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While IRACON is ending, 5G is being deployed all around the world. The total number of mobile subscriptions¹ at the end of 2019 was around 7.9 billion. While 3G and 2G mobile subscriptions tend to decrease, the number of 4G subscriptions increased, reaching a total of 4.3 billion, or 55 percent of all mobile subscriptions. At the same time, 5G started its deployment. The world's first commercial 5G services were launched in 2018 and 5G is expected to penetrate the market much faster than 4G, the very early adoptions in China being one of the reasons. The number of 5G subscriptions reached around 13 million at the end of 2019 and are expected to represent nearly one third of all subscriptions by 2025, so 2.6 billion.

Looking at these impressive numbers, one may think that 5G is not only a done deal, but that all the goals of wireless communications for the foreseeable future are met. But, as it has been discussed all along in the IRACON project, 5G is not fulfilling all its original promises and telecommunication networks based on it do not reach the ultimate performance limits. The road to those goals will be long and difficult, with many alternative routes, external threats, and dead ends. Yet it will be exciting, requiring the understanding of increasingly complex phenomena.

In this chapter we provide some discussions about which topics are left for future research. We intend to present these perspectives in two stages. The first is to identify certain promises of 5G that are not yet possible and where research and engineering must work hand in hand to come up with effective solutions. The second will look beyond 5G, what could be called 6G, namely, what applications can be envisioned and which could be the key technologies that will enable a seamless interaction between humans and the cyber-physical world.

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¹ Ericsson Mobility Report | November 2019 and Q4 2019 Update.

10.1 Implementing 5G

Expectations on 5G are high, but - even though deployment has started - many of the advanced aspects are not available yet. Various ‘verticals’ (specifications for different applications) have been defined, whose requirements are partially conflicting with each other. While higher data rates remain an important objective (just like in previous generations), new scenarios, such as IoT characterized by a massive number of devices, critical communications for connected industries, or autonomous vehicles requiring high reliability communications, are emerging.

Along with the increased number of requirements, 5G relies on technologies that have not been previously deployed on a large scale. Massive MIMO and mmWave communications require extremely efficient hardware and software. The complexity gap with 4G is huge and the core network is highly impacted by the shift as well. Combined with the shortest ever time to market, 5G will require many adjustments and, without a doubt, improvements to move towards optimal 5G operation. The many advances in 5G take the use of dimensions, frequency, and space, to an extreme, which increases throughput and density of users and connected objects. It is the first time that such large bandwidths are introduced for intensive commercial use in spectra (mmWave) where the efficiency and the stability of the communications still leave questions. Also, the large number of beams formed by the massive number of co-located antennas enable efficient spatial/angular reuse of the resources, allowing denser networks. At the same time, the requirement to connect billions of distributed devices can only be partly addressed through network densification, but also requires some completely different approaches to find a solution.

As a consequence, in the coming years, engineers and researchers will face, at unprecedented pace and scale, the introduction of complex and new technologies in public and industrial spheres. A significant number of problems that will encounter 5G may not be solved yet. Without being exhaustive, we give here some key elements which we believe are essential to the full success of 5G.

- *Fundamentals and global network design.* Heterogeneities of future networks (devices, radio solutions, quality of service, constraints) make it very complex to assess the performance of a 5G network and to optimize its operating mode. Existing models, such as those based on stochastic geometry, either deviate from the deployment realities allowing only a macroscopic performance evaluation but not a fine adjustment of the network; or present complexities that we no longer know how to handle analytically. Fundamental solutions for quantifying network performance in a multi-dimensional space (throughput, delay, energy, reliability, etc.) and tools (probably a judicious mix between data-based approaches, derived from AI, and model-based approaches, more common in telecommunications) still need to be developed to better manage 5G. Non-Gaussian models and new ways to account for dependence (in time and space) will be necessary.
- *Better know the channel.* One of the objectives of 5G is to increase the used spectrum to allow an increase of peak and user data rates: the current versions of 3GPP

5G NR (Rel-15 and Rel-16) operate in a spectrum below 52.6 GHz. However, the use of such frequencies for outdoor / broadband applications has not been explored for large-scale deployment yet. A more comprehensive understanding of radio wave propagation is required to access efficiently the large available contiguous bandwidth above 6 GHz, especially in highly dynamic scenarios. It is important to fully capture the channel complexity and its characteristics in time, space, and polarization. Tests in real conditions (over-the-air) will also be crucial to evaluate the real impact of the environment on the wireless links. Such better understanding will also have to be reflected in future channel models.

- *Channel state information.* Many of the Physical Layer techniques rely on the knowledge of CSI. However, it becomes unrealistic to estimate the state for all the channels involved when considering massive MIMO and/or IoT, especially in dynamic environments. To help the system estimate the CSI, deterministic channel models or location-aware channel-database can be used. However, their real-time use in localization, signal processing, and resource allocation algorithms still remains in its infancy. Machine Learning approaches could also be a significant help.
- *Reliable links in mobility.* Another advanced mechanism deployed in 5G is massive multiple antenna systems and beam forming. This can become very important in the mmWave bands to combat the high isotropic free-space path loss we face when reducing the wavelength. It is crucial to develop efficient beam steering and tracking. Enabling radio links in the mmWave band between vehicles and infrastructure or among vehicles, would allow to transfer at a high data rate in a smart mobility context. While the current 5G standard foresees appropriate mechanisms, they have not been fully implemented in the existing deployments, and may furthermore be too slow for use in some highly dynamic environments.
- *Ultra reliable communication:* beyond the traditional requirements of high rate transmission for, e.g., video streaming, some verticals like industry automation require much more reliable communications for some critical applications. A common goal is to reach 5 nines (99.999%) for the success rate of packet delivery, even sometimes with a delay constraint. Coupled with limited resources on the nodes and harsh industrial operating environments, such a target is a real challenge that is difficult to reach in IoT conditions (low cost, low power devices). Improved or even new strategies to access the channels and carry the information are needed. On one hand, deterministic channel access, orthogonal by construction, as traditionally used in cellular networks or proposed in TSCH for Low-Power devices can ensure reliability and short delays. On the other hand NOMA can improve the network capacity and increase the number of connected devices. The best compromise between orthogonal multiple access, requiring a precise scheduling, and NOMA with a reduced scheduling is an important topic.
- *Density.* Recent works forecast more than 40 billion connected devices by 2025, and more than half of them related to the IoT, from sensors to connected cars and wearables. It is not sure that the current status of 5G or LPWAN technologies can support these deployment densities. This will impact the whole network from the physical layer to the data management.

- *Positioning accuracy.* While no target is given today in 5G for positioning accuracy, 3GPP tries to achieve an accuracy of less than 3 m to improve 5G NR location awareness. Several challenges remain when dealing with indoor localization, especially in the virtual reality contexts, where very high accuracy is requested, or in the framework of logistics-type applications.
- *Latency.* Today in 5G NR, the URLLC target for the user plane of 1 ms of latency was abolished because it could not be achieved, and now 5 ms is the goal. Realizing the original 1 ms has to take into account the whole network, from the Physical link to the IP core. Edge computing could play an important role in solving this challenge, by avoiding entering the core of the network and by being very close to the source for a faster reaction.
- *Network and terminal energy efficiency.* Energy is becoming one of the main concerns of society. Telecommunication networks play a particular role in this context, being both a tool for reducing consumption, whether in the home or by enabling remote meetings, as well as being a large consumer. At the same time, in applications such as IoT, energy is the resource that sometimes defines the life of the network, when the batteries cannot be replaced. In all cases, saving energy is a crucial factor posing challenges both at the hardware level and in the organization of the network. Fully autonomous nodes, with harvested energy, can also be developed and near sensor computing becomes an important challenge. New hardware design can significantly reduce the energy consumption of devices, for instance implementing artificial neural networks or spiking neural networks.
- *Co-existence issues.* Connectivity will be ensured through multiple radio access technologies in licensed and unlicensed spectrum. How these technologies will live together remains an unsolved question, both for coexistence between different 5G services, and between 5G and other applications, such as WiFi. Especially in the ISM bands, inter network interference could become a significant problem. Duty-cycle or carrier sensing approaches are not sufficient or sometimes not adapted to mitigate the generated interference. Better modeling and understanding are needed to define adapted co-existence rules. Exploiting more unlicensed bands such as 60 GHz, to mitigate the traffic in existing bands, may also be helpful. Such possibilities need to be further incorporated to offer wider solutions for networks.
- *Network orchestration.* Providing increased peak data rates to a few users or low rates to many, with a reduced latency requires a new approach to signal processing and physical layer communication techniques. But handling the wide varieties of applications, requesting significantly different performance, also requires an improved resource management and orchestration. SDN and NFV are strong current trends, where each step of the transmission is controlled in software, offering significant gains in cost, flexibility, ease of deployment and efficiency. However, orchestration of networks characterized by high dynamicity, due to user mobility and changing of traffic load distribution, is still an open issue. In addition, effective real-time network resource orchestration in the presence of multi-dimensional resources, many service types, and unknown traffic models, is another challenge. Dynamic network slicing, according to which a network operator may generate,

in a dynamic way, dedicated virtual networks to support the optimized delivery of any service toward a wide range of users, will be an important element of future networks.

- *Security and privacy.* One cannot list important topics that still need research effort without mentioning the security and privacy aspects. Security threats, ranging from access to the physical network structure to pure software attacks, are getting more and more numerous and it is essential to protect the integrity and the verifiability of the received data. IoT also brings new risks with many low cost devices transmitting information. The low cost makes this information difficult to protect and increases the many threats to users' privacy, whether they come from organizations with a legal right to access data and data brokers or criminals seeking to invade privacy.

It is difficult to cover the full list of areas that still needs research and engineering. The new network technologies, for 5G or IoT, definitely need time to achieve what we expect from them. The multiplicity of verticals, the new frequency bands, the intense spatial usage (massive MIMO and ultra dense networks) are requiring a wide range of different optimizations, that is a network able to understand the end user needs and to adapt to them.

10.2 Preparing 6G

10.2.1 Applications

Nowadays we are moving toward a society of fully automated and remote management systems. Autonomous systems are becoming popular in every sector of society, and require to embed cities, vehicles, homes, and industries with millions of sensors. Hence, a high data-rate with reliable connectivity will be required to support these applications. Although 5G will provide better QoS as compared with 4G, it will not have the capacity to deliver a completely automated and intelligent network, that provides everything as a service, and a completely immersive experience. In contrast, it is expected that 6G will be able to jointly meet all the stringent network demands (e.g., ultra-high reliability, capacity, efficiency, and low latency) in a holistic fashion, in view of the foreseen economic, social, technological, and environmental context of the 2030 era. Some key prospects and applications of 6G wireless communication are briefly described below.

Full and immersive experience. This application aims at providing to humans immersive experience with machine/things, making the human-to-machine communication seamless. To this aim, a digital real-time experience that mimics the full resolution of human perception is needed. Extended reality, five-sense communication and haptic communication will be essential for the realization of this full experience. Extended Reality (XR) services, including Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (ViR), use 3D objects and artificial intelligence as key driving elements. ViR uses headsets to generate realistic sensations

and replicate a real environment or create an imaginary world. AR is a live view of a physical real world, whose elements are augmented by various computer-generated sensor inputs; it uses the existing reality and adds to it by using a device of some sort. MR merges the real and the virtual worlds to create new atmospheres and visualizations to interact in real-time. With MR the artificial and real world contents can respond to one another in real-time. XR refers to all combined real and virtual environments and human-machine interactions generated by computer technology and wearables. It brings together AR, ViR, and MR. XR will require a data rate above 1 Tbps, as opposed to the 20 Gbps target defined for 5G. Additionally, to meet the latency requirements that enable real-time user interaction in the immersive environment the per-user data rate needs to touch the Gbps, in contrast to the more relaxed 100 Mbps 5G target. A true XR environment engages all five senses, requesting the *communication and transfer of information related to the five senses* of hearing, sight, taste, smell, and touch. This technology uses the neurological process through sensory integration. It detects the sensations from the human body and the environment and uses the body effectively within the environment and local circumstances. The research in this field is at a very early stage. Finally, a full experience involves the *haptic communication*, that is a branch of nonverbal communication that uses the sense of touch: remote users will be able to enjoy haptic experiences through real-time interactive systems. The implementation of haptic systems and applications will be facilitated by the superior features of 6G communication networks.

Industry 4.0. The industry today undergoes a major transformation due to the increasing role of the new technologies - robotics, the IoT, and AI. This revolution, which is often referred to as Industry 4.0, will make it possible to increase productivity and safety, ensure the quality of products, and contribute to reducing material and energy wastage. Automation comes with its own set of requirements in terms of reliable and real-time communication. For example, high-precision manufacturing requires very high reliability - up to the order of 5 nines or more - and extremely low latency - in the order of 0.1 to 1 ms of round trip time. Furthermore, industrial control networks require real-time data transfer and strong determinism, which translates into a very low delay jitter, in the order of 1 μ s. While existing technologies, such as LoRa, NB-IoT, and even 5G, could be useful for monitoring purposes, they have issues when it comes to controlling loops. This calls for the design of novel transmission techniques, for example moving to the use of sub-THz and THz bands (allowing extreme high-data rates and low-latency), and the need a precise knowledge of the radio channel in such harsh environments.

eHealth. 6G will revolutionize the health-care sector, eliminating time and space barriers through remote surgery and guaranteeing health-care workflow optimizations. Besides the high cost, the current major limitation is the lack of real-time tactile feedback, together with the challenge to meet the stringent requirements, that are continuous connection availability, ultra low latency (sub-ms), and mobility support. In addition, absorption of radio signals by living tissues, including human and animals, from radio devices operating in the proximity of or inside a body is another concern that hinders wide-spread deployment of these applications.

Unmanned mobility. The evolution towards fully autonomous transportation systems offers safer traveling, improved traffic management, and support for infotainment, with a market of 7 trillion USD. Future transportation scenarios will be characterized by high mobility and involve cars, trains, and unmanned aerial vehicles flying at low altitudes. Connecting autonomous vehicles demands unprecedented levels of reliability and low latency (i.e., above 7 nines and below 1 ms, respectively), even in ultra-high mobility scenarios (up to 1000 km/h), to guarantee passenger safety, a requirement that is hard to satisfy with existing technologies. In addition, the increasing number of sensors per vehicle will demand very-high data rates (e.g., Terabytes generated per driving hour), beyond current network capacity. The 6G system will promote the real deployment of self-driving cars (autonomous cars or driverless cars). A self-driving car perceives its surroundings by combining a variety of sensors, such as light detection and ranging, radar, Global Positioning System (GPS), sonar, odometry, and inertial measurement units. The 6G system will support reliable vehicle-to-everything and vehicle-to-server connectivity. Also UAVs, a.k.a. drones, represent a huge potential for various scenarios. Swarms of drones may be used to provide network connectivity and capacity when and where needed. The ground-based controller and the system communications between the UAVs and the ground will be supported by 6G networks. Full 3D vision of the networks will have to be handled, increasing complexity in comparison to the mainly 2D networks considered in 5G.

10.2.2 Technologies

The large range of new applications will motivate research in a wide range of new technologies, both to improve the efficiency of existing concepts, and to arrive at completely new structures. We suggest the following in a (necessarily incomplete) list of interesting topics that is arranged to progress from the physical layer to the higher layers:

- *New spectral bands.* While mmWave systems were a hallmark of 5G, it can be expected that 6G will exploit even larger swaths of hitherto unused spectrum. The spectrum bands between 140 and 1000 GHz offer the bandwidths required for applications requiring hundreds of Gbit/s. Related research will range from channel measurement, to hardware technology that can efficiently generate such frequencies, to algorithms for multi-antenna technology in those ranges. Going even higher in frequency, free-space optics based on either Light Emitting Diodes (LEDs) or lasers is promising for extremely high data rate applications.
- *New hardware for information processing.* With the end of Moore's law and the impossibility to evacuate more heat from the electronic components, new chip designs have been proposed (e.g., neuro inspired like spiking neural networks or quantum computing). Such components will modify the way to process information and could significantly impact the communication networks.
- *Spectrum adaptivity and aggregation.* The usage of spectrum will be made more efficient by adaptive use of the available spectrum. For example, each UE might be

able to transmit in different bands, but will select the most suitable spectrum based on the propagation conditions, existing interference, and interference to existing primary users. This will differ from standard cognitive radio in the ability to exploit multiple bands with different propagation characteristics and beamforming capabilities.

- *New modulation formats and coding approaches.* While research for 5G in this area has mostly concentrated on variants of OFDM, the requirements of new applications for extreme broadband (sampling and processing with hundreds of Gsamples/s) and extremely low energy consumption merits the investigation of completely new modulation formats and detection methods. The transceiver structures need to be considered holistically, involving investigations into clock-free architectures and backscatter communications. On the coding side, codes with short block lengths deserve further attention, as the polar codes used in 5G might not be sufficient. Since in delay-sensitive applications retransmissions might not be permissible, residual error rate and latency also need to be traded off with each other.
- *New spatial multiplexing methods.* Massive MIMO, usually realized with hybrid beamforming, was a major factor in 5G. For 6G, a number of new topics arise for the spatial multiplexing of data streams. For the field of massive MIMO, promising avenues for use of low-resolution Analog-to-Digital Converters (ADCs) need to be further pursued. For the reduction of complexity, index modulation, such as spatial modulation, is also worth further exploration. For high-speed LOS connections over relatively short distances, Orbital Angular Moment technology is well suited for multiplexing of data streams. While proof-of-principle implementations exist for mmWave and optical frequencies, various implementation aspects and practical optimization require more work. Another rapidly emerging area of interest is *large intelligent surfaces*, which could, e.g., occupy a whole wall.
- *Reduction of channel estimation effort.* The acquisition, and possible feedback, of CSI and other control information may consume a considerable percentage of the radio resources for a user. This is especially true for massive MIMO, high-speed vehicles, and trains, but also for IoT systems where the transmitted packets are short and therefore the CSI acquisition overhead becomes *relatively* important. A variety of overhead reduction methods have been proposed, ranging from exploiting low-rank signal space, to combined CSI acquisition and demodulation, to the use of noncoherent or differential modulation that largely obviates the need for CSI; further refinement of these ideas, and derivations of other suitable ones should be part of 6G research.
- *Physical-layer security and quantum communications.* Security has emerged as one of the most important topics for IoT. In addition to traditional cryptographic methods, *physical-layer security* has become an important topic for keeping information safe from adversaries. While the information-theoretic basis of physical-layer security has been well established, the practical implementation is currently lacking. Authentication is also important and can exploit the hardware imperfections of RF devices. These imperfections can be extracted from transient or steady state received signals. Many different fingerprints can be obtained thanks

to clock shifts, digital-to-analog converters, power amplifiers, or RF oscillators... Furthermore, a key variable, namely the channel strength between transmitter and snoopers, is generally unknown, and schemes that can improve security under those circumstances, are needed. On the other hand, quantum communications are provably secure, and research into their realization at optical frequencies, as well as adaptation to lower frequencies, will be important for 6G.

- *Integrated sensing and communications.* Industrial, vehicular, and IoT applications often need to sense the environment and then communicate the results to other nodes. While such sensor networks have been explored since the early 2000s, a new emphasis lies in the integration of the communications and the sensing functionality. This is especially true for radar-based sensing, since channel estimation based on pilot tones is a form of bi-static radar. Similarly, Lidar (which is often used in self-driving vehicles) can be naturally combined with optical communications.
- *Massive multiple access.* Traditional multiple access schemes rely on orthogonality of users in time, frequency, code, and/or space. NOMA provides a new paradigm for multiple access, relying on different strength of signals to separate users (note that NOMA is really based on the pioneering work of Poor and Verdú on multi-user detection in the 1980s). Another important question is how to provide access to thousands or more devices, each of which might have only a very low data rate, to a single base station. Traditional orthogonalization of the users is not feasible, since contention-free access is inefficient when the duty cycle of the UEs is very low, while Carrier Sense Multiple Access (CSMA)-like schemes are not efficient when the SNR between devices is low, as can be anticipated for many IoT applications. New schemes like SigFox and LoRa have been proposed, but a search for more efficient methods will be a cornerstone of 6G.
- *Cell-free massive MIMO.* The continuous densification of networks has made inter-cell interference the dominant factor limiting the throughput per user. The idea of having a UE connected to several of the infrastructure nodes that are closest to it, without the formation of explicit cell boundaries within which, and between which, the UE moves, promises to reduce the interference and at the same time make the SINR and thus rate more uniform. While similar concepts have been explored in the past, under the name of base station cooperation, network MIMO, and cloud-RAN, the implementation that minimizes overhead and avoids creating “cluster boundaries” at which SINR would be low promises greater gains.
- *Vehicular and aerial networks.* One of the most important applications for 6G will be vehicular networks. While V2I was already considered a goal for 5G, progress has been slow, and is mostly concentrated on creating low-data-rate links that can carry some fundamental control information. The transmission of raw sensor data, in particular camera and Lidar images, between cars, will be a topic for 6G. The networking between many, highly mobile, nodes will present significant challenges from physical to network layer. Similar issues will arrive in aerial networks, which encompass both the communication between ground and UAVs for the purpose of communicating control and sensor information, and for setups in which

UAVs could serve as flying base stations or relay stations. The joint optimization of flight patterns and resource allocation will require significant research.

- *Integrated communication, computing, and caching.* Many of the services for mobile devices require extensive computations, and the computational capabilities of those devices are often not sufficient - cases in point are video games, as well as control for factory automation. This has given rise to Mobile Edge Computing (MEC), where a device offloads computations to edge servers. A more general version is known as Augmented Information services, where the source and destination of the information need not be the same, and the necessary computations can be performed on multiple devices that lie along a multi-hop route over which the information is forwarded. The load of computation and communication can be reduced by caching of information close to the destination - current edge caching investigations mostly concentrate on wireless video files, but in a more general context, the “3C” - computation, communication, and caching - should be optimized in a joint manner, and take into account a variety of constraints such as energy consumption, latency, and cost for hardware.

Some final conclusions: Communication is an essential means to make things happen. It is worth remembering how fundamentally wireless communications have changed our lives- from interactions between people to availability of content. These concluding words are written in the middle of a pandemic, where communications via cellphones and WiFi are a lifeline - both figuratively and literally - for hundreds of millions of people. In the future, wireless communications will have an even broader purview, enabling new human-machine and machine-to-machine interactions that will make our lives more convenient and contribute to better well-being.

Even though so much has been done in the past 5 years, including significant contributions from IRACON members, much more remains to be done so that networks can deliver a completely new experience for the relationship between humans or between humans and the physical world. Due to constantly evolving, and always more challenging, requirements and applications, wireless is far from “mature”. The COST actions, ranging from IRACON, to IC 1004, COST 2100, COST 273, COST 259, COST 231, all the way back to COST 207, have played an essential role in fostering this research, crossing national boundaries and opening research and technology for the benefit of all participants, as well as companies and citizens. The role that COST has played in creating collaborations and synergies across national borders cannot be overemphasized. The research and cooperation between European countries, and between Europe and other countries, are key elements of these crucial technologies at the heart of the profound transformations experienced by our society, ranging from digital content to industrial, urban, environmental, mobility, energy, and many more applications.