6G: The Next Frontier

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Abstract

The current development of 5G networks represents a breakthrough in the design of communication networks, for its ability to provide a single platform enabling a variety of different services, from enhanced mobile broadband communications, automated driving, Internet-of-Things, with its huge number of connected devices, etc. Nevertheless, looking at the current development of technologies and new services, it is already possible to envision the need to move beyond 5G with a new architecture incorporating new services and technologies. The goal of this paper is to motivate the need to move to a sixth generation (6G) of mobile communication networks, starting from a gap analysis of 5G, and predicting a new synthesis of near future services, like hologram interfaces, ambient sensing intelligence, a pervasive introduction of artificial intelligence and the incorporation of technologies, like TeraHertz (THz) or Visible Light Communications (VLC), 3-dimensional coverage.

I. INTRODUCTION

About every ten years, a new generation of wireless communication systems has been engineered and deployed, revolutionizing the way people interact, work and live. The first generation (1G) has enabled mobile voice communications, the second generation (2G) has introduced capacity and coverage, the third generation (3G) has enabled wireless networks to support mobile wireless broadband and data communication. The fourth generation (4G) has provided a large and heterogeneous range of communication and cloud services in multi-user environments bringing the fixed internet broadband experience also to mobile devices. In 2018, intensive
successful testing, proof-of-concepts and trials [1] have supported the launch in 2019 of the fifth generation (5G) services, which will fundamentally transform current industries, create new industries, and impact societies and revolutionize the way people connect with everything and everything connects to people and things.

5G has the ambition to provide a single platform enabling a variety of different services, or verticals in 5G terminology, from Enhanced Mobile Broadband communication, providing in the order of tens of Gbps links, Industry 4.0, automated driving, massive machine type communications, etc. These services are characterized by very diverse sets of key performance indicators (KPI’s), so that the design of a single platform enabling all of them in an efficient manner is a very challenging task. The approach taken by 5G to address this challenge builds on the exploitation of two important tools: softwarization and virtualization of network functionalities. Building on these basic tools, different services can be provided by properly orchestrating (software) resources through what is called network slicing, using resources when and where needed and then releasing them. At the physical layer, the accommodation of stringent requirements in terms of data rate and latency, has required the introduction of millimeter-wave (mmW) communications, the exploitation of massive multiple-input/multiple-output (MIMO) links, and the (ultra) dense deployment of radio access points.

With its distinguishing connotation of being an enabler of very different services, 5G represents a major breakthrough with respect to previous generations. Given this context, the fundamental question we wish to address is: Given the enormous potentials of 5G networks and their foreseeable evolution, is there a real motivation for thinking of 6G networks? If yes, what should there be in 6G that is not in 5G or in its long term evolution? Typically, a new generation arises at the confluence of two major paths: a technological path that brings to maturity new groundbreaking technologies and societal trends that motivate new services that cannot be efficiently enabled by the current technologies. The '6G or not 6G' debate has indeed already started. Academic, industrial and research communities are working on the definition and identification of relevant key enabling technologies that might define the so called 'beyond 5G' (B5G) or sixth generation (6G) [2], [4], [5].

In our vision, predicting the evolution of technology in a time span of a decade and looking at high level next decade societal needs, there is a strong motivation to start thinking about a 6G. We envision the following major thrusts:

- **new communication infrastructures**, incorporating **new architectures, ubiquitous super**
**3D connectivity** bringing access points and cloud functionalities on drones and very-low Earth orbit (VLEO) satellites, very high data rate links exploiting **sub-THz and visible light spectrum**, and **sub millisecond latency** communications;

- a **pervasive introduction of distributed artificial intelligence mechanisms**, including semantic and machine learning tools at the edge of the network;

- **new human-human and human-machine interaction mechanisms**, including 5-sense and holographic interactive communications;

- **new embedded distributed security/privacy mechanisms**, enabling the share of large amount of information without jeopardizing users’ privacy and preventing misuses of the new technologies.

The motivations arising from the societal perspective start from the need to improve quality of life through the deployment of smart environments, including smart cities, smart transportation, smart factories, etc., improve and personalize healthcare and education, improve human interaction mechanisms offering a truly immersive experience incorporating possibly all senses. Some of these services, like holographic communications, requiring Terabits/sec data rates, or high precision remote control of smart factories, requiring sub millisecond latency, are not supported by 5G [5].

Even though 5G is not in place yet, but it will arrive gradually, 6G research has already kicked-off and in our vision a tentative 6G roadmap is reported in figure [1].

In the ensuing sections, we will discuss some of the major thrusts of 6G.

### II. A new communication infrastructure

The communication infrastructure able to support future use cases of 6G has to evolve at both the architectural level as well as at the physical level. We identify the following aspects:

- a **new architecture**, to support a nearly deterministic service provisioning, under very tight physical constraints, as latency or energy consumption;

- **3D-ubiquitous connectivity**, exploiting the integration of terrestrial and non-terrestrial links, including drones and very low Earth orbit (VLEO) satellites to support coverage on demand;

- **very low latency (sub millisecond)** communications to support, for instance, high precision remote control of industrial processes and 5-sense interactive communications and media;

- **very high volume data rate** (in the order of Tbps/sec/m³) to support haptic and holographic communications;
• *battery-free communications*, targeting communication efficiency in the order of 1pJ/bit, exploiting ambient backscattering or energy harvesting mechanisms.

The need of guaranteeing an almost deterministic delivery of delay-sensitive applications over intermittent random channels, as e.g. mmW links, is stressing more and more the current Internet paradigm. The TCP protocol is very robust in handling packet drops due to network congestion, but retransmitting packets lost because of blockage events in millimeter [3] (or even worse sub-THz) links may be highly inefficient.

In a general rethinking of the Internet architecture, it might be advisable to consider alternative, more flexible and scalable structures, like Recursive InterNetwork Architecture (RINA), whose fundamental principles are that computer networking is just Inter-Process Communication (IPC), and that layering should be done based on scope/scale, with a single recurring set of protocols, rather than functions, with specialized protocols. Potentially, IPC principles can be reapplied for different scopes in the same manner than computing caching policies and federating learning approaches to achieve innovative predictive and recursive use of communication, computation and caching resources. The goal is to strongly limit processing of the same task computation and related data exchange and (inter-process) communications. This is a potential key enabler
for 6G distributed autonomous intelligent networks. Main research challenges and advantages are discussed in [2].

The incorporation of links with aerial access points placed on drones or very low Earth orbit (around 300 Km) satellites is an effective way to provide coverage on demand and cope with the high variability of data rates as a function of space and time. These access points will most likely operate over the lower frequency bands (up to a few tens of GHz). Their use, coupled with a dense deployment of terrestrial access points placed from lampposts to tall buildings, will give rise to a truly 3D connectivity.

As in all revolutions, 6G will also have to support higher data rates than previous generations. Thinking about future interpersonal communications, the deployment of holographic communications, employing multiple view cameras, will demand data rates in the order of Tbps [5], that are not supported by 5G. In 10 ten years from now, the current ways of remote human interaction through the exchange of voice, images and videos, will become obsolete as new forms of interactions will arise leading to a true immersion into a distant environment. Five dimensions (5D) communications and services, integrating all human sense information (sight, hearing, touch, smell and taste) will arise, together with holographic and haptic communications, immersive tele-presence and any applications enabling generalized and diffused digital skills for humans and machines [4]. Sub-THz and Visible Light Communications (VLC) are the expected enablers of such high data rate services. In Section V we will specifically focus on the recent advancements in these fields to show their potentials and trade-offs for 6G.

Energy-efficiency is expected to become more and more important, especially in view of a pervasive deployment of the Internet-of-Things, with myriads of tiny sensors. Energy harvesting mechanisms have been developed in many sensor network applications. The potential of future wireless charging technologies and their fundamental limits are presented in [10], with a focus on promising distributed laser charging techniques showing that wireless charging might approximately deliver 2W of power up to a distance of about 10 meters. An even more drastic approach is ambient backscatter communications, enabling tiny devices to operate with no battery, by redirecting ambient radio frequency (RF) signals (for example using on/off encoding) without requiring active RF transmission [13].
III. Pervasive AI and Holistic Management of C4 Resources

Artificial intelligence (AI) mechanisms, and more specifically machine learning algorithms, are already permeating many applications running on today smartphones. It is not difficult to predict an ever increasing usage of learning mechanisms at both network and mobile terminal sides. A recent survey on the usage of deep learning algorithms in wireless networks is [12]. The current research on 5G already contemplates the usage of AI tools as a way to enhance mobile applications or to make a more efficient usage of network resources. Nevertheless, we believe that a truly leap forward in a pervasive exploitation of AI tools in the smart environments foreseen in the decade to come, with a special attention to all delay-critical applications, requires a new design. The new architecture should handle communication, computation, caching and control (C4) resources as parts of a single system, whose efficient management requires a joint optimization. Consider, for instance, the autonomous control of an industrial process in an automated factory.

Fig. 2: Automated factory.
sketched in figure 2 where mobile robots take videos of the industrial process and send the data to the cloud, where learning algorithms run to detect anomalies and take decisions that are sent back to an actuator aimed to implement the proper countermeasures. A key performance indicator in this scenario is the end-to-end (E2E) delay, which includes: communication time, i.e. the overall time spent to share data among the various actors (robot, cloud, data-base, actuator, etc.); computation time (the time necessary to run the decision algorithm); and the time needed to access a maybe distant data-base. Running the learning algorithms in a distant cloud may be critical because of the delays encountered along the transport network. To reduce these delays and approach a nearly deterministic condition, it is necessary to bring resources, i.e. access points, cloud computing and contents, closer to the end user. This strategy is promoted by the deployment of mobile edge computing (MEC), which is already an important component of 5G. However, in 5G communication and computation resources are handled separately. Conversely, we believe that the inevitable limitation of resources that can be available at the edge of the network calls for a holistic management of all C4 resources. In this new scenario, the assignment of users to access points, dynamic caching and migration of virtual machines will all need to be orchestrated jointly to guarantee the E2E requirements and an efficient use of resources. The need for a joint C3 (computation, communication and caching) optimization was advocated in, e.g. [8], and a C4 approach was analyzed in [9], where control was still referring to computation offloading. However the true challenge will be how to enable an intelligent control with stringent E2E delay guarantees, as required in, e.g., autonomous driving, autonomous factory, etc.

At the architectural level, information-centric networking (ICN) can help in providing seamless service continuity to moving users accessing the edge cloud. Even though ICN may be supported from 5G on top of current Internet, a native ICN architecture might help to make the shift of resources across the network much more efficient. This is just an example where a systematic rethinking of the network architecture might help facilitating the percolation of AI tools throughout the network.

Besides machine learning, we expect AI to contribute significantly to 6G in semantic aspects as well. Consider for example the transmission of data needed to create a dynamic hologram at the receive side. Clearly, not all information has the same semantic importance (the background for example may not be so relevant as opposed to the speaker). This requires new source coding schemes that go beyond current information theoretic tools and exploit tools able to extract semantic features from the data.
Finally, a further aspect expected to play a key role in 6G is distributed spectrum management algorithms and policies. In 5G and its long term evolution (but still 5G), machine learning algorithms will be adopted to attempt to improve effectiveness and quality of dynamic spectrum management. In such a context, a major challenge is to assist the network in self-organizing to deploy, optimize, and coordinate a very large number of devices in 3D dense environments. This is still possible in an evolved long-term maturity of 5G technologies by defining centralized conflict resolution mechanisms between different types of control loops related to different tenancies. Conversely, effective distributed self-x (self-organizing, self-defining, self-predicting, self-discovering) conflict mechanisms will require a native distributed architecture that should be made available by 6G networks. Recently, decentralized authentication and opportunistic exploitation of resources (spectrum, communication, computation, caches, etc.) have been suggested, based on blockchain [14]. The scope is to achieve in future 6G networks dynamic sharing of spectrum and resources rather than the binary unlicensed/licensed current 5G model.

IV. EMBEDDED DISTRIBUTED SECURITY/PRIVACY MECHANISMS

The vision delineated so far foresees a huge exchange of data to enable a pervasive use of AI techniques. Clearly this poses a major challenge in terms of security, privacy, and trust. Some of the major critical issues are:

- tracing and managing the ownership of data and devices in a distributed architecture (i.e. without a central trusted authority), to achieve scalability and low vulnerability;
- running machine learning algorithms while ensuring data privacy;
- assuring high data trustworthiness to provide reliable decision-making;
- detecting suspicious behaviors.

6G networks must be able to give an effective answer to these issues. As far as privacy is concerned, we believe that innovative cryptographic techniques should be used to get an effective merge of AI and privacy. Homomorphic encryption is one possibility [15]. This is a form of encryption that enables a user to send encrypted data, let the machine learning tool operating over the encrypted data and still be able to recover the desired answer by applying an efficient operation to the corresponding cipher text. Existing schemes are not practical yet due to high computation complexity, but we might expect that in a decade or so from now, the complexity issue could be alleviated.
Another critical issue is trust: How can a simple device offloading its data to the cloud verify that the operations carried out by the cloud is trustworthy? This problem can be tackled using the so-called *verifiable computation* algorithms, namely a class of algorithms able to verify the correctness of data processing at the cloud in order to enhance its trustworthiness, especially for encrypted data processing, without of course repeating the computations.

Decentralized authentication is another key aspect to provide scalability, especially in a truly massive IoT deployment. A key role will be played by the design of distributed ledgers, using for example blockchain mechanisms. The challenge will be to devise proof-of-concept mechanisms, enabling the blockchain, that can be efficiently implemented over a decentralized network.

V. Communicating through Sub-Terahertz and Visible Light Links

The never ending quest for more bits, more spectrum and higher network densification set the target for the future decade of wireless services to provide at least the challenging Tbps aggregated bit rate in small regions. This would represent about two orders of magnitude of higher bit rate [2] than what is expected from 5G.

To tackle this truly challenging task, 6G will have to exploit different enabling technologies. The possible strategies to increase the volume data rate (bits/sec/m\(^3\)) are: increase bandwidth, by using sub-THz and visible light spectrum; increase spectral efficiency, using advanced MIMO technologies exploiting, for example, orbital angular momentum (OAM) multiplexing; combine multi-RAT and 3D multi-link connectivity at a scale going well beyond 5G; (ultra) dense deployment of radio access points.

The European Telecommunications Standards Institute (ETSI) and other agencies are currently considering the bands beyond 90 GHz to provide high-data rate wireless services for short (5 to 20 meters) and medium distance (50 to 200 meters) fixed links. However, beyond 5G and 6G current research is already focusing on how to efficiently exploit the sub-THz (90-450 GHz) and visible light bands as solutions to provide optical-fiber like performance from 100 Gbps up to a few Tbps.

Spectral efficiency can also be increased using for example OAM multiplexing [6]. OAM is a property of electromagnetic waves expressing phase rotation on the vertical plane in the propagation direction and it provides many more (theoretically infinite) degrees of freedom than polarization. OAM multiplexing can be achieved by superimposing multiple electromagnetic waves having different OAM modes. Properly tuning the receiver to the right number of phase
rotations, it is then possible to separate the different data streams with virtually null mutual interference. Recent laboratory experiments have successfully shown 100 Gbps transmission at 10 m distance, in the 28 GHz band [6]. Its applicability for sub-THz is still an open research challenge.

A. The sub-TeraHertz Opportunity for 6G

Sub-THz communications are envisioned for beyond 5G communications at both device access and network backhauling and fronthauling. For example, we expect for device access communications with (ultra) dense deployments of access points within 10 meters of line of sight communication range that, 1 Tbps is achievable in principle by a single link with 250 GHz of carrier frequency (assuming 20% of BW, antenna gains of 40 dBi at both transmitter and receiver and, a noise figure of 20 dB) but it requires very high spectral efficient modulation (and coding) schemes. While in future, the evolution of transceiver and antennas technologies will provide solutions for achieving such challenging performance, the energy consumption related remain still a severe limitation for the applicability of such technology for terminals that are battery powered. In first a generation of sub-THz communications very likely, simple modulations schemes with lower spectral efficient will be used to communicate at very short distances (cm-range) by using large amounts of BW with very simple transceiver architectures, therefore avoiding power hungry complex digital signal processing and coding. Then, technological breakthroughs will be needed otherwise the peak data rate will be limited by available supply power. The first exploitation of sub-THz communication for fronthauling and backhauling links will require, even with ultra densification of 5G and 6G networks, to cover at least between tens to hundreds of meters. Nevertheless, due to the challenging electromagnetic distance at such high frequencies the single link peak capacity falls well below 1 Tbps. After all, the Graal of the Tbps can be reached also at such communication ranges allowing more complex and less power constrained communications, engineering antenna array with higher gains and investing in more hardware complexity for combining multiple parallel links (of the order of 100s of Gbps) using diversity (polarization, frequency, spatial, ...). Achieving several hundreds of Gbps over a single wireless links is a today research and prototype reality. Figure [3] shows recent realizations of multi-Gbps wireless transceivers implemented using different integrated circuit (IC) technologies. The points on the figure include labels displaying the data-rate, the technology, the modulation scheme and the antenna gain (if available). The trade-off between carrier frequency and range is clearly shown


in the figure. The larger carrier frequency solutions use a large amount of RF bandwidth in a single RF channel and simple modulations schemes such as Amplitude-Shift Keying (ASK)/Binary Phase SK (BPSK) which allows for digital-less demodulation. Such transceivers have been demonstrated for carrier frequencies up to 300 GHz and achieve communication in the range of 1 m up to 1 km using high gain antennas, as shown on Figure 3. On the other hand, CMOS based transceivers are limited to lower frequencies and bandwidths. They use higher order modulations such as Quadrature PSK (QPSK), 16QAM or even 64QAM. This second type of transceivers have demonstrated high data-rates at lower carrier frequencies, comparable to those of much larger bandwidth III-V transceivers, as shown on figure. Recent photonic-based modulation transceivers have also been included in the figure, and correspond to the highest carrier frequencies, but their degree of integration if currently very low. Today’s advanced digital baseband systems data-rate processing capabilities are somehow limited to a few tens of Gbps, and are also power consumption bonded. There is indeed a trade-off to explore between complexity/power consumption of transceiver and antennas and the exploitation
of diversity techniques (i.e. number of single links) to reach the (aggregated) Tbpps target. For instance, a reasonable trade-off needs to be done between single link BW and the overall number of channels required to cover the full RF band to provide the desired throughput. With the advances of materials and technology such trade-off might be relaxed opening cost effective Tbpps communications in 6G networks.

B. The Visible Light Communications Opportunity for 6G

In order to provide optical-fiber like performance, one possible complementary technology for future 6G networks is to exploit the visible spectrum with visible light communication (VLC) techniques for short range (up to few meters) links, which compared to classically adopted RF bands offers ultra-high bandwidth (THz), zero electromagnetic interference, free unlicensed abundant spectrum, very high frequency reuse [7]. Today, currently available VLC indoor technology is clamped from several tenths of Mb/s to 100 Mb/s in the range of about 5 meters. Such limitation - due to commercial over the shelf (COTS) light fixtures and absence of beamforming - is forecast to disappear with the introduction of upcoming new light sources based on microLED. Such innovative components will soon offer 1+GHz bandwidth and near 10Gb/s have been achieved in lab on a single diode LED. In our vision, VLC has a huge potential of improvement in the next decade, catching up the current performance gap between VLC and 5G technologies that already proved the Gbps experience [1] and reaching the Tbpps with VLC technologies when 6G services will be launched. In our vision, VLC will be able to provide short range indoor connectivity reaching the Tbpps with full operational available demonstrators maturity by 2027 (see figure 4). The first milestone will be in 2019, by the launch of 5G services, when full 1 Gbps indoors short range capability will be demonstrated with thousands of LED active sources for lighting functionality. Then, a new challenge will appear at short term in order to pilot such huge matrices and preserve the high bandwidth. To this end, it will be required the hybridization of microLED matrices and CMOS driver arrays into a single chip. Then, in order to reach by 2024 the today claimed highest 5G link capacity (20 Gbps), it will be required a more complex device with the parallelization of several aforementioned chips and the introduction of a dedicated imaging optical system leading to a spatial separation of users, also known as optical beamforming, with a significant increase of cellular throughput. Eventually, by 2026 when both microLED technologies and spatial multiplexing techniques will be mature and cost effective, white light based on different wavelengths will unlock throughput thanks to wavelength division
multiplexing leading to potentially 100+ Gb/s for ultra-high data rate VLC access points. In 2027, adding on top of the above mentioned technologies massive parallelization of microLED arrays, the target Tbps aggregated throughput will be available.

Fig. 4: Visible Light Communication Roadmap from Mbps to Tbps.

VI. CONCLUSIONS

The visionary Nikola Tesla stated in 1926: “When wireless is perfectly applied, the whole Earth will be converted into a huge brain ...”. In 2020, 5G networks are expected to be fully operational and represent a global game changer from a technological, economic, societal and environmental perspective with very aggressive promised performance in terms of latency, energy efficiency, wireless broadband capacity, elasticity and reliability. In 2030, when 6G might potentially arise, we might expect Tesla’s prophecy to come to reality through the design of an architecture that makes end users perceive themselves surrounded by a “huge artificial brain” providing virtual zero latency, unlimited storage, and immense cognition capabilities. 6G research has already started around the world addressing innovative solutions to offer ubiquitous super 3D joint connectivity-computation-cache-control. In this article, we highlight some of the major thrusts enabling such a vision. At the physical layer, we believe that the level of maturity reachable
by sub-THz and visible light communication in a decade from now can be a powerful enabler. A more massive use of multi-RAT and multi-link techniques will be needed, to tackle the challenges arising in the propagation in these higher frequency bands. At a higher level, we think that new architectures will need to be designed to really bring delay-sensitive AI applications to the end user, pushing for a major integration and distributed optimization of communication, computation, caching and control resources.

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