Why 5G?

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Since the 1980s/1990s, a new "G technology" has been proposed every 10 years (2G, 3G, 4G, 5G and soon 6G already at the research stage) And why 5G if we already have 4G? These natural questions are difficult to answer.

This article proposes a first understanding of the key technologies for 5G and their impacts on the environment, climate, health and social life. ***It is based on the work of CEA-Leti Systems Division telecom team (see "Learn more")***.

1. A brief history of telecommunications techniques

We refer the reader to Wikipedia to discover all the details of the history of telecommunications.

We will therefore limit ourselves here to a few comments concerning the main milestones in the chronology of events, and we will quote a few extracts from this reference.

Everything starts with the smoke signals used by the peoples of North and South America, and with the drums in Africa, in particular. In the Middle Ages, I quote "towers placed on the summits allowed the transmission of orders and strategic information, but the information was limited to the equivalent of a modern *bit* like: the enemy is in sight".

In 1782, the Cistercian monk Dom Gauthey invented the acoustic pipes and sent a memoir of his invention to the Academy of Sciences.

In the important dates we can also note, I quote "in 1794, in France, the French engineer Claude Chappe realizes the first system of telegraphy the development of electricity gave birth to the era of the **electric telephone**. The invention of the first acoustic telephone, or string telephone [1], was made by Robert Hooke in the 1660s. The "classical" telephone was invented independently by Alexander Bell and Elisha Gray in 1876, but it was Antonio Meucci who designed the first device that could transmit voice over an electric line in 1849.

From 1880, we witness the beginning of the operation of the telephone network, attached to the Post Office, which will give birth to the Post Office Telegraphs and Telephones (PTT).

The first radio transmission will take place between Canada and England, in 1901, thanks to Guglielmo Marconi this earned him the Nobel Prize in 1909.

The history of telecommunications reached a new milestone in 1941 with the introduction of the walkie-talkie, a truly portable radio transceiver for establishing radio links over short distances, but already the era of miniaturization was announced by the discovery of transistor [2] in 1947 which will replace the electronic tube".

But it was in 1945 that the history of modern telecommunications began, with the first heavy and bulky non-cellular **analog cell phones**.

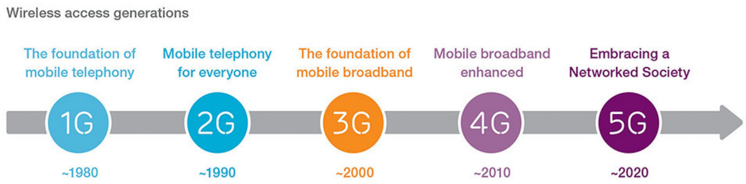

Figure 1. The evolution of telecommunications from 1G, to 5G. [Source: © Ericsson Mobility Report - CC BY-NC-ND 2.0]

This was the beginning of the era of mobile telecommunications and their successive generations, up to the 5G of today and 6G tomorrow (Figure 1).

2. So what is 5G?

"5G" is **the fifth generation of mobile networks,** succeeding 2G, 3G and 4G technologies. 2G enabled the development of cell phones (voice calls and SMS), 3G enabled the development of smartphones (internet connection, access to applications, development of social networks via cell phones), 4G brought higher speeds and easy access to video formats via our smartphones. The 5G should allow to combine broadband and mobility. In an optimal scenario, the use of new frequency bands will allow a 10-fold increase in throughput and a 10-fold decrease in transmission time [4].

Overall, until now, fixed telecommunication networks provided power and reliability, while mobile, i.e. wireless, networks accompanied freedom of movement. The deployment of 5G relies on a new radio interface (the *New Radio-NR*) capable of operating efficiently on new frequency bands. It will be based on three frequency bands, with different physical properties, according to the frequency frieze shown in Figure 2:

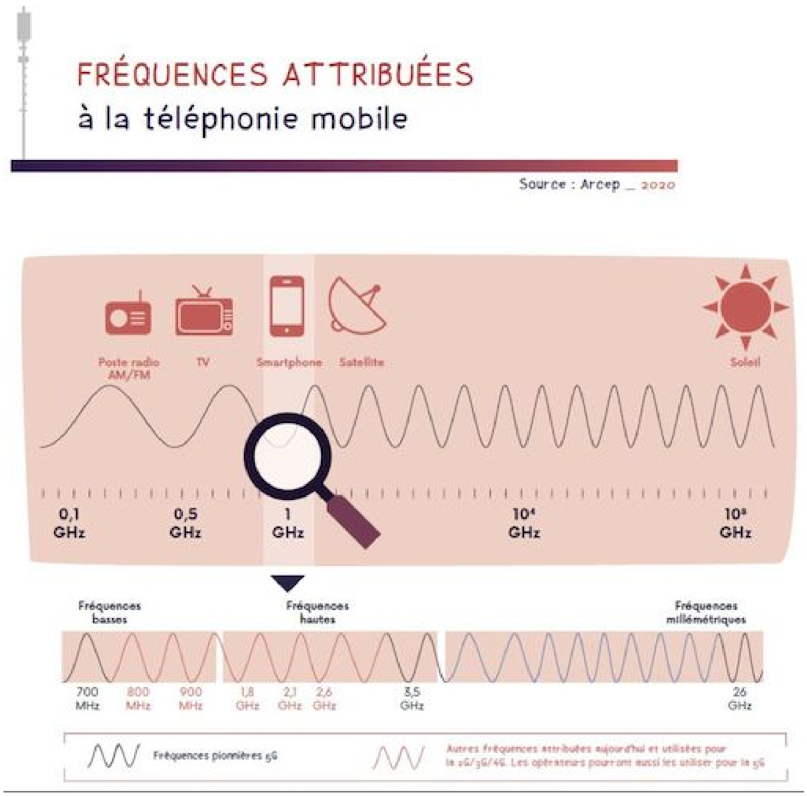

Figure 2. Frequency frieze. [Source: © [ARCEP](), 2020 - Detailed version on ANFR website: https: [//www.anfr.fr/gestion-des-frequences-sites/tnrbf/frise-interactive/]()]

The 700MHz band, already allocated to operators since the end of 2015 for the deployment of 4G. This frequency band offers very good coverage but bandwidths in the range of 10-20 MHz.

The 3400-3800 MHz band (3.4-3.8 GHz). It offers a good tradeoff between coverage and speed. It is identified in Europe as the "core 5G" band. It allows the deployment of spatial multiplexing technology.

The 26-28 and 40 GHz bands, the "millimeter" band of extremely high frequency (EHF), used until now for satellite or infrastructure links. The bandwidths offered vary from 100 to 400 MHz. The targeted data rates are very important in small coverage areas.

3. Technological aspects: interest of 5G compared to 4G

3.1. Ultra high speed

5G allows to **exchange a lot of data in a very short time and with a high reliability**.
Without being able to predict all the applications, the March 2020 confinement has shown the interest of having a powerful and reliable network to maintain the exchanges: implementation of telecommuting, virtual classes, medical teleconsultations....
The deployment of 5G facilitates the use of these collaborative platforms and improves service.

3.2. Massive and simultaneous connections

Many devices (up to several million per square kilometer) can be connected **without loss of throughput or service collapse**. This feature can for example facilitate the massive development of IoT (Internet of Things [5]) in daily life, with the key to personal service, smarter and more economical management of energy networks (e.g., only turning on streetlights or shop windows when a passer-by comes by) and the digitization of industries (e.g., production lines that can be reconfigured more easily).

3.3. Network virtualization

5G will rely [6] on a virtualized network. Virtualization relies on software to simulate hardware functionality and create a virtual system. Thus, the core of this network [7], i.e. the set of transmission and communication media in which the most important part of the traffic is processed, is no longer carried by physical equipment (as in the case of 4G) but is taken over by software. This virtualization makes it possible to decentralize computing capabilities as close as possible to the usage (*edge computing*). It also allows, on the same infrastructure, to allocate different bandwidth performance depending on the usage (*network slicing* [8]). For example: low latency for autonomous vehicles or remote surgery, higher throughput for virtual or augmented reality, massive connections for IoT and sensors.

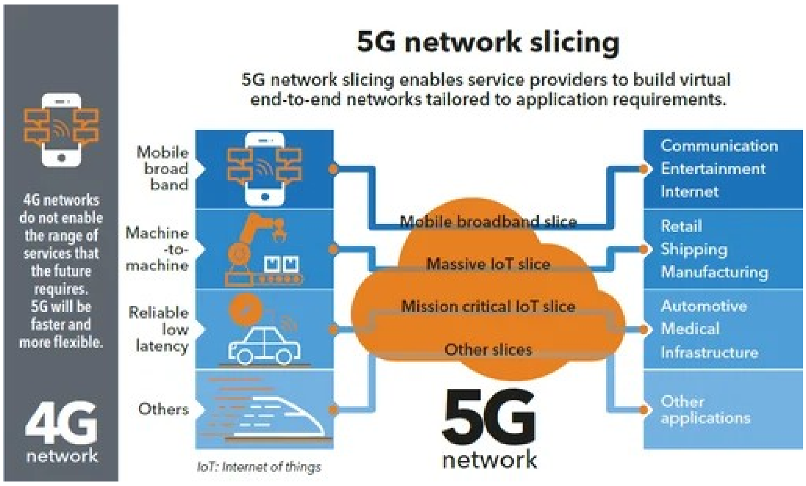

Figure 3. Network slicing. [Source: © ITU News - What Is 5G Network Slicing?]Thanks to Network Slicing, a single infrastructure can be reprogrammed for several uses, which allows to mutualize the deployment costs of the future 5G network.

3.4. Active antennas

With previous technologies, the network sends the signal indiscriminately over a large area in all directions (umbrella broadcasting); the active antennas deployed with 5G allow to **restrict the signal to the user's area of presence only**. They also allow users to be spatially orthogonal and thus increase capacity.

3.5. Energy optimization

5G has introduced mechanisms to put the infrastructure on standby to **reduce energy consumption in off-peak periods** (night or sparsely populated areas).

4. 5G and climate issues

The debate on 5G is particularly concerned with **the impact of digital technology on the environment**. This issue is much broader than the 5G issue, which is only a pipe, but it overlaps.

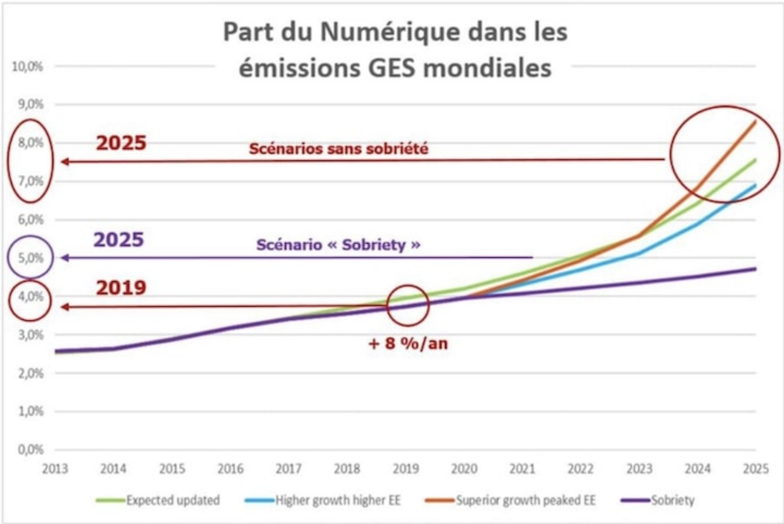

Figure 4. 2013-2025 evolution of digital's share of global GHG emissions. [Source: "[Lean ICT - Towards Digital Sobriety](#) " - © [The Shift Project](#), 2018]

In terms of greenhouse gas (GHG) emissions, **the digital sector has now overtaken the aviation sector** (4%), Figure 4, and this share is growing. There is much to be done in terms of thinking about usage. The French Senate has made recommendations in this area; Arcep (the French regulatory authority for electronic communications and posts) has published a note on the subject in 2019.

5G offers better energy efficiency than 4G for the same amount of data exchanged. But 5G will in turn open up new fields of application, and traffic is expected to increase even more. This is known as **the rebound effect** [9].

No one can predict in advance all the applications that will emerge from 5G. Technology creates opportunities; society develops usages. At the beginning of the cell phone, the SMS, not very ergonomic, had been thought of as a secondary gadget. To the great surprise of its designers, it actually met a user need and developed massively.

Some of these uses will make it possible to erase or reduce the GHG emitted in other sectors. For example, Home working, which was massively tested during the COVID 19 pandemic, prevents many people from rushing on the roads during rush hour and getting stuck in traffic. **Some vital services will be accessible remotely** and will allow territories to be opened up (telemedicine with remote control of robots for care and surgery).

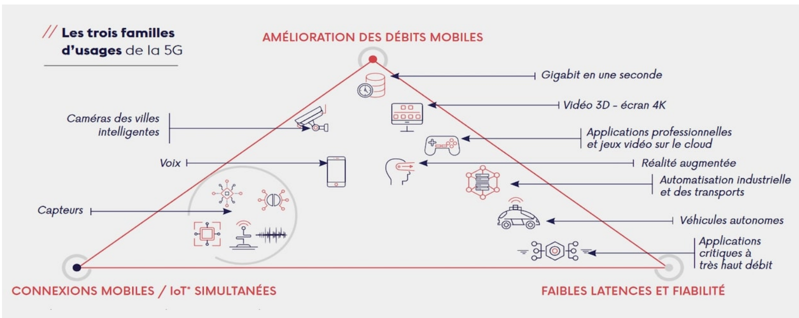

Figure 5. The uses of 5G. [Source: © [ARCEP](#) - [5G network: deployment in France, speed, coverage, compatible smartphones](#)]

In factories, thanks in particular to IoT, production lines should be more flexible, more easily reconfigurable, more modular, with less obsolescence... But this will obviously not be the case for all uses. This question of use is a crucial political and societal issue that goes beyond the technician, engineer or researcher working on these technologies, who are only one link in society (Figure 5).

Is it necessary to increase user awareness in order to spread good practices? Today, a car driver knows that driving at high speed leads to higher consumption. But who knows that **watching a movie on a 4G cell phone is 10 times more energy consuming than watching the same movie on a PC, after having downloaded it via fiber**? This extra consumption is absolutely invisible today for the consumer, especially since it is not reflected in his bill.

Should data consumption be further regulated, as recommended by the French Senate, which advocated the end of unlimited packages in a report released in June on the impact of digital technology?

Should we push for the eco-design of digital services? This is what Arcep [10] recommends, for example, noting that during the containment period, content publishers made efforts to lighten their content. Thanks to this effort, the networks were able to survive despite the massive use of teleworking. Arcep believes that there is a lot to be done to fight against *bloatware*: when traffic is not constrained, software tends to develop accessory but heavy functionalities. However, lightened versions with quite similar performances are sometimes developed for countries with lower speeds. It should also be noted that the telecommunications industry has always ensured backward compatibility between the "G" (2G, 3G, 4G and 5G). This leased compatibility also comes at the cost of system aggregation. This model may need to be rethought.

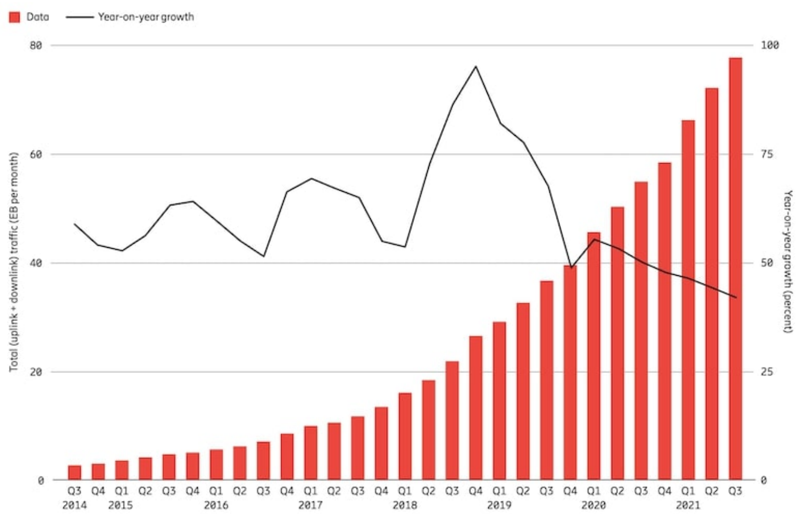

Figure 6. Measuring the evolution of data traffic since 2014. [Source: © Ericsson Mobility report 2021]

Over the long term, traffic growth is driven by a combination of an increase in the number of smartphones, an increase in the number of users, and an increase in the average volume per subscription, fueled primarily by increased consumption of video content. Figure 5 shows **the evolution of total global monthly network data and voice traffic** from Q1 2014 to Q1 2021, as well as the year-over-year percentage change for data traffic on mobile networks [11]. Total monthly data traffic on mobile networks in Q1 2021 exceeded 66 exabytes [12] (10^{18} bytes).

5. 5G and Health

At the Round Table on the health and environmental impacts of 5G, organized by the French Senate Committee on Spatial Planning and Sustainable Development11 on June 29, 2020, Anses (French Agency for Food, Environmental and Occupational Health Safety) explained that there are numerous publications and data accumulated over the past 20 years in the frequency bands that run up to 2.5GHz, i.e., up to Wifi and 2G, 3G and 4G.

Figure 7. Radio Frequency and health, where do we stand? [Source: © Leon Brooks, Public domain, - Tim Parkinson, CC BY 2.0, via Wikimedia Commons]

The health effects of the 700MHz band, which has already been allocated to operators since the end of 2015 for the deployment of 4G but also used for 5G, are therefore well controlled and, the exposure thresholds set accordingly.

The Anses also explains **that between 6 and 10 GHz, electromagnetic waves penetrate less and less deeply into the body**. From these frequencies, the interaction with the living is therefore superficial. The 26 GHz band, deployed for 5G later, especially for connected objects, is the subject of numerous publications that show **an absorption of waves limited to the surface of the skin** (on a thickness of a hundred microns).

On the 3.5 GHz frequency band (core band of 5G), the Anses believes it lacks information at this stage. It is not unreasonable, according to her, to transpose the mechanisms observed at 2.5 GHz, but it reserves its opinion to the release of the report. This extrapolation approach has been adopted by the various authorities that have expressed their opinion on the subject in different countries. The French Telecom Federation (FFT) points out that in Germany, Austria, Finland, Norway, Denmark, Ireland and the Netherlands, **the authorities considered that there was no reason to question the analyses carried out in the context of 4G**, and the WHO and the European Commission have done the same. The same exposure thresholds have been maintained [13].

In terms of exposure measurement, however, 5G changes one important point compared to previous generations. In 4G, the network sends the signal indiscriminately over a large area (umbrella broadcasting); **in 5G, the antennas are called active and the signal broadcasting is restricted to the area where the communicating smartphone is present** (see §3.4 Active antennas).

The antennas will therefore transmit towards the user if and only if he uses his cell phone. This point modifies the exposure scenarios which are therefore variable from one individual to another depending on the use he has of his smartphone. The debate is far from over and scientific studies will have to be conducted. In conclusion, **it is important to remember that our exposure is mainly due to our use of the cell phone** (more precisely, to the electromagnetic field it emits) and to our data consumption.

6. Theory of digital communications, the keys to understand 5G

In the field of telecommunications, it is necessary to specify the way two or more entities communicate. Regulators have chosen the domain of frequencies to organize communications.

In the absence of obstacles, electromagnetic waves propagate in space from the antenna and attenuate more quickly as the frequency is large.

The receiver, like any electronic device, is subject to noise due to the thermal agitation of electrons, which is proportional to the ambient temperature. To characterize the noise in relation to the signal power, the signal-to-noise ratio (SNR) is commonly used.

The **capacity of a channel** (also called Shannon limit) was introduced by Claude Shannon in 1948 [14] and remains a fundamental result of information theory. It represents the theoretical maximum capacity of a communication.

Since reliable transmissions are limited by Shannon's capacity, approaching it, has been the subject of countless research efforts. Reaching the limit rate for a given bandwidth and signal-to-noise ratio (SNR), means that the resource is used in the most efficient way possible.

The energy efficiency of a transmission system is defined as the amount of information bits (transmitted and received) per unit of energy consumption of the modules used for that same transmission and reception. This applies to any entity in a telecommunication system, from the user to the entire network. The unit is the bit/Joule.

The spectral efficiency, expressed in bits per second and per Hertz, characterizes the modulation technique of the wave that allows the transmission of information bits in the allowed frequency band [15]. Transmitting with high spectral efficiency implies a high signal-to-noise ratio, and therefore a high transmission power. This is done at the expense of energy efficiency. Thus, the optimum given by information theory is approximated by **a trade-off between spectral efficiency and energy efficiency**.

Since reliable transmissions are limited by capacity, approaching it has been the subject of countless research efforts. Achieving the rate limit for a given bandwidth and SNR means that the resource is used in the most efficient way possible. According to information theory there is **always a trade-off between spectral efficiency and energy efficiency**.

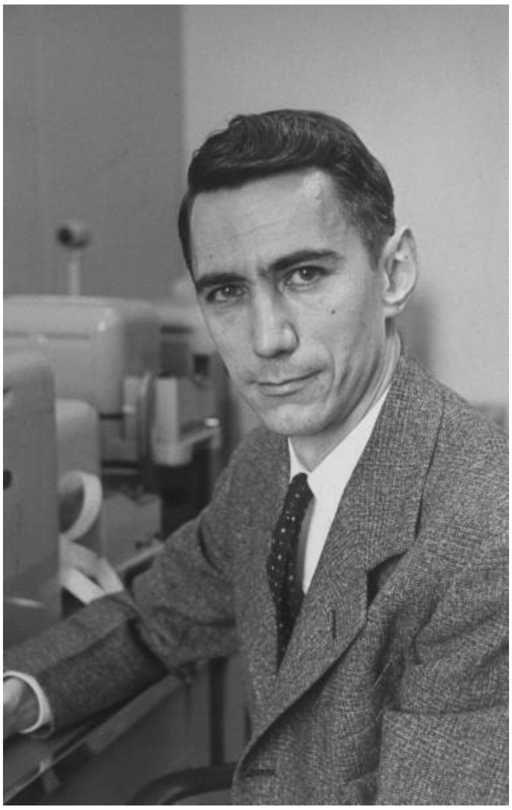

Figure 8. Claude Shannon, father of information theory. [Source: © Life Magazine, Alfred Eisenstaedt, 1951 - https://journals.openedition.org/bibnum/568]

A reliable transmission with high energy efficiency will necessarily result in low spectral efficiency, and by comparison, a system with higher spectral efficiency must consume more energy to transmit the same amount of bits with the same energy efficiency.

Faced with the exponential increase in digital consumption, a new post 4G standard has been studied to meet the needs of the next twenty years. Modern communication systems (4G) are already working at the limit of the capacity defined by the theory of information, **two options have been retained for 5G**.

As the channel capacity varies linearly with the bandwidth, allocating new spectrum simply increases the network capacity. The bands at 3.5GHz and between 20-40 GHz (called millimeter bands in reference to the order of magnitude of the wavelength) have been reserved for 5G. As discussed earlier, as free space attenuation increases with frequency, the price to pay is more difficult propagation. This motivates **the use of antennas that concentrate the energy or to increase the number of access points**. This last solution, when pushed to the extreme, allows to reduce the level of transmission power as well as the exposure to electromagnetic waves which mainly come from the mobile in transmission mode - this is the extension of *small cells* (small cells introduced as of 4G). Nevertheless, the multiplication of access points has a cost for operators, which is currently slowing down deployments.

As spectrum is scarce and expensive, an alternative has been introduced by the 5G standard: spatial multiplexing, which consists in being able to **have several users communicate at the same time in space, without them interfering**. This technology is based on the progress of the integration of digital processing and by the fact that increasing the frequencies allows to dimension small antennas that can be put in networks

7. Spatial multiplexing: the key technology for 5G

Spatial multiplexing is based on the **use** of *massive MIMO* **antenna arrays**.

The principle lies in the **"orthogonalization"** (see focus at the end of the article) in space of signals from different users. This means that two users can communicate at the same time without interfering with each other by processing the information. **On the scale of the human body, our brain can decode two simultaneous conversations thanks to our two ears and thanks to processing.**

By playing with the phases and amplitudes of the signals on each antenna, we can find a set of parameters that will make the signal of a user of interest combine constructively (stronger signal) in one direction and combine destructively (resulting signal reduced to 0) in the direction of the other users.

As an example, Figure 9 shows the power distribution in the orthogonal signal space for four users. The access point with 400 antennas is placed in the center. For all configurations, the received power in the direction of interest (blue square) is maximum (-60dB). On the other hand, in the direction of the other users, the received power is zero.

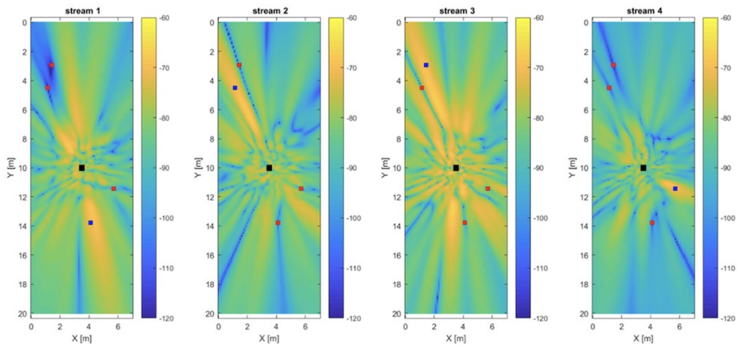

Figure 9. Example of power distribution in space of different users using spatial multiplexing technology. The black square represents the position of the antenna array, the blue square the user receiving the signal and the red squares the users to be "orthogonalized". [Source: © CEA / LETI]

In this example, the 4 users can exchange information in the same spectrum simultaneously without interfering. The capacity is multiplied by four.

In theory, one can multiplex N users with an array of N antennas and N digital transmission channels. The complexity of such a system is much higher than in previous generations.

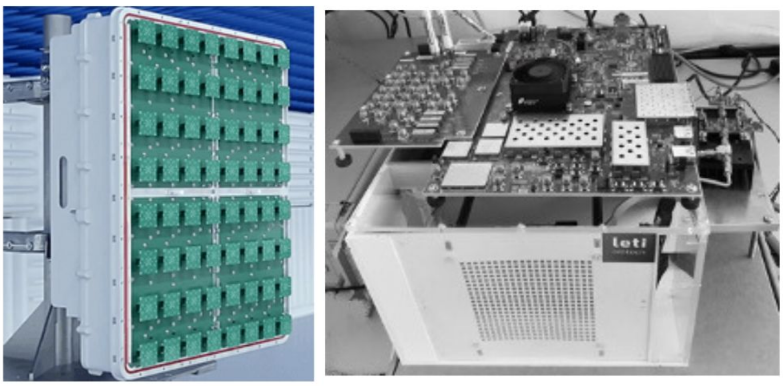

Figure 10. Left: Nokia 64-antenna system - Frequency: 2496 to 2690 MHz (3GPP Band 41) - Right: Cea/Leti 400-element antenna system prototype - Frequency 25 to 32GHz [Source: © CEA / LETI]

Note that the current state of the art of 5G systems is N=64 antennas for frequencies around 3.5 GHz, and about a hundred for millimeter bands. Figure 10 below shows examples of antenna systems designed and developed by Nokia and Cea/leti including a demonstrator with 400 antenna elements.

8. Messages to remember

5G relies on a new radio interface (the *New Radio-NR*) capable of operating efficiently on new frequency bands. It is based on three frequency bands, with different and complementary physical properties.

5G combines ultra-high throughput with simultaneous massive connections, notably thanks to active antennas that limit the signal to the user's area.

For a given traffic, the energy efficiency of 5G leads to much lower greenhouse gas emissions than previous generations . But the expected large increase in traffic could offset this positive effect on global warming.

Spatial multiplexing, which relies on the use of large number of antenna arrays, allows multiple users to communicate at the same time without interfering with each other.

Notes and references

Cover image. [Source: Pixabay]

This article was written with the participation of Christophe Delaveaud, Eric Mercier, Camille Giroud, Camille Decroix, Roland Blanpain, based on the work of the Telecoms team of the CEA/Leti Systems Division.

[1] "The "string telephone" or yogurtophone, is an acoustic telephony device (not relying on an electrical system) made of two cans, cardboard cups or similar shaped objects connected by a wire." (https://fr.wikipedia.org/wiki/T%C3%A9l%C3%A9phone_%C3%A0_ficelle)

[2] "A transistor is a semiconductor device with three active electrodes, which controls a current or voltage on the output electrode*(the collector* for a bipolar transistor and *the drain* for a field effect transistor) through an input electrode*(the base* for a bipolar transistor and *the gate* for a field effect transistor)" (https://fr.wikipedia.org/wiki/Transistor)

[3] "Handover refers to the set of operations implemented to allow a cell phone or a smartphone (called mobile station - MS in GSM, or " *user equipment"* in 3G and 4G networks) to change radio cell without interrupting the conversation or the data transfer"(https://fr.wikipedia.org/wiki/Handover)

[4] Arcep, "Grands dossiers : la 5G": https: //www.arcep.fr/la-regulation/grands-dossiers-reseaux-mobiles/la-5g.html

[5] "The Internet of *Things*, or *IoT*, is the interconnection between the Internet and physical objects, places and environments." (https://fr.wikipedia.org/wiki/Internet_des_objets)

[6] *The future is used here, because as of the date of writing this article (May 31, 2022), the core network for 5G is based on a 4G core network that does not allow for slicing (Figure 3). This is called 5G NSA (for Non Stand Alone). 5G SA (Stand Alone) is expected to be deployed in the coming months, but this deployment will not be effective in all countries quickly. The slicing as such is therefore not for immediately, at the earliest by the end of 2022.*

[7] The core network is evolving towards 5G: https: //www.ericsson.com/fr/blog/3/2021/9/le-coeur-de-reseau-evolue-vers-5g

[8] What network slicing is for: https: //reseaux.orange.fr/actualites/5g-network-slicing

[9] Arcep Note n°5 "The carbon footprint of digital technology", 21 October 2019: "in the long term, improvements in energy efficiency will not be enough to offset the increase in traffic. Thus, by rebound effect (...) a technological development that appears to allow a reduction in GHG emissions for constant use is likely to produce an overall increase in emissions due to the multiplication of uses that it allows."

https://www.arcep.fr/uploads/tx_gspublication/reseaux-du-futur-empreinte-carbone-numerique-juillet2019.pdf

[10] Arcep Note No. 5 "The carbon footprint of digital technology", 21 October 2019: https://www.arcep.fr/uploads/tx_gspublication/reseaux-du-futur-empreinte-carbone-numerique-juillet2019.pdf

[11] *Ericsson mobility report, June* 2021. https://www.ericsson.com/en/reports-and-papers/mobility-report

[12] A byte is a group of 8 bits; an exabyte is equivalent to 1000 petabytes or one billion gigabytes

[13] Nicolas Guérin, president of the French Federation of Telecoms, at the round table on the health and environmental impacts of 5G held by the Senate's Committee on Regional Planning and Sustainable Development on June 29. https://www.senat.fr/les_actus_en_detail/article/impacts-sanitaires-et-environnementaux-de-la-5g.html

[14] C. Shannon. "A Mathematical Theory of Communication." The Bell System Technical Journal 27.3 (1948), pp. 379-423. https://people.math.harvard.edu/~ctm/home/text/others/shannon/entropy/entropy.pdf

[15] Digital Communications 5th Edition. Proakis. McGraw Hill, (2007), OR W. Gappmair, "Claude E. Shannon: the 50th anniversary of information theory," in *IEEE Communications Magazine*, vol. 37, no. 4, pp. 102-105, April 1999, doi: 10.1109/35.755458. https://www.leti-cea.com/cea-tech/leti/english/Pages/Leti/About-Leti/mission-organization.aspx

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