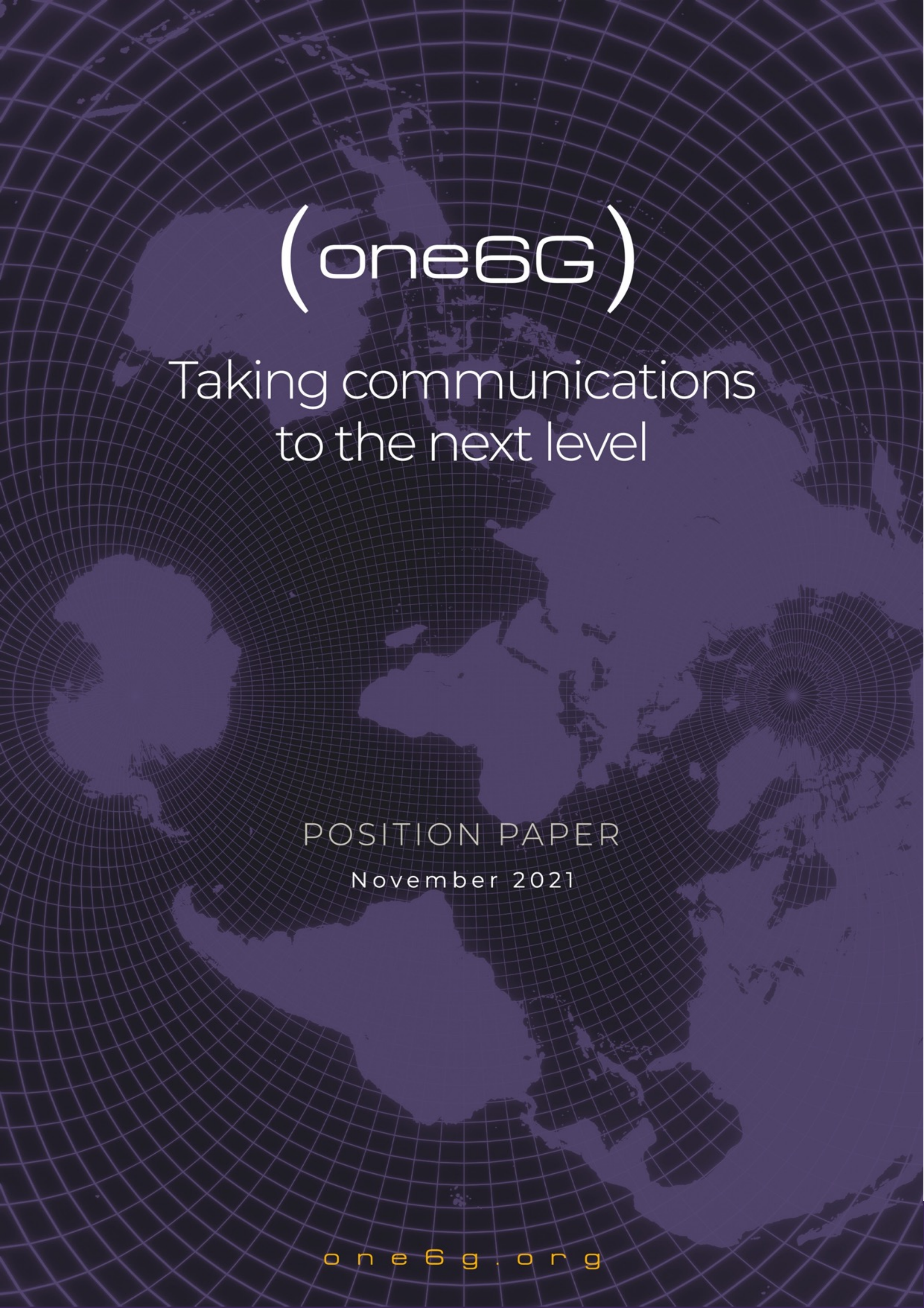

(one6G)

# Taking communications to the next level

POSITION PAPER

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one6g.org

# 1 Objective

With the deployment of the 5th Generation of mobile networks (5G), the question raised by the research community is … "what comes next?". What would be considered "beyond 5G" or even "6G"? What is the roadmap for specifying and designing the new capabilities of a 6G system? What are the features that will drive the standardization activities? Should 6G tackle the primary limitations of 5G or introduce novel, radical approaches, paradigms and technologies to be considered along with novel appealing research questions?

The softwarisation and virtualization extensively used as technology enablers in 5G will drive further the innovation in 6G. Already, both academia and industry have started several initiatives on "6G research" in Asia, Europe and North and South America, in order to address the foundational aspects of the system. The 5G development targeted the connectivity of different types of users and devices in a broad scale with varying roles. While 5G was successful in giving rise to new types of usage in vertical stakeholder industries, there is still fragmentation of service per domain. 5G provides the enabling framework for connecting digital spaces and domains. The "lessons learnt" from the 5G experience shows that the engagement of vertical stakeholders in the design process came at a later stage compared to the ICT sector stakeholders, which impacted the whole development phase, and the priority use cases. Moreover, the initial vertical stakeholders that were engaged in the process were the ones mostly influencing the specification of use cases (e.g., Automotive). The interactions between ICT and vertical stakeholders have followed a liaison approach between ICT and vertical stakeholders associations. This has proven problematic in the context of common standardization efforts.

Following on the 5G+ development dynamics, one6G Association aims at becoming a "6G innovation hub" which will drive the effort in designing and implementing novel solutions in an open and collaborative way. The early on-boarding of vertical stakeholders and their active engagement in the requirements, specifications and user-driven validation is one of the targets of one6G. one6G will provide an open platform for stakeholders networking, co-creation and collaboration in the context of addressing societal, business and development needs in a digital world. Sustainable growth and shaping the vision of future digital worlds based on industry consensus will be indicative outcomes of the one6G activities. Moreover, novel technology enablers will have to create the opportunities for radical service innovation and business efficiency. The issue of building a common "language", influencing effectively the 6G features based on business scenarios from the vertical sectors and cross-domain requirements. Vertical services and applications require a redefinition of how the system exploits network resources and data, both for communication, as well as sensing purposes.

one6G will address trends that will push the development of the new generation of telecommunication in the direction of an information infrastructure that is a shared, open, heterogeneous and evolving socio-technical system. Societal requirements like inclusivity, sustainability, resilience, and transparency will grow considerably, while access to data, as well as data ownership, -which are major factors in value creation- will also contribute towards the same goals. While the popularity of ICT services, as well as the share of the ICT infrastructures in the overall energy consumption has increased, the Green Deal challenges posed by the environmental aspirations need to be overcome by focusing more on the ecological sustainability of the future infrastructures of 6G, which is also of utmost importance.

The one6G Association was launched in March 2021 and is a global, non-profit and membership fee free association to work on 6G mobile network technology. It targets to address technologies such as AI, IoT (Internet of Things), symbiotic share of resources by mobile/wireless/satellite coms, cloud computing, time sensitive networking etc, which will play key roles in future innovation for developing the fundamentals of 6G. Compared to other 6G related organizations, one6G was founded to enter into an early and open dialogue with various industrial stakeholders for functional gaps and new requirements beyond 5G. 6G is in discussions since 2019, as it is anticipated that 6G products will be available by end of this decade. Hence, one6G will support industry and digital economies to develop the essential technology components needed for the 2030 and contribute to a fully connected and intelligent world. Through open, fertile dialogue and contributions, the association aims to become a forum which will explore a vision of how to expand current technology and business boundaries for new growth over the next few years.

There are several challenges in the path of defining a 6G network that addresses the demands and requirements of several verticals and services. The one6G Association has organized a set of working groups (WGs) to cover the necessary tasks to define the next generation of mobile network. The WG structure of one6G Association and scope are illustrated in Figure 1. Each WG contains different work items (WIs). WG1 collects and analyzes 6G related use cases, scenarios and requirements, WG2 deals with 6G enabling technologies and system architecture, WG3 takes care of communication and dissemination, and WG4 is responsible for evaluation, proof-of-concept and demos. Currently running WIs include use cases and requirements, higher and THz frequencies, radio building blocks, next generation MIMO, integrated sensing and communication, distributed/federated AI, flexible programmable infrastructures, etc, which will be briefly elaborated in next sections. Further WIs, such as security and privacy, are planned.

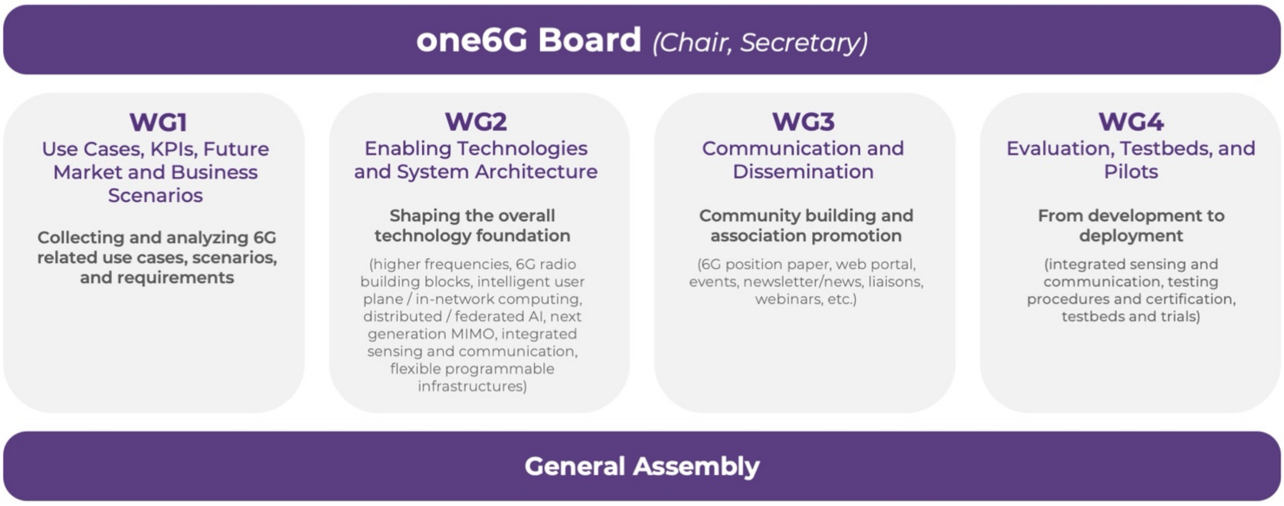

*Figure 1: Current working group (WG) structure and scope of one6G Association.*

# 2 Use Cases and Requirements

The 5G wireless system is designed to provide high-speed data transmission in the order of several Gbps, low latency in the order of a few milliseconds, and high reliability (up to 99.9999%). With prominent features such as network slicing and an evolved core network towards a service-based architecture, it is possible to customize 5G to realize diverse use case categories falling into one of the three categories: enhanced Mobile BroadBand (eMBB), Ultra-Reliable Low Latency Communication (URLLC) and massive Machine Type Communication (mMTC). With these features, along with its focus on vertical sectors, 5G has attracted a lot of attention from various industries, e.g., manufacturing, agriculture, healthcare, logistics, construction, entertainment.

While industries are considering how to make use of 5G in their domains, several technical challenges and potential further improvements of 5G have been identified, e.g., coverage in a non-line-of-sight (NLOS) environment and uplink performance. Such challenges along with other aspects such as “solving social problems”, “enhanced communication between humans and things”, “expansion of communication environment” and “sophistication of cyber-physical fusion” are driving many researches to start thinking about visions and considerations for 6G [1][2][3][4]. To realize such a future world in 2030, when 6G is anticipated to be introduced, it is expected that novel use cases and applications from certain vertical domains/industries will demand extreme requirements in several performance indicators that cannot be supported by 5G, either by exceeding the capacity of 5G or by having conflicting requirements that cannot be met jointly. Typical 6G use cases and scenarios are depicted in Figure 2.

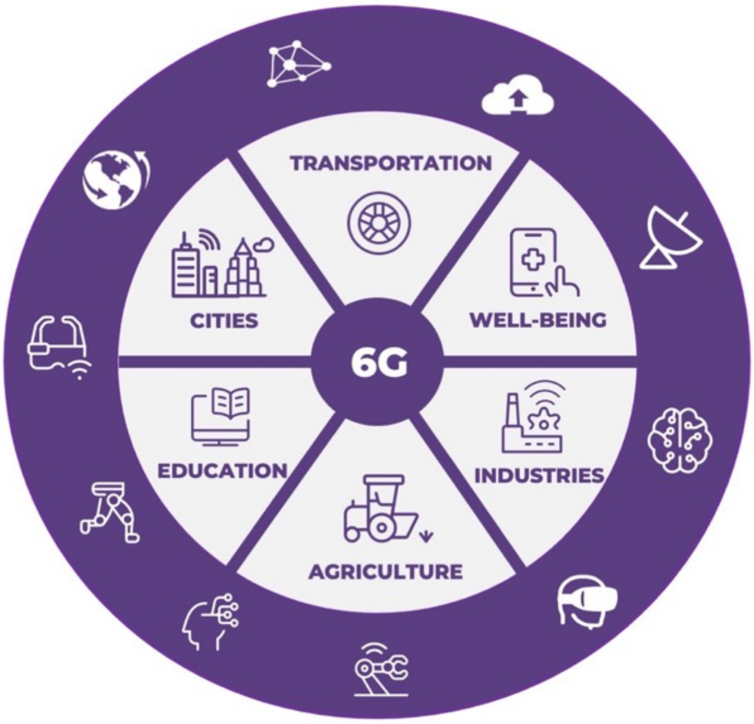

*Figure 2: Typical 6G use cases and scenarios.*

Below, we briefly describe a few vertical domains and what do they expect 6G to fulfill.

## Healthcare

Healthcare systems are continuously evolving and improving due to the advances in information and communication technology, including the 5G. The goals are to eliminate time and space barriers by increasing patient access to health services from anywhere and anytime, and to improve patient care through remote health monitoring, remote diagnostics, remote supervising, or even remote surgery. To fulfil the needs of eHealth verticals, 6G is supposed to meet their extreme requirements, i.e., ultra-high reliability with 99.99999%, ultra-low latency in sub-milliseconds. Additionally, such “on-line” healthcare applications must protect anonymity and privacy of everyone, while exploiting the power of massive amounts of data. Federated and distributed systems that harness data from many different sources while preserving data privacy and anonymity will be a key technological factor that need to be supported in 6G.

## Maritime and Aerial

Ships are normally having sporadic connectivity services for ship-to-shore connection, as it relies on a Very Small Aperture Terminal (VSAT) satellite. Airplanes also suffer from poor VSAT connectivity, reducing the quality of experience (QoE) and increasing connection costs for passengers. 5G has made progress on integrating satellite networks, but it is still far from providing a truly ubiquitous high speed maritime and aerial mobile wireless networks. Hence, it is expected that 6G should be further enhanced to expand the coverage of high-speed wireless communication to airplanes and maritime vessels, even underwater. This is beneficial for the maritime and airline industries, so that everything from an airplanes, marine end-users, vessels, marine and aerial sensors, automated marine robots and drones, and remote-end users located on the main-land are connected, which would enable all kinds of IoT use cases in maritime and aerial domains, triggering inclusively remote control of airborne and maritime vehicles and drones. Also, it can be used for route optimization to reduce cost for shipping and airline companies.

### Factory

Remote control and factory automation usually requires stable low latency that will never fluctuate. This, to some extent, has been supported by the 5G Time Synchronization Network technology being developed by 3GPP. However, future automation systems in factories are expected to support mixed types of traffic, e.g., in a production line, there may be a control system consisting of robot-arm and location sensors monitoring the products being assembled, and in addition, there may be a video camera that requires high-capacity communication. Hence, 6G shall be designed by taking into account such a mission critical industrial network with various contrasting requirements.

### Education

Under certain circumstances when traditional teaching methods cannot be employed, 6G with the capability to support extremely immersive experience can improve the digital interaction among teachers and learners. Additionally, acquiring skills such as those obtained via lab work and hands-on experience can be enabled virtually using haptic and multi-sensory communication. With the availability of artificial intelligence based techniques, the teaching and/or learning material and methods can be personalized in real-time for individual learners.

### Agriculture

Food production is a huge challenge for the near future. Nowadays, an increase in agribusiness production follows an increment in the area exploited for crops and livestock. Clearly, it is necessary to change this scenario and increase the productive per $km^2$ of exploited area. Ubiquitous wireless coverage over farming lands that are spread across vast areas and in remote regions can be efficiently monitored and managed for abnormalities such as, growing weeds and parasites, using connected devices such as robots and drones. Beyond mere monitoring, 5G has already enabled remote farmers to spontaneously capture photos, analyze and take suitable measures. 5G can be enhanced further by having artificial intelligence and sensing, which would allow plants to be aptly identified and to develop a customized plant-based methods. Furthermore, enabling a data-driven agriculture industry, which is capable of collecting data from farms, region specific sustainable farming solutions can be developed, improving the efficiency and reducing the use of fertilizers and pesticides.

### Transportation/Logistics

6G needs to enable intelligent and shared transportation, such as connected autonomous driving. In addition to ultra-low latency and high reliability wireless links, future advanced automotive use cases could rely on capabilities like artificial intelligence, sensing and precise localization to deal with unforeseen situations in a safe and efficient manner. By providing ubiquitous access using very large constellations of Very Low Earth Orbits (VLEOs) and Unmanned Aerial Vehicles (UAVs), the ability of vehicles to remain connected to a wireless network and communicate at all times is further enhanced.

Figure 3 depicts what 6G is expected to fulfill various extreme requirements in terms of “bandwidth”, “coverage”, “energy efficiency”, “latency”, “reliability”, “location sensing and “density of connectivity”. Delivering and provisioning of services with various extreme requirements from different vertical domains would be a key challenge for designing and developing 6G wireless communication systems.

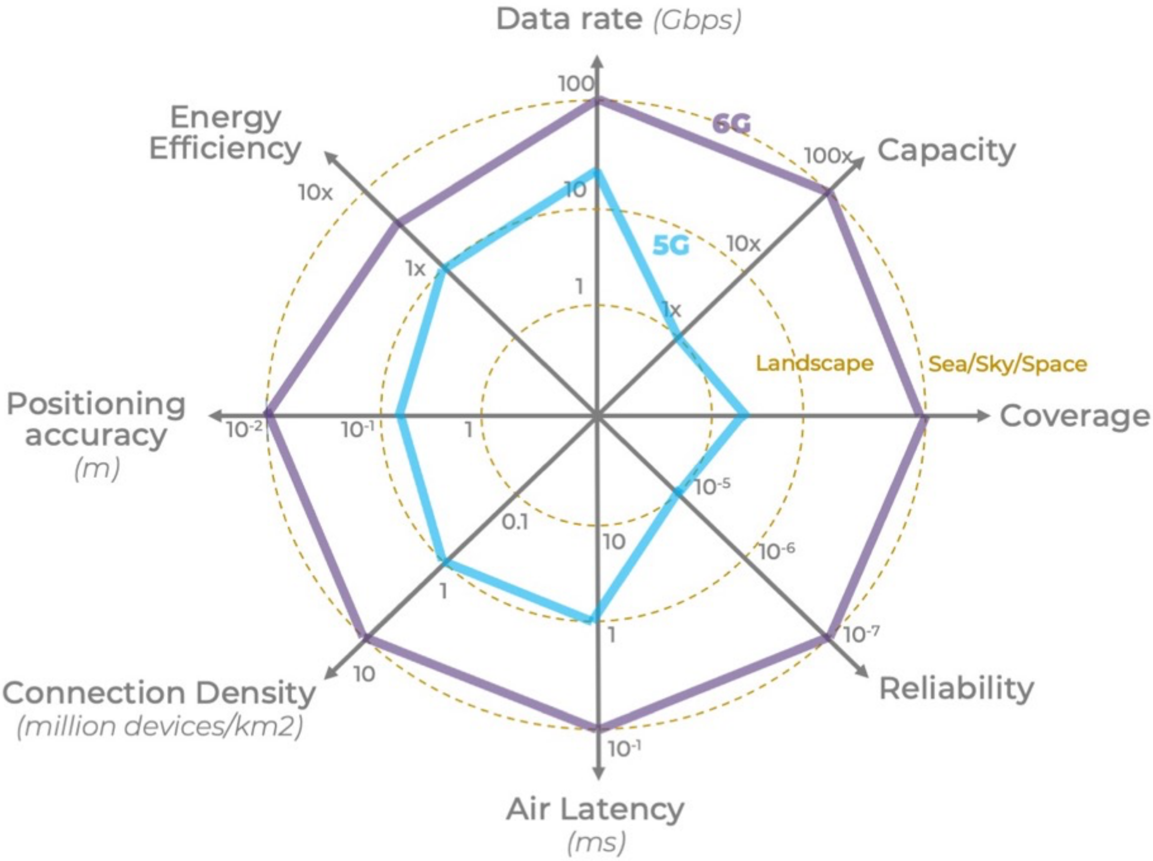

*Figure 3: Requirements for 6G wireless technology.*

# 3 Technology Pillars

## 3.1 Higher and THz frequencies

In the last two decades THz Communication, which addresses the spectrum well beyond 100 GHz, has been subject to intense research. While in the beginning of this research significant effort has been put to propagation studies and channel characterization, in the more recent years several demonstrators have proven the feasibility of THz communications [5]. Progress has not been made in research only. In 2017 IEEE has published IEEE Std. 802.15.3d-2017, the worldwide first wireless standard operating at a frequency range around 300 GHz [6] with a bandwidth of up to 69 GHz. Applications addressed by this standard are fixed point-to-point links, e. g. intra-device communication, kiosk downloading, wireless links in data centers and backhaul/fronthaul links. At the last Word Radio communication Conference (WRC) 19 additional spectrum between 275 GHz and 450 GHz has been identified for the use of THz Communications. Together with the already allocated spectrum between 252 and 275 GHz, totally 160 GHz in the frequency range 252-450 GHz are now available for THz Communications [7]. This large chunk of spectrum has the potential to achieve data rates of 1 Tbps in the future without too complex baseband processing. The potential ultra-high data rates in this frequency range have been pointed out more recently by the 6G Flagship project, which has explicitly mentioned THz communications as a candidate for 6G [8]. THz frequencies are also attractive for sensing and imaging services, and open large opportunities for integrated communications and sensing applications [9].

Still, there are great challenges to be addressed. High-gain antennas are required to overcome the high-path loss in this frequency range. This brings complications with the implementation of THz communications for mobile applications, where device discovery, beam steering and beam tracking are more challenging than at millimeter wave systems. Non line-of-sight (NLOS) links are also very challenging, where the use of large intelligence surfaces (LIS) and intelligent reflecting surfaces (IRS) integrated in building can play an important role in THz communication applications. Further challenges stem from the need for integration. The best performance of the demonstrated systems has been achieved with the expensive III-V semiconductor technologies [5], whereas baseband systems are typically based on the more cost-efficient CMOS technology.

If these challenges can be overcome, THz communications has a great potential to contribute to a successful implementation of 6G.

## 3.2 Radio access

Being able to support the requirements of the widely diverse applications and use cases for 6G is a major challenge. In particular, the requirements' 'space' of 6G applications will span a wide range of throughput, latency, reliability, scalability, service availability, service continuity, and security dimensions (among others), presenting a considerably more complex challenge than in 5G [2][10]. At the same time, achieving a much higher resource efficiency than in 5G is an essential step towards increased spectrum capacity, but also towards fulfilling the ambitious energy reduction goals for the networks of the future. Hence, 6G radio access design must be flexible and resource-efficient, being capable of adapting in real-time, both at the infrastructure and user terminal side, while fulfilling the application requirements.

A major step towards flexibility and adaptability is to relax the constraint of orthogonal resource allocation and slicing. Non-orthogonal multiple access (NOMA) occurs in non-orthogonal time and frequency resources, and enforces the separation of users in the power or code domains to apply multi-packet reception techniques. Significant work on the capacity (i.e., achievable rate) regions of single-antenna NOMA systems has been performed in the downlink [11]. However, NOMA cannot achieve the capacity region in the multiple antenna case, but more sophisticated techniques like rate-splitting or dirty-paper precoding including time-sharing have to be applied. Furthermore, the outcomes of capacity region analysis are only applicable to the resource allocation problem when the users aim to maximize their throughput, assuming a homogeneous scenario with full-buffer users. Throughput maximization is, in essence, a performance target that sets expectations on the capabilities of the protocols and infrastructure, but gives little information about the performance in practical scenarios without proper context. Moreover, service requirements nowadays do not comprise only throughput, but also latency, reliability and related novel metrics like the age- and value-of-information; energy efficiency; as well as security and privacy of the communication, especially when communication involves the delivery of short-packets as in many IoT applications [12][13]. All these metrics add a whole new dimension to the definition of resource efficiency and capacity and, hence, to the problem of slicing the resources in the radio access network (RAN). In 6G, it will be essential to advance RAN slicing and resource allocation mechanisms, including NOMA techniques by including centralized and distributed MIMO capabilities and multi-connectivity and optimize them according to the traffic patterns and requirements of the multiple coexisting applications. For this, one of the major milestones towards 6G is the design of stochastic and distributed optimization mechanisms, as well as machine learning (ML) techniques to achieve an effective and dynamic resource sharing that considers the available resources and capabilities of state-of-the-art infrastructure: MIMO, carrier aggregation (CA), modulation and coding schemes, and multi-connectivity.

The design of novel radio access protocols, e.g. in the uplink, and the mechanisms for self-adaptation is another essential aspect towards a flexible 6G radio interface that complements advanced physical layer techniques. To be able to fulfill the heterogeneous application requirements, a set of access grant-free and grant-based access protocols must be available, so that the most efficient one can be implemented. To this end, a data driven approach is needed, where the infrastructure learns an appropriate model of the environment, including the wireless conditions and the characteristics of the applications [14], that allows it to make decisions to fulfill the performance requirements of the current combination of services in the RAN with the optimal use of resources. Another essential aspect to consider in such optimization are the greatly diverse capabilities of the user terminals. In the downlink, the choice of the protocols and techniques to communicate with user terminals must depend on whether these can implement advanced multi-packet reception or interference cancellation techniques. On the other hand, power and signal processing limitations, as well as activation patterns must be considered in the uplink.

Finally, novel architectures such as cell-free are key for flexible infrastructure densification and to increase the macro-diversity of communication. By having groups of remote radio heads (RRHs) connected via fronthaul links to a baseband unit (BBU), the number of simultaneously active connections at the user terminals can increase when compared to traditional cell-based infrastructures. This can significantly increase the reliability of communication but may compromise resource efficiency and the overall transport capacity if over-provisioning occurs. Hence, the central controller must correctly coordinate and process the signals from the RRHs.

Figure 4 shows the distinct characteristics and requirements of distinct types of users and applications in a cell-free architecture.

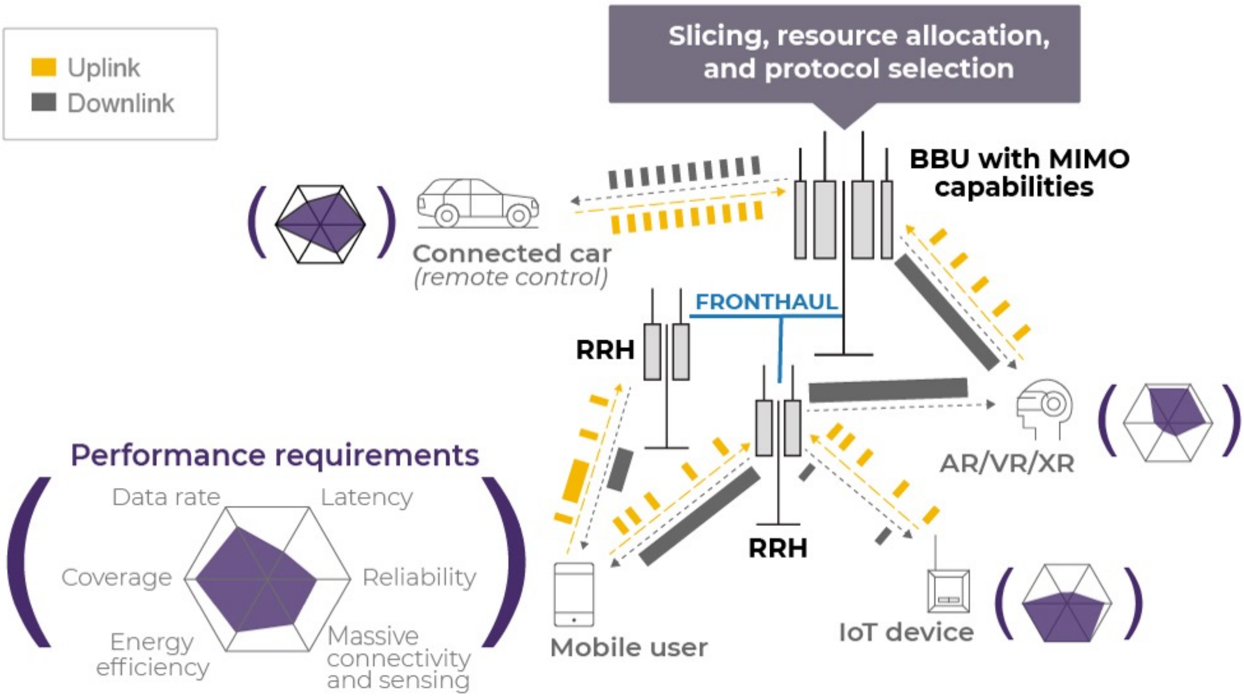

*Figure 4: Different characteristics and requirements of distinct types of users and applications in a cell-free architecture.*

## 3.3 Next generation MIMO

Multi-antenna communication is a fundamental and indispensable component of modern wireless systems. One main challenge for the next generation MIMO is achieving extremely high data rates, which are needed, for example, for advanced human-to-human communication in the mobile cloud, e.g. digital twin, haptic communication, augmented/virtual reality, ultra-high definition video, gaming, etc, requiring throughputs per user of 2 Giga bits per second, for dense networks with many users per area, combined with high reliability and a high degree of adaptability everywhere. Similar requirements hold, e.g., for industry campus networks for manufacturing.

In the context of mmWave and sub-THz bands, MIMO is essential for compensating the extreme path loss (e.g. via aligned beams). Since high frequencies cannot penetrate walls and human body, multi-connectivity is needed for ensuring robustness towards blocking. The spatial diversity can be further improved by deploying IRS and LIS. The concept of multi-connectivity can be generalized to include multi-IRS, multi-TRPs, multi-RAT, multi-operator, and other potential sources of diversity. This must be supported by new channel models for sub-THz frequencies (100-300 GHz), which are not covered by current ITU/3GPP models.

Cellular MIMO and decentralized extensions (cooperative multi-point/CoMP and centralized RAN/CRAN) follow the old cellular paradigm, which is inefficient in dense networks due to excessively frequent handovers and pilot sequence re-assignments. This motivates a new, user-centric cell-free MIMO approach, where the mobile device is navigating seamlessly through a "sea of access points" that are associated dynamically (see Figure 5). In this context, we need to explore how to do User-centric MIMO with or without IRS/LIS, with reasonable scalable complexity for beam-formed (mmWave, THz, optical wireless communication/OWC) or non-beam-formed systems. This has multiple issues related to backhaul/fronthaul, central or distributed controller, user scheduling, reference signal design, distributed precoding, etc. Taking all these aspects into account, User-centric MIMO has a large potential of providing a stable service quality across the entire coverage area, thus offering increased reliability and resilience, especially for mmWave/THz.

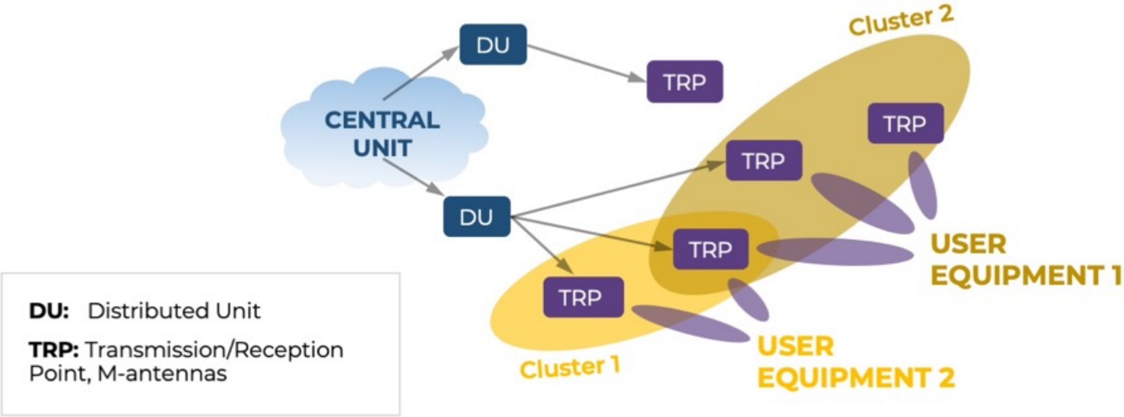

*Figure 5: User-centric cell-free massive MIMO.*

But the benefit of MIMO is not limited to high frequencies. Sub-6GHz bands are the most valuable spectrum, and MIMO can significantly improve spectral efficiency in this range. Also, distributed user-centric MIMO holds great potential for improving coverage because the allowed EIRP for each base station is limited.

Along with developing a new MIMO architecture, fundamental building blocks of the radio interface need to be revisited. This includes, for example, channel acquisition (e.g. pilot decontamination, feedback overhead, reciprocity and MIMO duality), space-time coding, and modulation, full duplex, as well as MIMO multiple access. The achievable MIMO gain crucially depends on hardware impairments and limitations. Hybrid analog/digital solution, which were favored in the past, should be revisited in the light of the latest developments. In the user-centric MIMO context, the functional split between fronthaul and backhaul determines the system performance. Also, new components, e.g. nano arrays for sub-THz facilitate ultra-massive MIMO structures implemented at chip-level.

To conclude, Next Generation MIMO offers a new dimension in system design that is not limited to the physical layer. The range of use cases is wide. Also new promising 6G applications, such as Integrated Sensing and Communications, can benefit, e.g. MIMO for sensing, sensing aided MIMO, etc. New, as yet unforeseen use cases based on MIMO will undoubtedly evolve in the future and more fundamental research is required.

## 3.4 Integrated sensing and communication

Sensing has many different meanings, ranging from basic detection of the presence of an object to refined information about the environment and the related object(s) of interest (i.e., object's location, velocity, micro-Doppler characteristics, etc.). Sensing capabilities via radio frequency (RF) (or other) signals have gained increasing interest for various applications, such as autonomous driving, assisted living, safety and human-machine interface. Consequently, there is an increasing demand for systems exhibiting both sensing and communications capabilities. Sensing and communications have however traditionally been performed separately by different entities, functions and/or frequency bands [15]. Machine learning-based approaches based on soft information (SI) for localization-of-things have been proposed in [16] for accurate positioning to overcome the limitations of classical approaches. In particular, the SI encapsulates all the information available from measurements and contextual data at the UE at a given position, including sensing measurements (e.g., using radio signals), digital map, and UE profile.

For the next generation of mobile systems, a key goal is to provide both sensing and communications functionalities. This is further enhanced by the use of new frequencies (70 GHz and above),  with very wide bands which can be utilized to provide sensing with high-resolution capabilities. There are several possible sensing and communications integration options which include:

- *Different systems and different bands* – Integration at the higher layers. For this type of integration, the separate sensing and communications systems exchange information with each other at higher layers to aid operation in some way (i.e., sensor-based communications).
- *Different systems and shared bands* – Integration in terms of scheduling. The sensing and communications signals are multiplexed in time, frequency, and / or space for this type of integration, enabling the two functions to share the spectrum and also partially share hardware resources.
- *Full integration* – Same system and band. For this type of integration, the sensing and the communication system are fully integrated and share the hardware, transmitted signal and the frequency band [17]. This approach is also known as joint sensing and communication (JSC) and exploits the waveforms transmitted by a communication network to perform sensing [18].

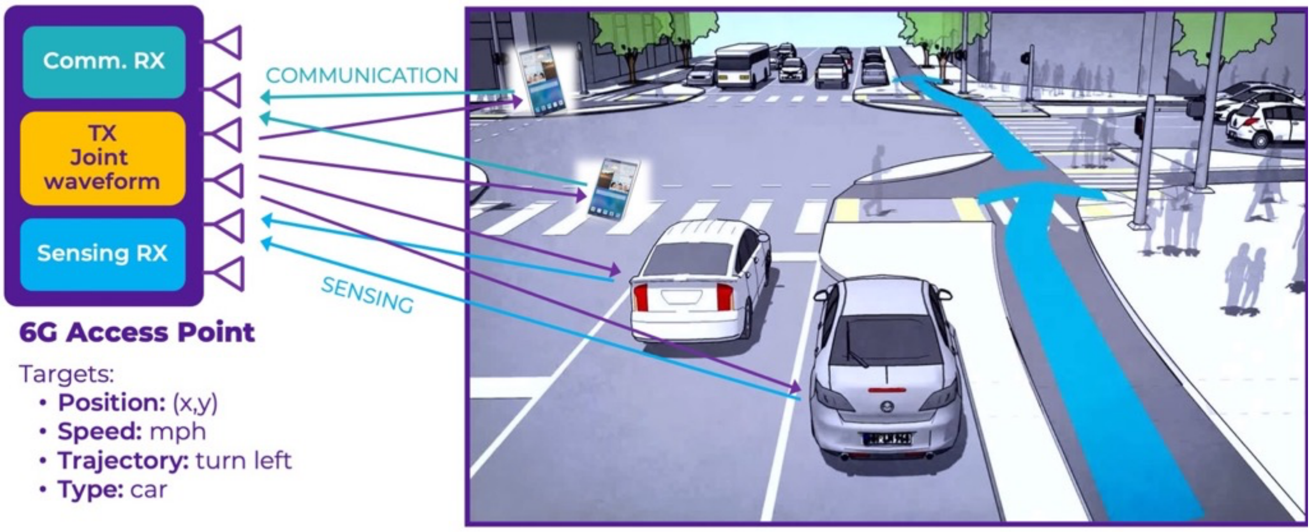

*Figure 6: Joint sensing and communication in an urban scenario.*

By fully integrating sensing and communications, we need to implement systems capable of supporting both functions together, using the same spectral resources and hardware which thereby reduces cost, power consumption, latency, and size.

To reap the full benefits of such a fully integrated solution, it is important to investigate different approaches and address several key technical challenges. The two main approaches are:

1) Integrate sensing into existing communication waveforms (e.g., OFDM / SC-FDE) which has the following subtopics;

    - Optimize the spectral allocation by suitable transmission parameters for the combined use of sensing and communications;
    - Investigate systems with very large RF bandwidths (several GHz) for sensing but with low ADC sampling rate and complexity (i.e., stepped or sparse OFDM);
    - For monostatic arrangements, a full duplex transceiver is needed and the requirements in terms of dynamic range for long rang sensing is needed. For multistatic setups, the impact of signaling, resource allocation and coordination of Tx / Rx network entities is needed.

2) Design new waveforms for integrated communication and sensing, (e.g., orthogonal time frequency space modulation (OTFS) [19]) and study the in-depth advantages and disadvantages of such waveforms.

To conclude, integrated sensing and communications represents a key innovation in 6G that paves the way for new applications and expands the mobile network concept. However, this poses challenges that will require considerable research effort. In particular, the radical revision of the physical layer design requires integrating functionalities with diverse and competing objectives.

## 3.5 Distributed and federated AI

The majority of current AI/ML solutions perform centralized learning, where data are gathered all over the system, but the training is performed in a single location [20][21]. In a distributed platform, e.g. in carrier networks, performing centralized learning is not optimal and often too costly, due to data gathering overhead, considerable energy supply requirements at the centralized data center (DC) to be shouldered by the responsible tenant/owner, and privacy issues. Towards 6G, it will thus be of utmost importance to define novel techniques, which will enable the system to perform and coordinate the learning and execution in a distributed manner, over a pool of -possibly heterogeneous- resources (e.g., computing, connectivity, storage and energy resources), which are available from the core to the deep edge (see Figure 7).

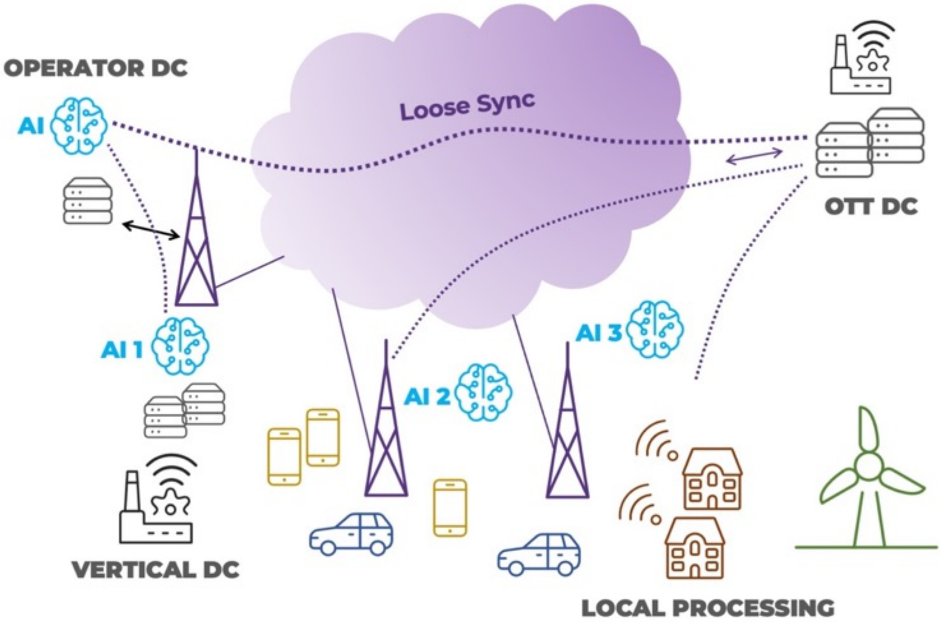

*Figure 7: Distributed AI agents residing at base stations, cloud centers or end users (e.g., vehicles).*

This will require adaptation and extension of current AI technologies, such as federated learning, as well as development of new distributed AI techniques and algorithms. The energy source nature of the resources to be used should be a key consideration, so as to achieve a preferential usage of renewable energy sources (such as local wind and solar energy) for compute-intensive AI computations, therefore making the innate 6G AI greener and more sustainable.

A carrier network along with connected terminals forms a distributed platform, where computational resources are distributed from the core to the edge computing and goes down to deep-edge resources (such as smart homes, smart factories, smart cars, drones). Data is also gathered and collected all over that distributed system, and hence in a distributed manner, including on and from end devices (vehicles, mobiles, etc.), on BSs, on routers, on NF instances, on application servers. Therefore, there is a great interest for distributed learning and execution; to offload computation tasks, and, thus, to increase the speed of learning; to bring computation closer to data, decreasing latency, transmission overhead, and cost; and to conform to privacy constraints, letting users make some privacy-crucial calculations on their own resources.

Besides, due to the advances and recent policies in smart-grid technologies and renewable energy production e.g. in Europe, we expect the energy production to be also more and more distributed, with many (smaller) energy resources (such as wind turbines and solar cells) deployed closest to the edges. By distributing the learning and execution of AI, and by making informed choices for compute nodes, we could overall benefit from these green energy resources, e.g. by training or distributing the models when and where there is an excess of energy production, in the distributed edge, or when the cost per W is lowest, therefore making the AI greener and moving toward a more sustainable design [22].

To this end, the main challenges that are identified towards enabling the afore-discussed technology can be summarized as follows:

**Engineering**, by adapting, modifying, current techniques such as federated learning:

- Dealing with heterogeneity of resources (computation, storage, energy)
- Dealing with dynamicity (e.g., moving vehicles, resource churn)
- Efficient online-learning (AI-as-you-go)

**Fundamental research/algorithmic**, via developing novel schemes and algorithms, respective robustness and convergence studies, etc. Some questions that are raised and which target to lead to promising, novel solutions comprise:

- How to enable learning when the state or reward information are partial, or if the reward is sparse (specific to deep reinforcement learning)
- How to make learning more efficient in dynamic environments
- How should the system handle competing, selfish, partly- or non-collaborative agents
- How to enable transfer learning, so that the trained policy can be adjusted to new settings with limited retraining effort
- How to detect and prevent wrong decisions, when an anomaly occurs? Could/should we apply hybrid solutions, to fall back to safe mode (e.g. applying heuristic), when such occurs
- How to learn the reasoning, and not only the policy, so that what is learnt can be generalized to similar situations? (Curiosity learning, etc.)

## 3.6 Flexible programmable infrastructures

While previous generations of mobile systems were using a central office paradigm, 5G has kicked off a transformation process tending towards core and (radio) access network disaggregation. 5G can be deployed leveraging virtualized and cloud resources from several data centers, including edge data centers. The support for network slicing will require more flexibility with regard to resource assignments and request-to-resource mappings, both in the compute and storage and the interconnecting networking infrastructure. We believe, and many ongoing activities related to 5G deployments confirm this belief, that this trend will be present in 6G too. Therefore, in 6G the consideration for a distributed and controllable resource pool becomes one of the crucial research questions to be addressed.

6G is often believed to provide full-service support (including services beyond network connectivity, such as compute, storage but also intelligence, in contrast to the previous generation networks, which are often limited to network service provision only. A full-service support would transform the notion of the “session” from a “connectivity session” to a full-service execution and therefore, require provisions for compute and storage service allocations (‘in-network’ computing and caching) in the user plane as well as the corresponding extensions in the control and management planes. Together with the trend to distribute more the involved resources, this would further amplify the requirements for dynamic resource assignment and control. This dynamicity will be essentially on a per-request basis, in runtime, and versatile, i.e., spanning the overall resource pool (networking, compute, and storage resources). In addition, the resource pool is expected to encompass a high mix of runtime technologies (e.g., ad-hoc HW, FPGAs, bare-metal, containers, VMs), public and private deployments, and mobility patterns.

A coherent, holistic control of a running network, which includes controlling access, routing and network function nodes at the same time, is essential for making informed, optimal runtime (and even autonomous) decisions. This enables efficient and effective operation of the network from the point of view of both its users (providing a range and quality of services as expected by the end user) and of the network operator (e.g., reducing the total cost of ownership, the network footprint, etc.). With the core disaggregation initiated by the service provision flexibility stipulated by the virtualization and data center technologies usable in 5G (“in-compute networking”), this same runtime controllability must equally comprehend compute, storage and network nodes.

6G holistic approach unifying the whole previously defined resource pool, requires the knowledge of each participating entity capabilities (connectivity, security, and QoS among others) in the resource pool. Spreading service components across a distributed pool of resources raises the concern of whether the expected service requirements will be met. Due to its distributed and heterogeneous nature, it is important to characterize, standardize and expose resource capabilities, to guarantee the performance of service components allocated in the resource pool.

Recent years show the ever-increasing trend in mobile systems of using real-time and historic data for optimizing and forecasting resource utilization, service quality, and security threats. This trend is expected to become pivotal in 6G systems where many aspects related to supervision and decision-making will be based on available data and contextual information. Dealing at scale with the amount of monitoring information that will be generated in 6G systems, both from the infrastructure and the services, nonetheless requires current systems to evolve and embrace a more distributed paradigm for data distribution and storage. Furthermore, location-transparent access to data should be provided in 6G systems to facilitate the consumption of information throughout the system, regardless the location of the storage or the data consumer.

As a result, full-service monitoring, control, and management could be significantly streamlined in the case of data interfaces and capabilities are standardized and exposed.

These changes should be accompanied by an advance in the adopted programmability model. Instead of network focused, low level programmability mode, as available now, 6G systems should adopt a more generic, declarative programmability model, where a high-level desired status is stated, as opposed to the set of corrective actions to reach it. That model should focus on all parts of the infrastructure, including the access, transport network, higher level network processing, and storage, i.e. be holistic in its nature, just as the other aspects of the system discussed above.

## 3.7 Non-terrestrial networks

Global connectivity cannot be achieved solely with terrestrial infrastructure. This is due to multiple geographical and economic factors, in combination with the limited coverage of terrestrial communication technologies. Furthermore, while cell-less infrastructures have a much greater densification potential than traditional cell-based networks, the varying traffic demand may locally exceed the network capacity. Hence, the major use cases for non-terrestrial networks (NTN) in 6G include backhauling, providing service availability guarantees in remote and underserved regions, service continuity, and traffic offloading [23][24].

Low Earth orbit (LEO) satellites are usually deployed between 500 km and 2000 km over the Earth's surface. Compared to satellites in higher altitudes, the footprint of LEO satellites is small. In exchange, the altitude of deployment is sufficiently low so that user terminals can communicate with them in both uplink and downlink, either directly (e.g., NB-IoT) or via terrestrial or aerial relays, with one-way latencies of a few milliseconds. Common aerial relays include unmanned aerial vehicles (UAVs) and high-altitude platforms (HAPs), but LEO satellites can also communicate with satellites at other LEO altitudes, at medium Earth orbit (MEO), and at geostationary orbit (GEO). This enables the deployment of a widely diverse infrastructure at different altitudes; the so-called 3D-networking.

A fully functional NTN communications infrastructure implementing, among others, proper access protocols, inter-satellite communication, routing, congestion control and load balancing mechanisms would be able to provide global connectivity for low latency services, delivering data around the globe within a few tens or hundreds of milliseconds. Furthermore, NTN networks can be used to provide ubiquitous edge computing capabilities and artificial intelligence as a service (AIaaS) in both a centralized and distributed manner. However, the rapid movement of the satellites with respect to Earth (up to 7.5 km/s) and with respect to each other introduces many major communication challenges. For instance, NTN links are affected by a relatively large and varying Doppler shift, requiring frequent and precise antenna pointing and potentially benefiting from adaptive modulation and coding to achieve proper throughput and reliability trade-offs. Because of these challenges, inter-satellite communication technology is still in its infancy, with only a few private companies (*the* driving force in the New Space era) planning to implement inter-satellite links, and typically considering free-space optical (FSO) technology. Moreover, standardization efforts towards an integrated terrestrial and non-terrestrial infrastructure are progressing slowly. The considered architecture for release 16 of the 3GPP only included the bent pipe architecture, where the received data at the LEOs is immediately relayed back to a terrestrial base station [24]. Since a full integration may not be possible in the 5G era, 6G presents an excellent opportunity for the design of an integrated terrestrial and non-terrestrial infrastructure.

# 4 Outlook

6G has to be ONE sustainable, affordable, accessible, and open system. In our commitment towards such endeavor, we set the first driver of 6G to be sustainability and social responsibility, embracing connectivity for everyone, everything, and everywhere. It is crucial that deploying, operating, monitoring, and managing 6G networks and services be cost- and energy-efficient, easy, and automated. one6G will empower smart connectivity for a better future. The one6G initiative will help unlock the full potential of both public and private organizations in the digital decade, empowering international co-creation. one6G will foster participation of visionary researchers from academia and industry, global operators, major market players in selected verticals, regulatory agencies, market analysts, as well as innovative SMEs. one6G will on-board major players from several vertical industries to be engaged from the beginning and will promote cutting-edge technologies through joint initiatives, working groups, pre-standardization efforts, testbeds, user engagement, trials, demonstrations, dedicated liaisons and other activities.

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