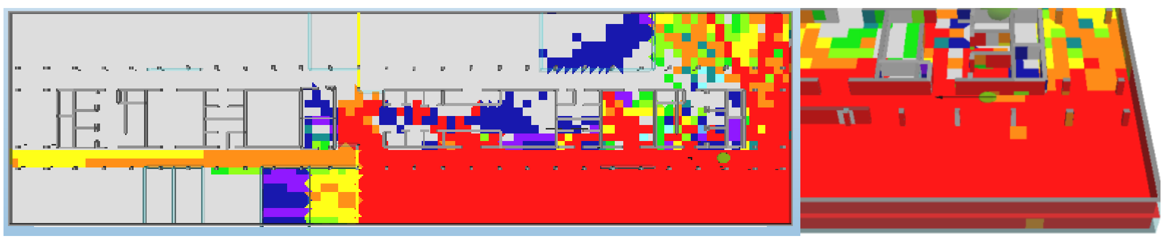


Figure 19: Indoor coverage example

4.2.3 Exposure to electromagnetic fields

In the design phase, the EMF assessment procedure of a Radio-Base Station (RBS) requires verifying via simulation that the maximum exposure to which the population will be exposed, i.e., the exposure under maximum RBS traffic-load condition, does not exceed the permitted exposure limits.

The deployment of 5G systems required a revision of the EMF assessment procedure, as well as an update of the simulation tools used by mobile operators and health authorities: in fact, the usage of MaMIMO antennas introduces a space-time variability, not predictable a priori, of the radiated field distribution.

For this purpose, within IEC [10], [15] a new formulation for the Effective Isotropic Radiated Power (EIRP) computation, namely the “actual max approach”, has been defined to consider the variability of the radiation pattern and the transmitted power in the time. This formulation – valid, strictly speaking, not only for 5G systems – allows to derive a methodology for calculating the EIRP based on the configured power, on the envelope radiation pattern and on statistical factors describing the space-time variability of the radiated electromagnetic field. Basically, the EIRP computation for MaMIMO antennas is reduced to the case of passive ones, i.e., the product of power and gain. The envelope radiation pattern is obtained as “superimposition” of all the radiation patterns the MaMIMO antenna can generate and maximizes, by overestimation, the actual radiation. Randomness of the radiation, introduced in the Actual Max Approach by statistical factors, is taken into account by monitoring counters (ie. power usage, beam usage, etc.) provided by the MaMIMO antenna system and allows to mitigate the overestimation of the electromagnetic field levels due to the usage of the envelope radiation pattern.

The approach based on the envelope radiation pattern has given rise to new needs in terms of numerical representation of radiation patterns. The radiation pattern description based on two main planes only, widely used with PAS, results to be potentially insufficient to describe and reconstruct the whole 3D radiation pattern, because a MaMIMO antenna can generate several beams outside principal planes.

Correct management of statistical factors and envelope radiation pattern (“actual max approach”) and acquisition of new 3D radiation pattern numerical format [16], need therefore to be included in the development roadmap of predictive analysis software tools.

4.3 Signal standard

5G NR specifies a new air interface to enable higher data throughput and low- latency use cases. Key to enabling higher data throughput is the addition of mmWave spectrum up to 52.6 GHz. At these higher frequencies, more contiguous spectrum is available to send more data through the channel. Release 15 of standard by 3GPP specifies a maximum carrier bandwidth up to 400 MHz and up to 16 component carriers that, when aggregated, add up to 800 MHz of bandwidth. Also, flexibility and scalability in the slot structure help support the many new and diverse use cases expected in 5G.

In 5G NR, cyclic prefix orthogonal frequency division multiplex (CP-OFDM) is the modulation format (or waveform) in the DL and UL. CP-OFDM use is well-known for DL transmissions, but it is new for UL transmissions in mobile. Having the same waveform in both UL and DL enables easier device-to-device communication in future releases.

Unlike 4G, NR allows for scalable OFDM numerology (μ) where the subcarrier spacings are no longer fixed to 15 kHz. With NR, subcarrier spacing scales by $2^{\mu} \times 15$ kHz to cover different services. Lower frequency bands use 15, 30, and 60 kHz subcarrier spacings, and higher frequency bands use 60, 120, and 240 kHz subcarrier spacings. Scalable numerology enables scalable slot duration to optimize for different service levels in throughput, latency, or reliability. Larger subcarrier spacing at higher frequencies also helps with the robustness of the waveform since integrated phase noise is an issue in mmWave designs. Figure 20 shows how the different subcarrier spacings and the transmission time interval associated with each scales the size of the slot.

Ultra-Reliable Low Latency Communication (URLLC) is one of three primary 5G use cases and is achieved partially through mini-slots. In LTE, transmissions adhere to the standard slot boundaries, but they are not optimized for minimal latency. A standard slot has 14 OFDM symbols, shown in dark blue in Figure 20. As the subcarrier spacing increases, the slot duration decreases, as shown in light blue. A mini-slot is shorter in duration than a standard slot and located anywhere within the slot. A mini-slot is 2, 4, or 7 OFDM symbols long. Mini-slots provide low-latency payloads with an immediate start time without the need to wait for the start of a slot boundary (Figure 21).

NR subframe structure also allows for dynamic assignments of the OFDM symbol link direction and control within the same subframe. By using this dynamic TDD mechanism, the network dynamically balances UL and DL traffic requirements and includes control and acknowledgment all in the same subframe. The slot format indicator denotes whether a given OFDM symbol in a slot is used for uplink or downlink, or if it is flexible.

In LTE, carriers are narrower in bandwidth — up to 20 MHz maximum. When aggregated, they create a wider channel bandwidth of up to 100 MHz. In 5G NR, the maximum carrier bandwidth is up to 100 MHz in FR1, and up to 400 MHz in FR2. New in 5G NR are bandwidth parts where the carrier is subdivided for different purposes. Each bandwidth part has its own numerology and is signaled independently. One carrier can have mixed numerologies to support a mixed level of services, such as power saving or multiplexing of numerologies and services in unlicensed bands. However, only one bandwidth part in the UL and one in the DL are active at a given time. Bandwidth parts will support legacy 4G devices with new 5G devices on the same carrier. With 4G, 5G, and potentially Wi-Fi multiplexing services, it is necessary to minimize both in-band and out-of-band emissions.

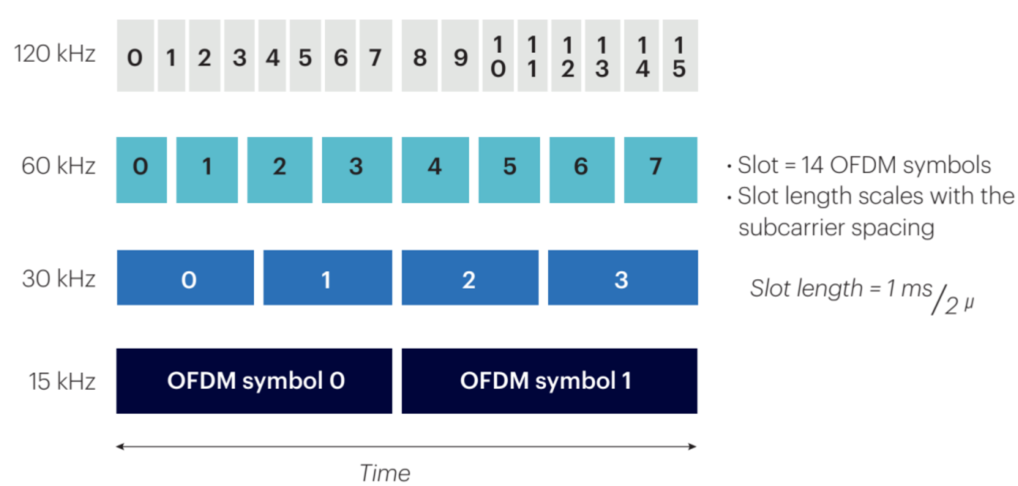


Figure 20: Relationship between subcarrier spacings and time durations

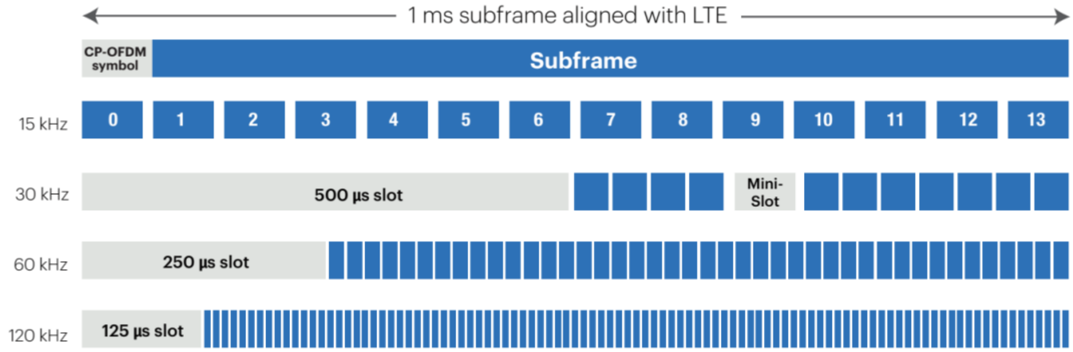


Figure 21: Slots and mini-slots within a subframe and their associated slot duration time

4.3.1 Frame structure

The frame structure has been conceived to obtain high energy efficiency, and NR avoids as much as possible "always on air" signals. Consequently, the fundamental pieces of information that are required by the UE for initial connection to the cell are 'packed' in a very compact structure, called the Synchronization Signal / Physical Broadcast Channel (SS/PBCH), or "SS Block" (SSB), that includes the Synchronization Signals (SS), the PBCH and the PBCH-DMRS. SSB is mapped into 4 OFDM symbols in the time domain and 240 contiguous subcarriers (20 RBs) in the frequency domain (Figure 22).

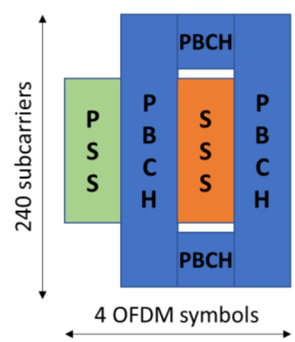


Figure 22: Synchronization Signal Block (SSB) in 5G NR

SS Blocks are grouped in block patterns called SS bursts. There are 5 block patterns which have different subcarrier spacings and are applicable for different carrier frequencies:

- Case A (15 kHz subcarrier spacing),
- Case B (30 kHz subcarrier spacing),
- Case C (30 kHz subcarrier spacing),
- case D (120 kHz subcarrier spacing),
- Case E (240 kHz subcarrier spacing).

The maximum number of SS blocks in a single burst is frequency dependent, and ranges from 4 to 8 in FR1 to up to 64 blocks per burst in FR2. Each SSB in a SS Burst is associated to a different beam of the grid of broadcast beams. The other signals are transmitted when required. They are usually transmitted on traffic beams and are "user-dependent". 5G uses a sophisticated signalling structure. In the following we limit our discussion on the physical channels and signals associated to downlink connection. The choice of the beam (broadcast or traffic) on which the signals are transmitted is generally left to the vendor decision. In the following the most common choices are indicated.

4.3.2 Physical channels

The Physical Channels defined in downlink are

1) The Physical Broadcast Channel (PBCH).

2) The Physical Downlink Shared Channel (PDSCH).

3) The Physical Downlink Control Channel (PDCCH).

Each Physical Channel has its own Demodulation Reference Signal (DMRS) for channel estimation and equalization, as discussed in the following.

Physical Broadcast Channel (PBCH): PBCH carries basic system information required to access the network, and in particular the Master Information Block (MIB). The PBCH is transmitted using QPSK in the PBCH-SS blocks with its own demodulation reference signal using broadcast beams. NR supports only one antenna port-based transmission for PBCH data in order to avoid blind decoding.

Physical Downlink Control Channel (PDCCH): The PDCCH provides scheduling decisions necessary for the reception of PDSCH, as well as special purposes such as slot format indication and power control. The information carried by the PDCCH is referred to as Downlink Control Information (DCI). PDCCH is transmitted in a CORESET (COntrol REsource SET) using QPSK modulation. A CORESET is a set of resource blocks which has varying time and frequency domain length. In time domain it may occupy 1, 2 or 3 OFDM symbols whereas in frequency domain it is a multiple of one resource block (12 subcarriers). A CORESET defines a resource where UE specific scheduling information can occur. PDCCH has its own PDCCH-DMRS signal and is transmitted on traffic beams.

Physical Downlink Shared Channel (PDSCH): This is the main channel used for data transmission, paging information, some parts of system information and also random-access response message. It decodes DCI from PDCCH which provides the necessary information to decode data in PDSCH. The frequency resource allocation is organized in resource blocks, with flexible modulation schemes selected on the basis of the SNR. PDSCH has its own PDSCH-DMRS signal and is transmitted on traffic beams.

4.3.3 Physical signals

Physical channels carry information originating from the higher layers. In addition, 5G NR defines additional physical signals that do not carry information from higher layers, but are used for functionalities like synchronization, channel estimation, tracking and beam identification. The physical signals defined in downlink are:

1) The Primary Synchronization Signal (PSS) and Secondary Synchronization Signal (SSS).

2) The Physical Broadcast Channel Demodulation Reference Signal (PBCH-DMRS).

3) The Physical Download Control Channel Demodulation Reference Signal (PDCCH-DMRS).

4) The Physical Download Shared Channel Demodulation Reference Signal (PDSCH-DMRS).

5) Phase Tracking Reference Signal (PTRS).

6) The Channel-state Information reference signal (CSI-RS).

Primary Synchronization Signal and Secondary Synchronization Signal (PSS, SSS): PSS and SSS play a key role in synchronization and cell search. PSS helps to achieve subframe, slot and symbol synchronization in the time domain, identify the centre of the channel bandwidth in the frequency domain and deduce a pointer to 1 of 3 Physical layer Cell Identities (PCI). SSS helps to achieve radio frame synchronization and deduce a pointer to 1 of 168 Physical layer Cell Identity (PCI) groups. PSS and SSS are transmitted in the SS-PBCH block using BPSK constellation on broadcast beams with constant power, so they are suitable as reference signals. SSS has been proposed as reference signal in [17].

Physical Broadcast Channel-Demodulation Reference Signal (PBCH-DMRS): PBCH-DMRS is a special type of physical layer signal used as reference signal for decoding PBCH. PBCH-DMRS is transmitted in the SS-PBCH block using broadcast beams with constant power and is transmitted also in absence of users. It is one of the signals proposed as reference in MPE techniques [18].

Physical Downlink Control Channel-Demodulation Reference Signal (PDCCH-DMRS): PDCCH-DMRS is a special type of physical layer signal used as reference signal for decoding PDCCH. It is transmitted together with the PDCCH in a CORESET using traffic beams. NR considers the possibility of a power boosting factor for the PDCCH-DMRS. In particular 3GPP defines the βPDCCH DMRS factor as the ratio between PDCCH Energy per Resource Element (EPRE) and PDCCH-DMRS EPRE.

Physical Downlink Shared Channel-Demodulation Reference Signal (PDSCH-DMRS): PDSCH-DMRS has a 'double role' in PDSCH decoding. In fact, NR assumes that precoding is used for data. PSDSCH-DMRS is transmitted on traffic beams using the same precoding of the data, allowing to estimate both the response of the propagation channel and the precoding. The position of the PDSCH-DMRS is characterized by a high degree of flexibility in order to match the characteristics of the communication channel and of the user application. In particular, PDSCH-DMRS is mapped in PDSCH RB according to Mapping Type A or B and Configuration Type 1 or 2. The Mapping Type A or B defines the mapping location in the slot. In Type A the DRMS allocation is in the symbol 2 or 3, while in Type B the DMRS is allocated in the first symbol of PDSCH allocation and is used when the PDSCH covers only a part of the slot, allowing a fast demodulation of the data required for low latency applications. The DMRS Configuration Type 1 or 2 specifies the density of the DRMS. Type 1 is denser in frequency, while Type 2 supports a larger number of orthogonal DMRS sequences, required to handle a large number of MIMO layers as in MU-MIMO.

The minimum number of DMRS symbols per slot is 1, but it is possible to add up to 3 additional DMRS symbols per slots to handle critical synchronization scenarios as high-speed applications. In case of multiple layers transmission, DMRS uses different locations in frequency domain to allocate the ports. Two orthogonal pseudo-noise sequences are used to map two antenna ports on the same frequency, allowing to half the number of frequencies. Each symbol can be associated to two different codes, and DMRS can be allocated in a single symbol or in a double symbols' configuration. Consequently, Type 1 can support only up to 4 orthogonal signals for single symbol DMRS, or 8 orthogonal symbols for double symbols, while Type 2 supports up to 6 orthogonal signals for each DMRS symbol, or 16 in double symbols configuration.

Finally, NR considers the possibility of a power boosting factor associated to the EPRE. In particular 3GPP defines the βDMRS factor as the ratio between PDSCH EPRE and DMRS EPRE.

Phase Tracking Reference Signals (PTRS): PTRS can be optionally used in PDSCH channel for compensating the phase noise and is particularly important in FR2, where phase noise is an important problem. It is sparser in frequency and denser in time as compared to DMRS. 5G introduces a power boosting factor associated to the EPRE. In particular 3GPP defines the βPTRS factor as the ratio between PTRS EPRE and PDSCH EPRE.

Channel State Information-Reference Signal (CSI-RS): CSI-RS is used by the device to acquire information about the downlink channel. It is decoded by the device and sent as feedback to the base station as part of reports via PUSCH and PUCCH uplink channels. In particular, CSI reports consist of three parameters: RI (Rank Indicator), PMI (Precoding Matrix Index) and CQI (Channel Quality Information). The Rank Indicator indicates how many independent layers can be transmitted by the base station. The Precoding Matrix Indicator indicates what precoding matrix should be used by the transmitter for beam-forming on the base of a codebook of precoded matrices. Finally, CQI gives information on the quality of the communication channel. Based on the report, the base station optimizes various parameters like the number of transmission layers, modulation and coding scheme, and the pre-coding matrix to be used. The CSI report only provides suggestions, and the transmitter is free to decide whether to follow the recommendation included in the report.

The CSI-RS resources can be allocated in three ways, namely in a periodic, semi-persistent or aperiodic basis. Semi-persistent is equivalent to periodic configuration, the only difference being that the activation and deactivation of CSI-RS transmission are controlled by MAC. Not all kinds of combinations among periodicity types for measurement and reporting are allowed.

CSI-RS can have a frequency density equal to 1 in which case it will be transmitted in every resource block for the full bandwidth, or density of 1/2 in which case it will be transmitted in alternate resource blocks. In a multi-port, the separation is achieved by modulating with different orthogonal codes, by separating in frequency, or by separating in time. The CSI-RS can be Non-Zero Power (NZP) or Zero Power (ZP, or Muted). The NZP REs are associated to a no-transmission condition. This allows to use the frequency-time resources associated to a ZP CSI-RS to estimate the interference level due for example to the presence of other cells active on the same bandwidth.

Finally, there is also a third kind of CSI-RS with 3 subcarriers for each RB. This kind of CSI-RS is very dense in frequency and is used for the Tracking Reference Signal (TRS). On the contrary of the other CSI-RS transmissions, the TRS is single port.

In practice, the high flexibility of CSI-RS allows to configure it for multiple purposes, as TRS, CSI acquisition, and beam management. This last configuration is particularly interesting in the framework of MPE procedures since it can be used to obtain UE-specific information.

4.4 EMF Measurement techniques

Before describing the solutions proposed in literature for the measurement of 5G signals in air, it is useful to introduce the problem.

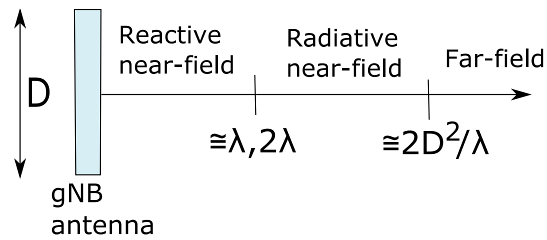


Figure 23: The zones around an antenna

With reference to a radiating system, in the specific case the antenna of the gNB or of the UE, it is convenient to consider three different areas around the radiating system (see Figure 23) [19].

In Table 4 the wavelength in case of different frequencies used in 5G communication system are reported as example. The free space wavelength λ ranges from about half a meter in case of FR1 lower band to about 1 cm in case of FR2 band. The area that extends up to a distance of the order of λ from the radiating system is called the "reactive near-field zone". In this area the field configuration fast changes with position in a complex way. Electric field amplitude, magnetic field amplitude and density power are related in a not trivial way and require different measurement. Any metallic object (for example a probe) placed in this area is subject to a significant electromagnetic coupling, that causes a variation of the field configuration. Consequently, measurement of the field level in this area is particularly complex and requires particular care.

Table 4: Extension of the different zones around the antennas at three frequencies used in 5G communication systems

Frequency	Band	Free space wavelength (λ)	Near field reactive zone limit	D	Far-field zone
700 MHz	FR1	43 cm	≅ 1 m	1.5 m	> 11 m
3.6 GHz	FR1	8 cm	≅ 20 cm	1 m	> 24 m
27 GHz	FR2	1 cm	≅ 2 cm	0.5 m	> 45 m

The medium distance area is the "radiated near-field" zone, or Fresnel zone. This area ranges for some λ to almost $2D^2/\lambda$, wherein D is the dimension of the radiating system (supposed larger than a couple of λ). Also, in this are electric field amplitude, magnetic field amplitude and density power are related in a not trivial way and require different measurements. However, the presence of metallic objects (for example probes) gives a usually negligible electromagnetic coupling, making measurement in this area less critical.

The third area is the "radiated far field" zone, of Fraunhofer zone. This area extends from almost $2D^2/\lambda$ to infinite. In free space condition the local field configuration around an observation point can be well approximated by a plane wave. Consequently, electric field amplitude, magnetic field amplitude and density power are related by the free space impedance ζ_0:

$$E = \zeta_0 H, S = \frac{E^2}{\zeta_0} \quad (1)$$

wherein E, H and S are the RMS value of the electric field amplitude, magnetic field amplitude and the power density in case of harmonic signals, and $\zeta_0 \cong 377\ \Omega$.

It must be noted that real environment is different from free space due to the presence of reflection, refraction and diffraction phenomena. Consequently, field configuration in the Fraunhofer zone is generally more complex, and the field is a superposition of plane waves. In any case, if only one contribution is dominant, it is possible to approximate the field as a single plane wave.

A further problem in the field measurement is the polarization that is related to the vector nature of the electric and magnetic field. Since polarization of the field in the measurement position is generally not known, it is required to measure the 3 orthogonal components of the field:

$$E = \sqrt{E_x^2 + E_y^2 + E_z^2} \quad (2)$$

$$H = \sqrt{H_x^2 + H_y^2 + H_z^2} \quad (3)$$

In the following the field strength measurement will be discussed with reference to the base station antennas radiated field, i.e., the field strength during the downlink connection, supposing that the measurement position is not in the reactive area of the antenna. The same approaches can be extended also in uplink condition, provided that the distance from the radiating system is large enough to be outside the reactive region.

5G NR is characterized by new technical solutions at the physical level of the OSI stack, that pose a number of new challenges in estimating the EMF of 5G signals for human exposure assessment. The gNB can use different antenna beams for broadcast data i) to transmit the SS-PBCH physical channel) and user payload data, ii) to transmit PDSCH physical channel; even if the control signals and payload data signals are transmitted at the same power, they are received at different power level, giving different field level. In particular, 5G gNB can use two different kinds of beams, the so-called 'broadcast' beam and the 'traffic' beam (see Figure 24), whose directivity is different. In particular, the traffic beam is used to send payload data to the UE and has a greater directivity than the broadcast beam, which instead transmits information of interest to all users of the cell. Consequently, even if the control signals and payload data signals are transmitted at the same power, they are received at different power level, giving different field level.

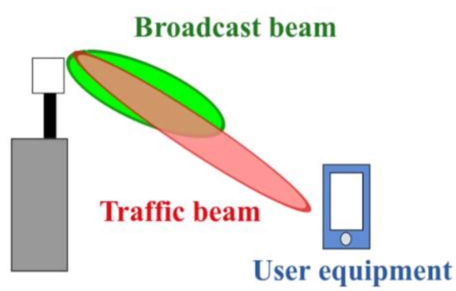


Figure 24: gNB different antenna beams

Furthermore, the most gNBs use directive antennas whose beam can be pointed toward the user. In the most commonly adopted solution, a grid of beams having different directions and gain are available to cover the sector of interest [16]. The specific beam is selected for the communication according to the position of the user. More sophisticated beam forming strategies considering the response of the channel (called 'eigenvalue beamforming') are also possible. In practice, the management of the antenna beams is dynamically decided by the gNB.

Finally, the radiated power depends on the traffic data to be sent to the user. Consequently, the period of time during which a UE is illuminated by the gNB and hence the field level depends on the amount of data that must be transmitted.

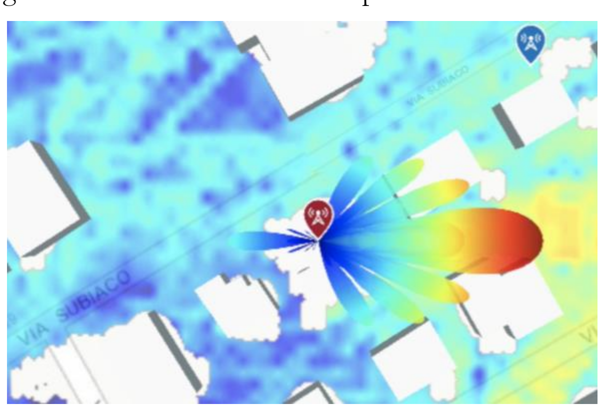


Figure 25: Measurement position of gNB antenna points toward a user

Furthermore, the field level in a measurement position depends, besides the amount of traffic in the measurement period, also on the position of the active users, i.e., UE that require payload traffic during the measurement instant, as shown in Figure 25. The measurement position is in the blue point, but the gNB antenna points toward a user, served during the measurement time, who is in a different direction; the field strength in the measurement position is consequently low (blue colour). Consequently, any 5G field strength measurement strategy must handle these two problems.

According to the indications of [10], there are two evaluation approaches, known as Case A and Case B. Case A gives an estimate of the field strength radiated by all the sources and frequencies at one measurement area, while Case B provides an estimate of the field strength for each source, frequency of frequency sub-band in the measurement area.

In case A broadband equipment is adopted. This approach allows a fast and simple estimation of the EMF field strength in the period of the measurement. However, it does not allow to single out the contributions of the sources. Furthermore, as noted above, field strength randomly changes according to the number of active users and the amount of data traffic required by the user.

Case B allows the identification of the sources. For exposure evaluation, frequency selective equipment is used. In this document the equipment is divided into two groups. Denoted as 'no ID selective', that includes standard spectrum analysers, and 'ID selective', that includes devices able to demodulate the signal, i.e., vector network analysers with 5G decoding software, or Network scanner able to gives the main parameters of the signal, or eventually 5G phones with proper software. The difference is that the 'ID selective' devices can identify the ID of the source, and hence to select a specific ID signal among many possible signals transmitted in the same frequency band.

Broadly speaking, the capability of the different class instruments with respect to the identification of the source are the following one:

- Broadband equipment: 'aggregate' field strength measurement; not able to distinguish the contribution of the different sources.
- Non-ID selective devices (scalar spectrum analysers): identification of the source on the base of the frequency; 'aggregate' field strength measurement of all the sources radiating in the same frequency range.
- ID selective devices (vector spectrum analysers, signal receivers, network scanners): identification of the source on the base of its ID; they are able to associate the field to the source even if other sources used the same frequency band.

Research on 5G signal strength measurement has been focused on Case B.

Estimation of the field strength using selective equipment can be divided in Channel power measurement and Maximum Power Estimation techniques. A further distinction used in the following description is between passive measurement techniques, that do not interact directly with the gNB, and active measurement technique, wherein there is direct interaction with the gNB using special UE.

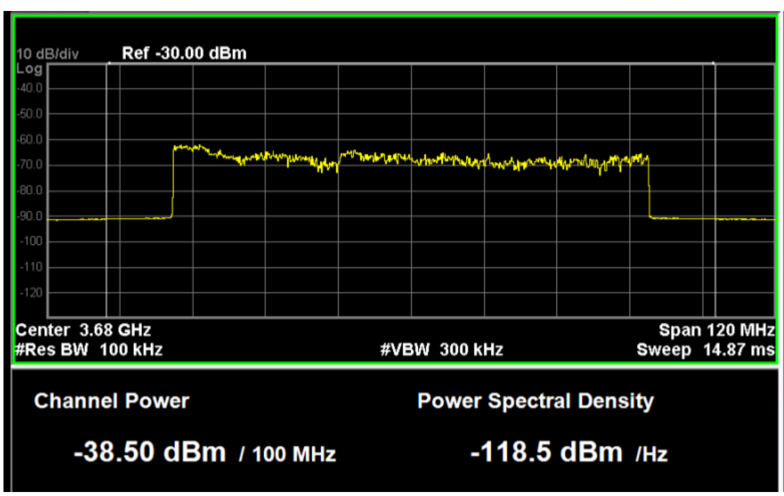


Figure 26: Example of Channel Power measurement of a 5G signal

In passive Channel power measurements, a calibrated antenna is connected to the frequency selective receiver by a calibrated cable. The RBW of the instrument should be set to span the entire band of the signal object of the interest, and the RMS detector is set. In this way an estimate of the power of the signal at the connector of the instrument in the whole band is obtained (see Figure 26). If the RBW range does not span the entire bandwidth, measurement is carried out in sub-bands and the power associated to the sub-bands is then summed up. The power measured at the connector of the instrument is then corrected considering the attenuation of the cable and multiplying by the Antenna Factor obtained from the antenna calibration certificate. Depending on the set of the instrument, the field result is the average value (if the instrument is set to give the average value of the swept traces during the measurement period) or the maximum value (if the instrument is set to give the maximum value of the swept traces) of the field strength in the measurement point in the period during which measurements are carried out. Since linear-polarized antennas are usually adopted, measurement must be repeated to collect the three components of the field object of the measurement (electric or magnetic field). The Channel Power measurements is suitable for a continuous monitoring of the field strength radiate by 5G in the environment [20].

However, in general this method gives an estimation of the field strength only in the period of the measurement session, making the result highly dependent on the traffic in the period of the measurement session.

In order to overcome this problem, a possible solution is to use active measurements, forcing the gNB to send a signal at maximum power toward the measurement position using a proper UE placed close to the measurement position [18]. In absence of other users requiring traffic all the resources will be assigned to the UE, giving the maximum data traffic and hence the maximum field level. However, in presence of other users, the gNB resources will be shared among the UEs. Consequently, the field level will depend on how the traffic request.

It is worth noting that Channel Power measurement can be carried out using scalar spectrum analysers, or also vector network analysers. Scalar spectrum analysers are not able to distinguish the contribution of different gNB radiating in the same frequency band, that requires the identification of ID of the gNB, and consequently the use of vector network analysers with 5G decoding software.

As noted above, research on field strength radiated by gNBs has been focused on Maximum Power Estimation (MPE) techniques that allow to overcome the problem related to the traffic level during the measurement session. Loosely speaking, in the MPE technique a component of the signal that is transmitted at constant strength is used as reference signal [10]. The maximum field strength (in the highest traffic condition) is extrapolated by the measured value of the field strength of the reference signal.

5G limits the "always on" signals as much as possible, packing all the fundamental information required for network access and handover in a signal structure (SSBs) highly concentrated in frequency, time and possibly space, associated to the SS-PBCH physical channel. This is the only "always on" signal in NR, and consequently all proposed MPEs use the SS-PBCH as a reference [17], [21], [22], [23]. SS-PBCH has a number of other useful features, as it is transmitted at constant power and can be easily measured with high accuracy.

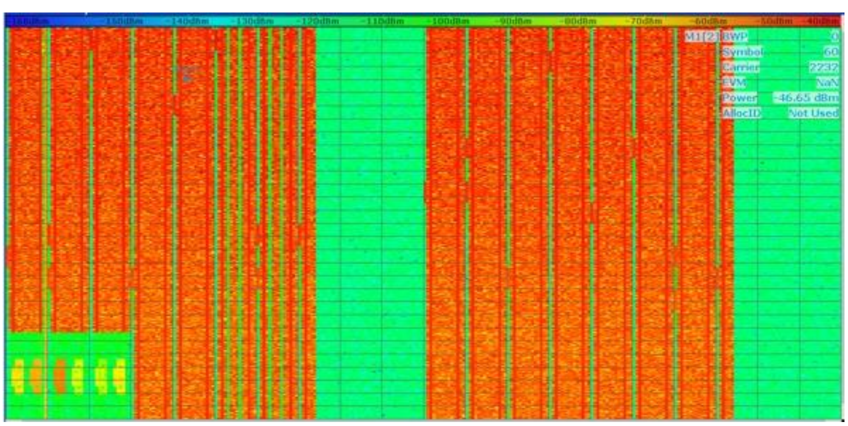


Figure 27: An example of full-loaded 5G frame in downlink connection; horizontal axis: symbols, vertical axis: subcarriers

An example of 5G frame is shown in Figure 27. The six SSBs are clearly visible in the left bottom of the figure; the two periods of time reserved for uplink connection are visible as green rectangular area covering all the subcarriers. In no ID selective measurement systems (scalar spectrum analysers) the maximum SSB power level is measured (the third

SSB in the figure). Then all the part of the frame involved in the downlink connection (the remaining red part) is supposed to be filled by REs (note that 5G uses time division multiplexing, and there are periods of times reserved for uplink connection).

In ID selective measurements, it is possible to measure directly the RE power of the signals carried in the SSB, for example the Secondary Synchronization Signal (SSS), or the PDSCH-DRMRS [18], or the SSS-RePower using Network Scanners [24], [25]. As a matter of fact, also with non-ID selective measurement with a real-time spectrum analyser it is possible to measure the RE power, with the limitation of not identifying the source of the signal. Measurement of the RE power associated to the reference signal does not allow to obtain the MPE of the field strength in general, since the REs of the SSBs are transmitted using broadcast beams, while the REs of payload traffic are transmitted using traffic beams, that have higher Gain. Consequently, a correction is required to take into account the different of Gain between broadcast and traffic beams.

The correction factor, called F_{beam}, can be obtained by the envelop of beams of the broadcast and traffic beams (Gain between broadcast (BERP, Broadcast Envelope Radiation Pattern) and the TERP, Traffic Envelope Radiation Pattern). The envelop of beams are basically the polar plot of the envelope of the Gain of the grid of beams. BERT and TERP are provided by the vendors.

A more accurate way is to measure the level of the signal transmitted by the broadcast and the traffic beams, using waterfalling measurements, that allow to observe the spectrum of the signal as function of time, identifying the signals transmitted by the traffic beam [22]. These methods do not require a direct interaction with the gNB, and consequently are passive.

An alternative method is to force the gNB to transmit a signal toward the measurement system. This 'active' measurement solution allows a simpler measurement of the F_{beam} [18]. Active measurements allow also to measure directly the REs of the traffic beam [26], [27].

The value obtained by the MPE procedure is an unrealistic upper bound, since it supposes that all the resources of the communication system are given to only one user. This quantity is then multiplied by a proper correction factor that takes into account the stochastic nature of the problem in order to obtain a realistic value [28], [29], [30], [31], [32], [33], [34].

4.5 Models

4.5.1 Statistical models

Field level in an observation point where the EMF exposure need to be assessed, placed in the far field region of an antenna can be shortly represented by the following equation:

$$E(r,\vartheta,\varphi,t) = \mathfrak{F}\left[r;\ \widetilde{EIRP}_{Tx}(\vartheta,\varphi,t,U(t)); G_{Rx}(\vartheta',\varphi',t)\right] \quad (4)$$

In which:

- E is the electric field in the evaluation point; H field or Power Density can be described similarly; the approach is anyway equivalent.
- r is the electromagnetic link distance between the transmitting point and the observation point.
- t is the time.
- ϑ is the elevation angle, in the reference system associated to the antenna, the transmitter is linked to the observation point in the electromagnetic direction.
- φ is the azimuth angle, in the reference system associated to the antenna, the transmitter is linked to the observation point in the electromagnetic direction.
- $\mathfrak{F}$ is a functional accounting for the pathloss between the transmitting point and the observation point along the electromagnetic link between the transmitter and the observation point.
- U(t) is the distribution of active users over the coverage area.

- $\widetilde{EIRP}_{Tx}$ is the EIRP radiated by the antenna in the electromagnetic direction of the observation point. This term depends on the type of antenna used at the transmission side:
  - For PAS

$$\widetilde{EIRP}_{Tx}(\vartheta,\varphi,t,U(t)) = \widetilde{EIRP}_{Tx}(\vartheta,\varphi,t) = G_{Tx}(\vartheta,\varphi)P_{Tx}(t) \quad (5)$$

  - For Grid of Beam[14] (GoB) AAS

$$\widetilde{EIRP}_{Tx}(\vartheta,\varphi,t,U(t)) = \sum_{n=1}^{U(t)} G_{Tx_n}(\vartheta,\varphi)P_{Tx_n}(t) \quad (6)$$

    - $G_{Tx_n}(\vartheta,\varphi)$ is the gain of the beam used by the antenna at the specific time for the n-th user.
    - $P_{Tx_n}(t')$ is the radiatesd power at the specific time dedicated to the n-th user.

  - For Eigen Based Beamforming [15] (EBB) AAS

$$\widetilde{EIRP}_{Tx}(\vartheta,\varphi,t,U(t)) = G_{Tx}(\vartheta,\varphi,U(t))P_{Tx}(t) \quad (7)$$

As can be noted, for any type of antenna there is a term that introduces randomness: the time variation of the power. For GoB and EBB AAS there is a further term of randomness related to the time variation of the antenna's gain function. Both terms accounting for randomness, make the field in an observation point characterized the same level of randomness as the traffic to be served in the coverage area.

Very often, to reconduct the design process to a condition like that used for PAS, the envelope radiation pattern is used to represent the space radiating characteristics of AAS. The envelope radiation pattern is defined as [16]:

"The Envelope Radiation Pattern is a non-physical radiation pattern obtained by taking, for each direction in azimuth and elevation, the maximum of the absolute, not peak normalized to its own peak, radiation pattern among the radiation patterns that the AAS can generate for a given operating condition (deployment/coverage scenario)."

The envelope radiation pattern is time static and is a very effective tool for coverage and performances network design while overestimates the field level in an observation point for exposure to EMF assessment since it removes the time-spatial randomness of the gain. Understanding, and then modelling, the effects generated by time-space randomness introduced by AAS is of paramount importance for network design and exposure to EMF purposes.

The specific computational and experimental activities in NextGEM foreseen for Task 3.4 and Task 7.3, are planned to get knowledge from the design and from the in-field experimental activities for the characterization of the randomness introduced by AAS and to derive a metric that matches together coverage, performances, and exposure to EMF at the design stage of the network, thus passing from the "minimization" to "efficient, effective and optimal" design paradigm.

4.5.2 Deterministic models

Deterministic models are based on the solution of Maxwell's equations. The exact solution is generally very complex, and, in many cases, it is almost an impossible task. Consequently, many different approaches have been developed, each of them allowing a specific balance between complexity and accuracy. In the following, the approaches will be divided into two categories: analytical solutions and high-frequency asymptotic solutions.

Analytical solutions: Analytical solutions allow a high-accuracy estimation of the field radiated or scattered by objects. They are often based on modal solutions that are limited to objects whose surfaces can be described by orthogonal curvilinear coordinates. The solutions are usually in the form of infinite series [35], which are often poorly convergent, in particular when the problem involves objects whose dimensions are much larger than the wavelengths. Recently, new approaches to increase convergence, for example the analytical regularization approach [36], in which the low

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[14] GoB AAS: an active antenna that has available a predefined and numerable set of beams; the antenna selects the best beam for the specific service at the specific time.

[15] EBB AAS: an active antenna able to generate a specific beam for the service requirements in the specific time frame with shape, peaks and nulls depending on the users' distribution and interference context.

convergent series is substituted by a fast convergent series in which the critical contributions are contributions are included directly in the basic functions of the series. Analytical solutions often require quite complex special functions, whose numerical evaluation is not straightforward at all. All these limitations exclude the use of this technique in electrically very large problems (i.e., very large compared to the wavelength) involved in indoor and outdoor propagation problems.

High-frequency asymptotic solutions: Among the deterministic methods, the most used in indoor electromagnetic problems are the ones based on high-frequency approximations. These techniques can be used to analyse many problems that are otherwise mathematically intractable. At high frequencies, reflection and refraction (as well as diffraction) are local phenomena that depend on the geometry of the object at the point of diffraction (edge, vertex, curved surface) and the amplitude, phase, and polarization of the incident field at the point of diffraction.

A widely used high-frequency approximation is Geometrical Optics (GO). GO is basically an approximate high-frequency method for the evaluation of reflected and refracted fields. The method is based on the ray concept [37], and is also referred to as ray optics. For reflection and refraction problems, GO approximates the reflected/refracted fields in the specular direction according to Snell's law. For example, in the case of reflection, it considers only the ray associated with an angle of reflection equal to the angle of incidence.

In case of smooth curved surfaces involving electrically large planar surfaces or smooth curved surfaces whose curvature is large compared to the wavelength the ray optic gives reasonably accurate results. The accuracy can be increased considering the effect of multiple reflections/refractions of the rays, at the cost of higher computational complexity. However, in general, the computational burden required by ray optics solutions is compatible with the analysis of large indoor/outdoor scenarios [38].

More accurate estimation can be obtained including the scattering phenomena caused by geometrical objects or discontinuities of the order of the wavelength of the incident signal. These discontinuities are treated as sources of further rays that are called diffracted rays. The diffracted field is determined by a generalization of Fermat's.

Two such techniques are the geometrical theory of diffraction (GTD) and the physical theory of diffraction (PTD). The GTD was proposed by Keller [39]. The theory was successively extended by Kouyoumjian and Pathak [40]. This extension is known as Uniform Theory of Diffraction (UTD) and overcomes some limitations of GTD that determine singular solutions for some particular observation angles. The PTD was introduced by Ufimtsev [41], and provides corrections that are due to diffractions at edges of conducting surfaces introducing "fringe" edge currents in addition to the physical optics surface currents. The PTD (as well as UTD) allows a very accurate estimation of the scattering field and was used for example to optimize the Radar Cross Section of the first stealth bomber.

4.5.3 Numerical models

The basic numerical approaches for electromagnetic simulations are:

Finite-differences-time domain (FDTD): FDTD [42] is a popular computational electromagnetic technique based on solving the Maxwell's equations using finite differences method. FDTD is stable and staggered-grid approach for electric and magnetic fields. One of the main advantages is that is based on the time domain, supports a wide range of frequencies, and the non-linearity of the materials is direct. One of the main limitations is the numerical dispersion error, which occurs when the propagation of a wave in the discrete grid does not precisely follow the dispersion relations of Maxwell's equations, but instead an approximation of them. This error can accumulate over time, especially for high frequencies, which can make long-time simulations and high-frequency propagation challenging to compute accurately with FDTD. To compensate for this error, a fine grid size may be required, which can result in longer computation times.

Another limitation of FDTD is related to the treatment of unbounded domains that are frequently encountered in computational electromagnetics. In such cases, numerically absorbing boundary conditions (ABC) need to be implemented to prevent wave reflections and artificial boundary effects. One popular method for implementing ABC is the Perfectly Matched Layer (PML) [42], which requires a large computational domain surrounding the geometry of interest. This further increases computation time and resources required. Overall, while FDTD is a powerful and widely used method for simulating electromagnetic wave propagation, its limitations should be considered when choosing an appropriate simulation method for a particular application.

Finite Element Method (FEM): FEM [43] is a widely used numerical approach for solving partial differential equations (PDEs). It is particularly well-suited to problems involving complex geometries, as it can easily accommodate a given triangulated geometry. In Electromagnetism, the FEM is typically employed for static or time-harmonic problems with such complex geometries. In addition to handling complex geometries, the FEM is also well-suited for multi-physics problems where electromagnetism is coupled with other physical phenomena such as elasticity, heat transfer, and fluid dynamics. This is because existing software can be reused for these multi-physics simulations.

FEM is typically used on the frequency domain and does not suffer from dispersion error like FDTD. However, if used as part of a time-stepping algorithm, numerical dispersion can still occur. One key feature of the FEM is that it is a volumetric discretization method, which allows it to handle anisotropic materials with ease. However, this can become a limitation when dealing with homogeneous materials as the FEM is not taking advantage of the simplified calculations that come with homogeneous materials. Additionally, the FEM requires a volumetric mesh, which can be more difficult to obtain than a surface mesh required by MoM/BEM. One specific limitation of the volumetric nature of the FEM is in the treatment of the air surrounding a geometry of interest. This air must also be discretized, resulting in large computational domains, similar to FDTD. However, this limitation can be addressed by using a coupled FEM/BEM approach, which is a step closer to the Method of Moments (MoM) or Boundary Element Method (BEM).

Finite Integration Technique (FIT): FIT is a consistent formulation for the discrete representation of Maxwell's equations on spatial grids. It was first proposed in [44] and can be viewed as a generalization of the FDTD method. It is also similar to the finite element method, and shares with them both advantages and disadvantages. By discretizing the integral form of Maxwell's equations on a pair of dual interlaced discretization grids, the finite integration technique generates so-called Maxwell's Grid Equations that guarantee the physical properties of computed fields and lead to a unique solution.

Method of Moments (MoM), or equivalently, Boundary Element Method (BEM): MoM [45] is a type of BEM, which is a frequency-domain method for performing electromagnetic simulations. BEM is typically used to solve partial differential equations (PDEs) in problems where the geometry is the main focus, and is particularly suited for electrostatic and magnetostatic problems, as well as for radiation and scattering problems in electromagnetics. The main advantage of the BEM is that only surfaces need to be meshed, which makes it more computationally efficient than volumetric methods like the FEM. Another advantage of the BEM is that it can handle unbounded domains with radiation boundary conditions without the need for a large volume of air around a given geometry of interest. The BEM also naturally deals with anisotropic materials, as the material properties can be incorporated in the surface integral equations. The main limitation of the BEM is that it is mainly suited for dealing with linear problems and piecewise homogeneous materials. Nonlinear problems can be handled with iterative methods, but they can be computationally expensive. Additionally, the BEM requires solving dense linear algebra systems, which can be challenging for large-scale problems.

As conclusion, the choice of the numerical approach depends on several factors:

- **Geometry**: Depending on the complexity and size of the geometry, different methods may be more suitable. For example, the FEM is typically preferred for complex geometries, while the MoM/BEM may be better suited for simpler geometries.
- **Frequency range**: Different methods have different limitations in terms of the frequency range they can handle. For example, the FDTD suffers from numerical dispersion at high frequencies, while the MoM/BEM is typically limited to low or mid-range frequencies.
- **Material properties**: The method used should be able to handle the electromagnetic properties of the materials used in the simulation. For example, if anisotropic materials are used, the FEM may be preferred due to its ability to handle anisotropic materials, while the MoM/BEM may be limited in this regard.
- **Available computing resources**: Some methods may require large amounts of computational resources, such as memory or processing power, depending on the size and complexity of the simulation. The available computing resources should be considered when choosing a method.
- **Accuracy requirements**: Different methods have different levels of accuracy, and the required level of accuracy should be taken into consideration when choosing a method.
- **Software availability and familiarity**: The availability and familiarity with different software packages can also be a factor in the choice of method, especially in industry or research environments where certain software packages may be preferred or required.

During the NextGEM project we will need to solve electromagnetic problems at high frequencies and with anisotropic materials, and for that, a FEM approach will be the most appropriate. We will use the open-source code ERMES (Electric Regularized Maxwell Equations with Singularities). ERMES is a finite element (FEM) code in frequency domain which implements in C++ a simplified version of the weighted regularized Maxwell equation method [46]. This finite element formulation produces well-conditioned matrices which can be solved efficiently with low-memory consuming iterative methods. Also, thanks to the null kernel of its differential operator, it can operate indistinctly in the quasi-static and the high frequency regimens.

4.6 Application scenarios and social impact of 5G technology

The roll-out of fifth generation cellular network aims to be the essential technological component in the digital transformation of society and the economy in the most advanced countries over the next decade. The new mobile 5G networks make it possible to improve mobile telephony services (higher quality, higher speed, mobile communications in vehicles, remote surgical interventions, etc.). Previous generations of cellular networks, like 3G and 4G, were mainly focused on expanding the capabilities of mobile communications, by enhancing the coverage and reliability of access points. In the case of 4G, significant steps were also taken in the direction of mobile Internet access that support video, packet data and VoIP. In general, hardware enhancements were targeted towards achieving network scalability, service portability and global mobility. The advancements in computing power, the diminishing cost of large storage and the progress in virtualization technologies in the last decade have paved the way for the employment of units of great processing capabilities to support complex applications, across different domains and operating systems. These eventually became the backbone of 5G networks that facilitate the principal requirements of ultra-low latency and high reliability. Additionally, Artificial Intelligence and IoT have also become key enablers of 5G usage in areas that had previously little to do with communication technologies. There are many applications that have benefitted or will benefit in the near future from 5G technologies like the automotive industry, industrial places (e.g., factories) and civilian infrastructure as shown in Figure 28 and detailed below.

- **Automotive industry**: Computers have been embedded in cars for some time now, mainly dealing with the mechanical management, but recent and more advanced models now use computing power to connect to cellular networks in order to i) assist in real-time navigation, ii) contact emergency services, iii) provide situational awareness to the driver.
- **Energy sector**: The digitalization of energy demand management has created opportunities for 5G technologies to enable a more efficient energy management in residential or industrial areas. For example, central management units can automatically take control actions by aggregating and analysing power consumption data from remote sensors, in order for the plant operation or house heating to be more cost-effective (and, by extension, environmentally friendly).
- **Industrial complexes**: In the manufacturing sector, the term "smart factory" means the adoption of 5G technologies and extensive use of AI for the benefit of improved quality of goods, more efficient waste elimination and less error-prone processes in manufacturing plants.
- **Smart Cities**: Communication technologies with 5G capabilities can be used to greatly increase economic development, quality of life and governance in highly urbanized areas. One of the applications that can have an immediate impact is intelligent street lighting. Multiple 5G-capable interconnected sensors, installed in key points within a city, can provide useful insights into a more elaborate and resource-effective public space illumination.

Figure 28: Main applications of 5G technology according to the EC. Source: Europe shaping the 5G Vision. Advanced technologies for Industry[16]

The European Economic and Social Committee has promoted initiatives [47] focused on civil society concerns about environmental and societal impact of 5G technology. Since 2019, the 5G networks have increased significantly in Europe. The European institutions promote several plans and projects related with the 5G technology because it is a priority to promote economic development, automatization, creation of job, digital education and smart economy. The greater speed, coverage and amount of information transmitted by 5G, and the stability it will provide, is expected to improve the population's relationship with the Internet. In many cases, it will also contribute to reducing the 'digital divide' within society, although there are also dangers that certain inequalities will rise. A good and visual description of the 5G impact in all sectors has been published by the European Science Media Hub[17]. The main social impacts of 5G can be summarized in 5 groups, with several subtopics such as i) needs, concerns and problems, ii) applications, iii) impact on democracy iv) health concerns and v) positive impacts, as shown in Figure 29.

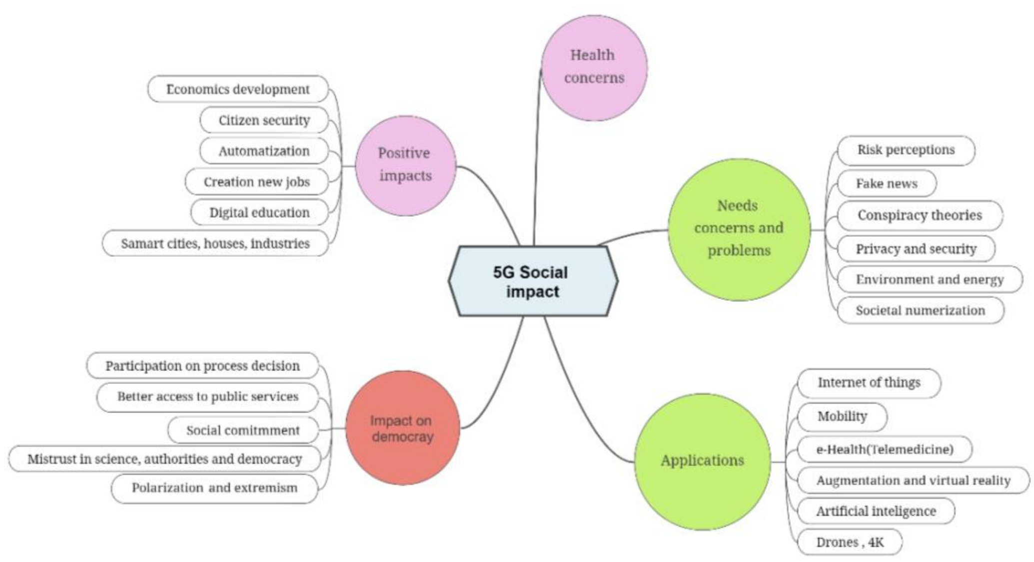

Figure 29: Descriptive summary of the main social impacts of technology 5G. Design: F. Vargas

In its 2016, 5G Action Plan, the Commission called for a 5G coverage of all urban areas and along main transport paths by 2025 and, in March 2021, for a full coverage by 2030. As of the end of 2020, 23 Member States had launched commercial 5G services and had achieved the intermediary objective of having at least one major city with access to

[16] https://ati.ec.europa.eu/news/europe-shaping-5g-vision

[17] https://map.sciencemediahub.eu/5g#m=4/410.26393/281.46965.

such services. In 2021, the total cost of 5G deployment across all EU Member States until 2025 has been estimated to range between €281 billion and €391 billion, split equally between building new 5G infrastructure and upgrading fixed infrastructure to gigabit speeds. 5G is expected to add up to €1 trillion to the European GDP between 2021 and 2025, with the potential to create or transform up to 20 million jobs across all sectors of the economy. However, the European Court of Auditors has observed that delays are putting at risk the achievement of the EU's objectives for 5G deployment and that further efforts are necessary to address security issues [48].

To achieve this goal, the Commission monitors the level of 5G deployment in the Member States through the 5G Observatory[18]. It provides information on 5G deployments and on Member States' 5G strategies on a quarterly basis. The Quarterly Report 14, January 2022 of the European 5G Observatory provides an overview of recent 5G developments and trends at EU27 level and contextualizes the main findings in light of international developments [49]. All these efforts warrant the responsibility to evaluate the social impact as well of 5G about need, concerns and problems related with risk perceptions and acceptance of exposure to EMF.

The adoption of new technology (5G) always implies rejection by some population groups as happened with the previous ones (2G, 3G and 4G). The most important potential negative social impact is health risks. Some people have perceived the electromagnetic fields emitted by 5G networks as a health hazard and have expressed concern about their social impact. In some countries (Korea, UK, Switzerland, France) protests and demonstrations against the deployment of 5G bases stations have occurred [50].

It is not possible at this time to know whether individual or collective exposure will increase as it will depend on the 5G deployment process and the cessation of 3G activity. The use of 3G and 4G technologies meant a significant reduction to the average peak power emission of cell phones. These technologies emit between 100-200 times less energy than GSM technology and, at the same time changed telecommunications usage habits towards written messages, social networks, music, games, etc. The impact of 5G on user habits from the new applications and possibilities that this new technology will generate is unknown. To assess whether 5G has any effect on health we should know the level of exposure of the population. However, objective and exhaustive measurement of real exposure to the new 5G systems will not be possible until this new technology is widely deployed.

Despite this, there is a study sponsored by the European Commission, regarding 5G which shows that 39% of participants believe that 5G is safe for health, while 21% believe that 5G is harmful[19] and 40% have doubts[20]. Another study was conducted by IPSOS in 23 European countries in 2020 [51], in a sample n=7350 adults, 18-65 years old. In terms of attitudes, 54% Europeans are "positive" about 5G, while 36% declare themselves "neutral". In general, Europeans think 5G will be useful and important for innovation, business and development.

As we have seen there are many possible social impacts to be addressed. The identification and better understanding about the main factors that determine these attitudes toward 5G is essential to promote public health policies on 5G based on the best evidence and citizens' rights.

[18] https://5gobservatory.eu/

[19] https://www.eesc.europa.eu/en/news-media/news/5g-networks-39-europeans-say-its-safe-21-think-its-harmful

[20] https://www2.deloitte.com/us/en/insights/industry/technology/technology-media-and-telecom-predictions/2021/5g-radiation-dangers-health-concerns.html

5 Antennas for mobile systems

The demand for higher mobile data rates is increasing exponentially due to the emergence of many advanced applications such as IoT, wearable devices, broadcasting, and smart cities. This enforces wireless communication systems to upgrade their capacity and performance. The most convenient solution to enhance the capacity and the data rate in wireless communication is to increase the bandwidth which is usually fractionally related to the carrier frequency [52]. The bandwidth increases up to 5G generations is limited and expensive. As mentioned in previous sections, in the later stages of 4G network deployments (LTE-Advanced), MIMO antenna systems were introduced to make use of multiple signal propagation paths (i.e., spatial multiplexing) in order to boost the maximum data rate [53]. Currently MIMO antenna architecture is widely applied in 5G wireless communication systems. In massive-MIMO technology large numbers of antennas are required both at the base stations (up to thousands of antennas) and mobile devices (up to tens of antennas) [54].

Antenna design for mobile handheld applications is more sophisticated and requires more than the antenna aspects alone. From a holistic perspective the major design factors are antenna design, antenna integration, biological effects and EMF exposure, and compatibility with existing technologies as shown in Figure 30.

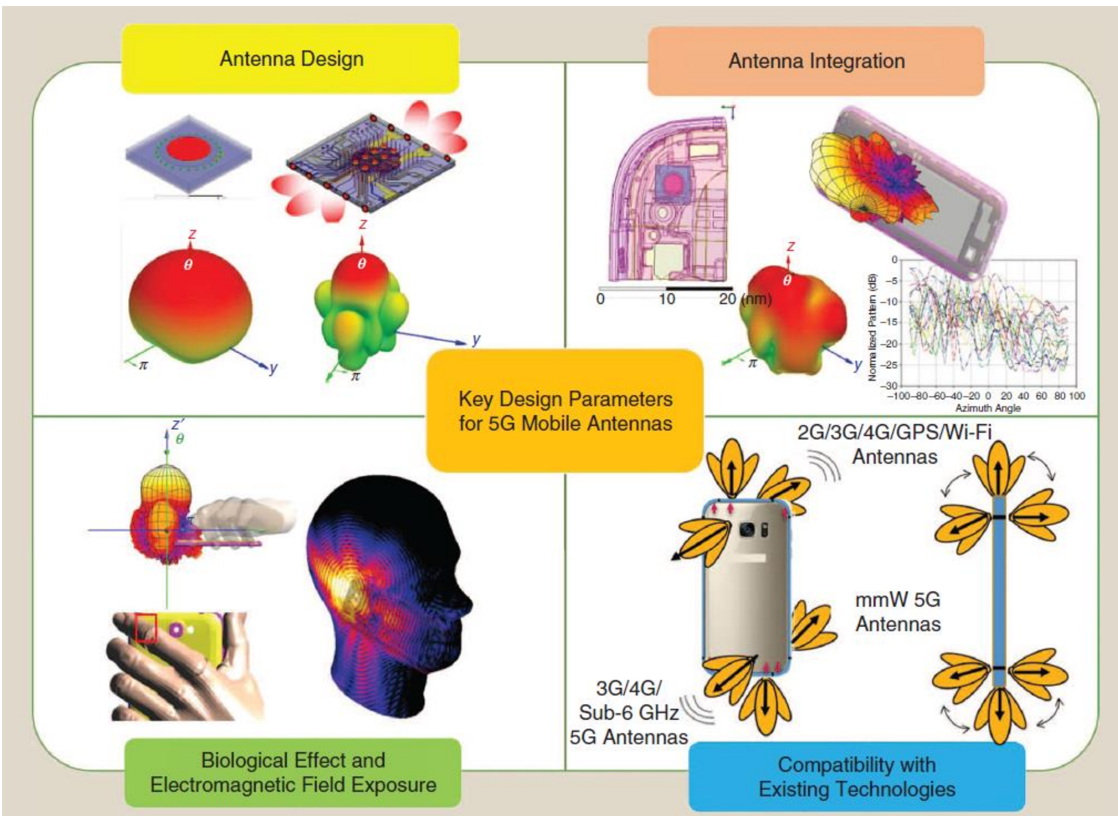

Figure 30: Key design parameters for 5G mobile antennas [52]

At mmWave frequencies (in FR2) the path loss is significantly larger than at sub-6GHz frequencies (FR1) [55], [56]. However, the major challenge is the limited available space in mobile devices. Current mobile devices are operating at multiple frequency bands (i.e., 4G, 5G, WiFi, and GPS) and the available space is congested. Hence, the need for multiband and more compact antennas is increasing. A generalized mobile antenna and hardware configuration for a modern smartphone is shown in Figure 31. The modern smartphones are equipped with 8×8 MIMO, existing LTE-advanced radio architectures. Wi-Fi, and Bluetooth. As an example, an integrated 5G smartphone antenna design in FR1 band is shown in Figure 32.

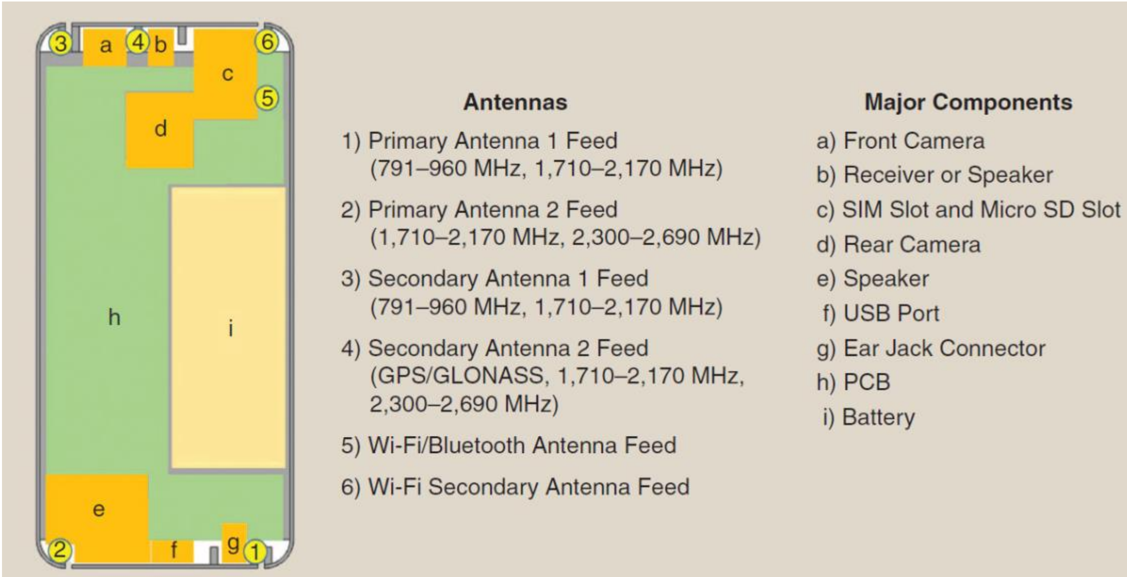

Figure 31: A general mobile antenna and hardware configuration [52]

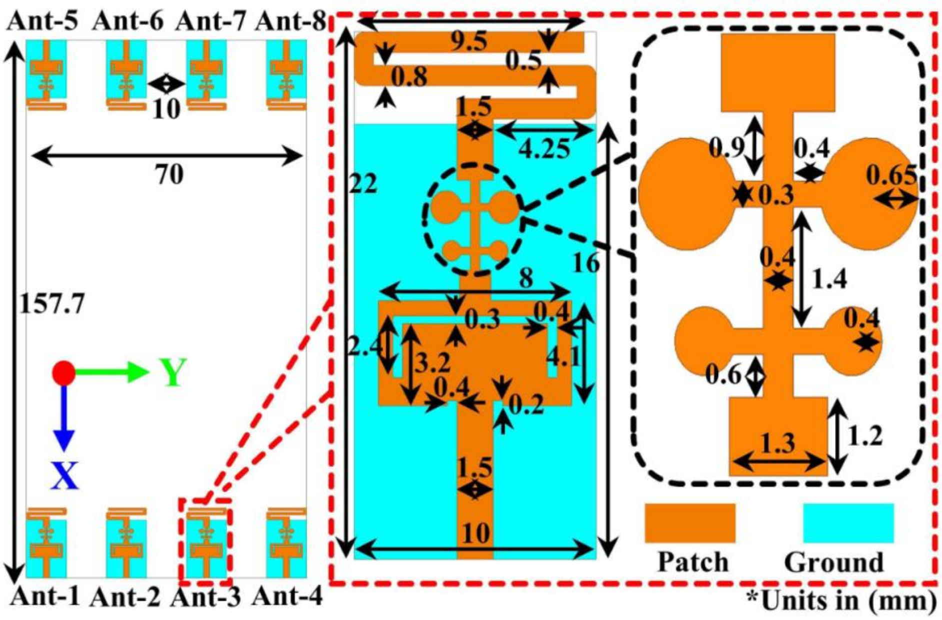

Figure 32: Structure of MIMO antenna that consists of 8 elements [57]

In order to mitigate the path loss, highly directive antennas are needed. To that end, beamforming technology is usually used to maximize the antenna array gain [58] as visualized in Figure 33. Furthermore, the direction of the beam with respect to base station is not consistent which makes it challenging to design antennas with full beam coverage in order to allow for all directions of the beam with respect to the base station. Beamforming on mobile phone platforms must be achieved with full consideration of realistic design constraints such as battery life, user hand posture, safety, and bill-of material costs [55]. However, compared to microwave frequencies, in mmWave 5G MIMO antennas the current distribution will become localized, and the effect of the entire cellular phone ground plane on the radiation characteristics will be relatively restricted.

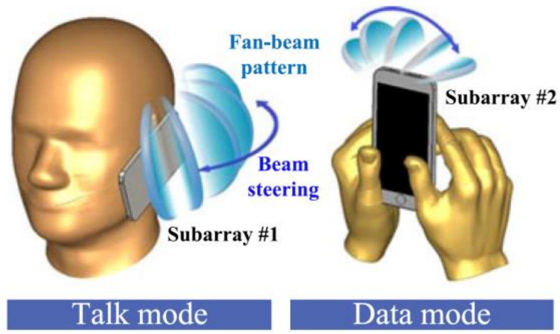

Figure 33: Concept of beam-steering characteristics of the designed 5G mobile handset antenna for a dual-mode scenario [59]

In addition, all wireless devices are subject to compliance with regulatory requirements and standards concerning human exposure to EMF. Currently, RF exposure-limit guidelines established by ICNIRP [60] and the FCC [61] have been adopted by most governments worldwide for existing cellular networks. For sub-6-GHz 5G mobile antennas, existing RF exposure guidelines, represented by the specific absorption rate (SAR), can be used to minimize local tissue heating and related thermal hazards. The penetration dept is inversely related to the frequency, hence at higher frequencies the penetration will be limited on the skin (especially for mmWaves, FR2). For mmWaves the beam steering and high directivity demands will cause higher SAR levels on the users' head in an active talk mode, and hence the current SAR regulation limits will be exceeded. Since power density is measured in free space, without the presence of the body or a body model, it is of interest to quantify the impact on energy absorption from coupling between the antenna and the exposed body [62]. For this reason, when designing the antennas at mmWaves the energy absorption mechanisms including the effects of body-antenna interactions should be analyzed.

The SAR can be related to the electric field at a point in the human body by

$$SAR = \frac{\sigma E^2}{\rho} \quad (8)$$

in which σ is the conductivity of the tissue (S/m), ρ is the density of the tissue (kg/m³), and E is the root mean square value of the electric field strength in tissue (V/m). The designed (MIMO) antenna in a 5G user terminal (smartphone) should be validated for the deplorability in view of SAR analysis. For instance, an eight-element MIMO antenna held against ear is analysed in active mode (shown in Figure 34).

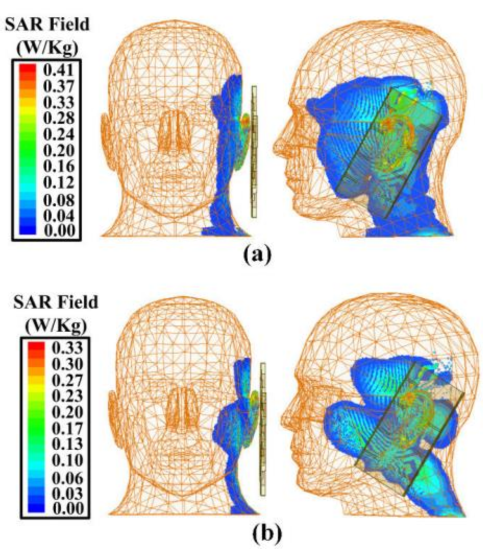

Figure 34. SAR distribution (a) at 3.9 GHz (b) at 5.8 GHz

6 6G Technology

New generations of mobile radio systems have emerged about every ten years. While 5G, whose first rollouts were envisaged to start around year 2020, is currently in its initial/partial deployment, research activities have already started on the new beyond 5G/6G system, aiming at a fully standardized set of specifications around year 2030.

It is in the operators' preview (see [64]) that, even though it is still too early to clearly identify the complete set of new technologies for 6G, 6G will need to comply with, among others, fundamental requirements on sustainability and human-centricity as a *trustworthy* answer to certain customers' needs.

From such a point of view, the EMF exposure topic is a key element to be considered in developing the next generation of mobile communication system. In that context, it is envisaged that the emerging technology of Reconfigurable Intelligent Surfaces (RIS) could be really promising in addressing EMF exposure issues.

In fact, RISs could be used as reconfigurable mirrors to provide UEs with the needed coverage, so that:

- there is no strong need for UEs to be pointed to by the BS main radiated beam
- there is limited need or no need at all to add new BSs.

These aspects have been investigated by WP6 within the RISE-6G EU-funded project, which introduced the specific concept of the *EMF Exposure Utility* (see [65] for details).

In terms of frequency band allocations for 6G, it seems that it is still too early for the identification of possible new bands. In this context, some preliminary assessments need to be carried out on the new 6G radio access technologies (e.g., in terms of technical capabilities, technology requirements and spectrum needs), in accordance with the ITU-R IMT-2030 process (see Figure 35) that will lead first to agree on the necessary studies on possible new frequency bands for 6G and then to a new set of specifications and proposals for candidate new frequency bands.

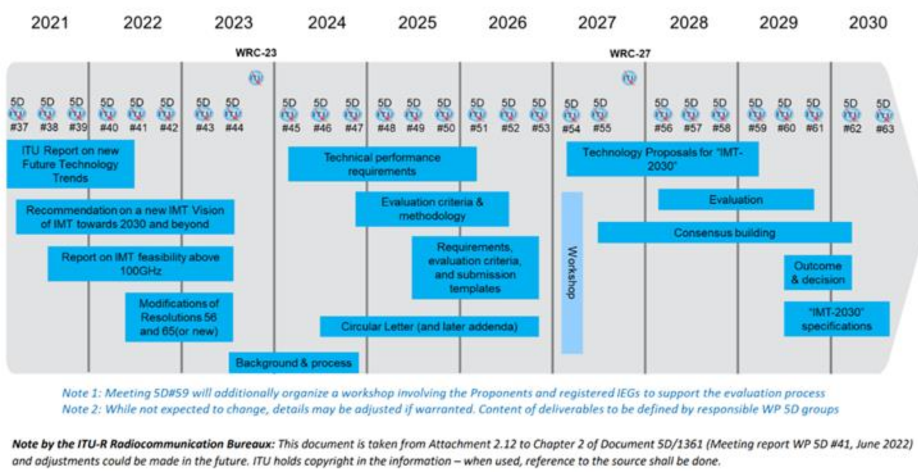

Figure 35: Overview timeline for IMT towards the year 2030 and beyond (source: ITU-R WP5D, [66])

The next World Radio Conferences (WRC) edition is due in 2023. By then, new study items might be proposed to start investigations in view of future frequency allocations for IMT-2030. Activities have already started at the regional level. For instance, in Europe the current CEPT view is that, to enable the full range of capabilities that are envisaged, additional spectrum should be studied and specific bands from within the 7.125-24 GHz and 92-275 GHz ranges should be considered, where the former range is considered as essential and the latter as complementary.

7 Conclusion

This deliverable presented an overview of mobile technologies, with a particular focus on the fifth generation 5G, describing the evolution over the years from a technical and social point of view. In each section, the main features of the signal standard of the different generations were given, as well as the basic characteristics of base station antennas.

Specifically, section 2 was devoted to 2G and 3G which represented a big step forward with respect to 1G, using digital modulation technology. The fourth generation of mobile communications 4G, presented in section 3, introduced key technologies making it the direct predecessor of 5G systems. 5G was thoroughly analysed in section 4 with a detailed description of the standard, as well as of the active antenna systems equipping 5G base stations, thus contributing to a completely new concept in which payload is delivered where necessary, when required and for the time it is required. A brief overview of the antennas for mobile devices and a reference to the forthcoming 6G generation completed the document.

The comparison of the different technologies was given for a better understanding of the advancements of the propagation models and of the measurement techniques over the generations, taking advantage of the progress in the knowledge and gaining a deeper insight in the related problems. As it turns out, the new exposure patterns introduced by 5G pose formidable challenges in the development of new techniques for monitoring and assessment of EMF exposure, which is one of the objectives of NextGEM project.

The aim of NextGEM's WP2 is to define the requirements and specifications for the activities to be carried out in the succeeding Work Packages. Consequently, the current document provides the technical background for the design of tools, technologies and experiments to be developed within WP3 and WP4 and later validated in WP7 utilizing real scenarios and case studies.

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