The 5G Infrastructure Association

European Vision for the 6G Network Ecosystem

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Executive Summary

In the coming decade, 6G will bring a new era in which **billions of things, humans, and connected vehicles, robots and drones will generate Zettabytes of digital information**. 6G will be dealing with more challenging applications, e.g., holographic telepresence and immersive communication, and meet far more stringent requirements. The 2030's could be remembered as the start of the age of broad use of personal mobile robotics.

6G is the mobile network generation that will help us tackle those challenges. 6G will likely be a **self-contained ecosystem of artificial intelligence**. It will progressively evolve from being human-centric to being both human- and machine-centric. 6G will bring a **near-instant and unrestricted complete wireless connectivity**. A new landscape will also emerge for the enterprises, as a result of the convergence that 6G will allow in the fields of connectivity, robotics, cloud and secure and trustworthy commerce. This will radically **reshape the way enterprises operate**.

In short, **6G will be one of the basic foundations of human societies of the future**. To enable a sustainable progress for society, in line with the United Nations Sustainable Development Goals, it is crucial that 6G addresses effectively pressing societal needs, while delivering new functionalities. This (r)evolution must be in line with Europe's primary societal values, in terms of e.g., privacy, security, transparency, and inclusiveness. Digital technologies are also becoming a critical and essential means of ensuring countries' sovereignty. **The development of Europe-based 6G infrastructures and solutions is one of the keys to secure European sovereignty in critical technologies and systems**.

The convergence of 6G with operation technologies raises the prospect of disassociating the location of manufacturing, industrial equipment, assets, and processes, from the actual location of the human operators. This will introduce unprecedented changes in our way of life as it is likely to redistribute the existing balance between urban and rural areas, potentially redefining the role of cities, by reversing the urbanisation trend. The COVID-19 pandemic has already amplified the social and economic significance of ICT infrastructure, in terms of e-working, e-commerce, and e-health. **End-user engagement** will be increasingly important for a smooth acceptance of new technologies like 6G. To ensure that 6G can be inclusive for all people across the world, it needs to be **affordable and scalable**, with a **great coverage everywhere**.

Key features of 6G will include **intelligent connected management and control functions, programmability, integrated sensing and communication, reduction of energy footprint, trustworthy infrastructure, scalability,** and **affordability**.

The 6G architecture should be sufficiently flexible and efficient so as to enable **easy integration of everything**, i.e., a network of networks, joint communication and sensing, non-terrestrial networks and terrestrial communication, encompassing novel AI-powered enablers as well as local and distributed compute capabilities. The use of AI everywhere in the network, where it can be beneficial, i.e., the "**AI everywhere**" principle, will be used to enhance network performance and to provide AI-as-a-Service in a federated network. AI and Machine Learning will help to maintain operation cost-effectiveness of envisioned complex 6G services, such as the interaction on human-digital-physical worlds and Internet of Senses, to automate some level of decision-making processes, and to achieve a zero-touch approach.

Several types of foundational technologies will drive the core development of 6G. Expanding network capacity to approach or even to try and go beyond the Shannon's and Moore's limits will be required for radio themes. Smart optical transport connectivity will allow the network to be always available, intrinsically secure, green, and with flexible scaling. Advances in photonic

integration will pave the way for a raft of new IT and networking devices in which optical, radio frequency, and digital electronic functions, can be combined. Modern security and reliability paradigms ("security by design"), as well as the application of modern software technology, will guarantee the dependability and trustworthiness of the system. New electronic technologies, components and devices, including processors, memories, analogue, radio frequency, digital access and cross-connect systems and analogue to digital converters antennas, packaging and optical components, will be required. The exploitation of properties from quantum mechanics needs to be explored to understand their potential for unprecedented performance in quantum sensing, communication, security, and computing.

Recommendations

Europe's goal shall be to **ensure leadership in strategic areas and find alternate ways of establishing a secure and trusted access to those technologies, where a European supply network cannot be established**. Such an approach would create business opportunities by **making Europe a sovereign, independent, and reliable source for 6G public and private network solutions and services**.

Public and private R&I investment shall focus on key 6G technologies, such as programmability, integrated sensing and communication, trustworthy infrastructure, scalability and affordability, as well as AI/ML, microelectronics (at least in design), photonics, batteries (e.g., for mobile devices), software, and other technologies that may help to reduce the energy footprint. Europe needs programmes to **foster Entrepreneurship with private and public participation**, with an effort in GDP comparable to other markets, complemented with **tax policies for start-ups**, to avoid relocation of promising businesses because of tax savings.

The ultimate completion of 6G requires full interoperability between all entities on all levels, i.e., **global standards**. This would ensure an affordable and scalable 6G system that may be utilized worldwide. Effective standardisation requires sound regulation and governance, which in turn require a **common certification process**, taking into account the growing number of vendors that will develop for an ecosystem (across Europe), plus a **lean process** which would allow verticals to sell their services from anywhere to everywhere.

The deployment of services using new 6G capabilities and the emergence of millions of specialised and localised subnetworks **may require further clarification for what concerns the applicability of net neutrality rules and of the data protection regulation (ePD and GDPR)**, potentially adding a new dimension to the current scope of Net Neutrality. The **emergence of new European players should be supported**, and **sovereignty and security requirements shall be well identified and enforced**. AI-based sophisticated automation to deliver services in 6G networks will require additional regulations, based on **ethics principles that conform to European standards**. The Intellectual Property Regime (IPR) might need to be reconfirmed, taking into consideration the ongoing geopolitical trends.

To compete globally in 6G, **Europe needs a world-class competence pool** in communication protocols and software, virtualization and cloud, cybersecurity, microelectronics (at least in design), photonics, both in industry as well as in academia. Core skills in Science Technology Engineering and Maths and Social Sciences and Arts should be strengthened, as broader and cross-fields knowledge and therefore successful innovations will also benefit from diversity of thoughts. A Responsible Research and Innovation approach should be applied, fostering public engagement and ethics, along with a specific effort to increase the number of female technical experts.

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1 Introduction

The COVID-19 pandemic has vastly demonstrated the key role of connectivity platforms to sustain economic and societal processes. The starting deployment of 5G in Europe and in the world will further increase the competitiveness and the resilience of European industry by enabling to digitise and automate business processes in domains as diverse as connected cars, smart factories, healthcare, media production and delivery, public safety, and many more. In the longer term, the convergence of multiple business process with connectivity platforms as initiated by 5G will further amplify and address domains where performance requirements will not be matched by 5G capabilities. Systems beyond 5G, or 6G, will hence have to meet new levels of vertical performance requirements not within reach of the foreseeable evolution of 5G systems as currently planned under 3GPP. In that context, extremely demanding immersive applications like holographic communications, digital twins, or massive XR/VR applications will require 6G capabilities to perform at scale and to be commercially viable. On the other hand, every new generation of mobile communication systems brings with it completely new application capabilities. In that respect, new applications prospects like the Internet of Sense, merging communication with sensing capabilities, offer new application horizons to connectivity systems. Because of the multiplicity of use cases potentially generating massive amounts of data, 6G systems will also have to natively incorporate analytic and intelligence capabilities beyond reach of existing systems, in view of enabling real time decision making on high data volumes potentially originating from very large collection of sensors. Connected intelligence is hence expected to become a distinguishing feature of 6G systems, both at the service of the 6G platform performance and efficiency and at the service of the vertical use cases running on top of it. At the same time, the very large volumes of data that will have to be processed by 6G system in a multiplicity of business-critical applications call for ultrahigh levels of security whilst respecting trust and data privacy.

Beyond these functional properties, 6G systems should be designed to take full account of key policy challenges that our societies are facing. 6G needs to be sustainable and we also need to look for opportunities for using 6G for sustainability in other sectors of society and industry. Affordability and accessibility are also important drivers for future 6G systems, especially considering that more than 3,5 Billion people on the planet do not have Internet access. Also critical, EMF are becoming issues of raising concerns with the populations, and 6G should of course continue fulfilling all health and safety related requirements. Altogether, a clear focus on key SDG (Sustainable Development Goals) should be considered for 6G systems.

6G networks are expected to deliver efficiency clearly superior to 5G and satisfy evolving services and applications, making them a key enabler for the intelligent knowledge society of 2030. This vision includes services with long range, low bit rate, ultralow capacity, and long latency, as well as ultrahigh bit rates, such as 100 or even 1,000 Gb/s, available only at special locations (up to 1 s). Moreover, 6G will link everything, provide full-dimensional wireless coverage, and combine all features, such as sensing, connectivity, computing, caching, monitoring, positioning, radar, navigation, and imaging, to enable full-vertical applications.

Overall, 6G is expected to be a self-contained ecosystem with flexible management and control and automated human-like decision-making processes. It will build on top of the current human-centric network architecture where service-specific variations (vertical-oriented network slices) apply to a holistic self-learning service provisioning platform, engaging any type of connectivity and device. To decode this vision, we have organised this document as described below.

In Section 2, we describe the positioning of EU and other stakeholders in the process of defining the societal and business potential of 6G era. Activity of regulation bodies is reported highlighting the EU role towards 6G, and the expected reshaping of the digital world.

In Section 3, the key objectives of 6G are decomposed, highlighting multi-dimensional benefits that justify the need for the 6G (r)evolution. Indeed, 6G is expected to move beyond the performance stretching of 5G. Aspects such as the convergence of physical and human pillars in a digital word are considered, where society is main receiver of the benefits that the technology evolution brings. KPIs such as the affordability, scalability and sustainability drive the design of the 6G era, while the network programmability (introduced in 5G), stands in the epicentre of a self-learning network management controlled by the infrastructure owners and the vertical service providers.

Digging into the technological advancements expected by 6G, the main related enablers are listed in Section 4. We summarise the directions regarding the architecture, the control, the computation, the connectivity, and the device design. For the perspective of the architecture and control, the recently coined zero-touch management defines the basis for 6G systems.

Connectivity agnostic service provisioning is also foreseen, where optical networks, wireless networks and non-terrestrial access networks are considered, through an evolutionary signal processing and chip design.

Considering the architecture of the mobile communication systems, the 6G principles are provided in Section 5. A point-to-point qualitative comparison between 5G and 6G is provided, highlighting the role of the infrastructure and the programmability features on top of it.

Essential information regarding the activity and the expected timing is provided in the last section (Section 6). As it is presented, the realization of 6G vision is endorsed by the Horizon Europe program and has the support of 5GPPP and SNS partnerships. Remarkably, ITU-R has formed group on IMT towards 2030 and beyond (6G) targeting to complete the study on 6G vision by end of 2023.

2 Societal, policy and business drivers for 6G

2.1 6G global activities

A key to fast and seamless adoption of new technologies across the globe is a timely and effective **standardization**, performed by Standards Developing Organizations (SDO), aligned among all relevant stakeholders. Several SDOs are expected to work on 6G, e.g., 3GPP, ETSI, IETF and IEEE, in a much tighter way than they did for 5G, as 6G intends to merge and make work together different technologies, which have been taken care of, so far, by different SDOs.

Effective standardization requires sound **regulation** and governance that surround the technical work of the SDOs and ensure proper legal frameworks among different geo-areas. In that context, the Intellectual Property Regime (IPR) for 6G might need a re-fresh, taking into consideration the ongoing geopolitical trends of indigenous agendas and bring-back-home approach. Indeed, there is a growing trend in Europe for regulatory sandpit concepts, as it is key to observe and debate innovation at close quarters when anticipating mass market impact. The national approach to regulation is an artifact of technological opportunities and institutional and social acceptance models. As 6G becomes pervasive the challenge of how and what to regulate becomes ever more intense. A future in the 6G timeframe were Artificial Intelligence (AI) agents of regulators are embedded in networks can be foreseen.

Standardization work on 6G is not expected to start till 2025. However, already in 2020 the **ITU-T *Focus Group on Technologies for Network 2030 (FG Net-2030)*** issued a set of visionary documents [2-1] and **in EU** several associations are currently working on devising what 6G is. For instance, ***NetworldEurope*** [2-2] issued a new Strategic and Innovation Research Agenda (SRIA) towards 6G, as they did in the early times of 5G [2-3]. That document was taken as the technological basis of targets that will be implemented in the scope of the ***Smart Networks and Services*** (SNS) Partnership [2-4] between the European Commission (EC) and the private side in EU. Finally, a set of EU-funded research projects has recently started to address the challenges of the path towards 6G [2-5], with Hexa-X as the Flagship project, and some major private Information and Communication Technology (ICT) companies have started issuing announcements about internal programs focusing on 6G.

Outside of the EU other areas have started to define their own vision on 6G, establishing think-tanks and associations for that purpose. For instance, **in USA** the ***Next G Alliance*** [2-6] started in 2020 with the aim to advance North American mobile technology leadership through private sector-led efforts. **In China** the ***IMT-2030(6G) Promotion Group*** was established in 2019 to promote 6G research and build an international view exchange platform. **In Japan** the government has recently announced a 70 B¥ plan to foster R&D and build a facility to develop 6G-related technologies [2-7]. **In South Korea** there is a plan to launch a pilot project for 6G mobile service already in 2026 [2-8]. At the moment of writing, other areas of the world have not yet disclosed clear and concrete plans for 6G.

2.2 Society

After the publication of the **United Nation Sustainable Development Goals (SDG)** [2-9], legislators worldwide are pushing for aligning country rules. For instance, the **EU issued the European Green Deal** [2-10], a set of policy initiatives with the overarching aim of making

Europe climate neutral in 2050 and focusing on aspects like sustainability, handling of climate change, strengthening of security (e.g., EU's security toolbox [2-11]), trustworthiness, minimization of digital divide, the support of inclusion, and equal opportunity provision. Most of the SDG objectives can be accelerated by the capabilities coming with new generations of networks (beyond 5G and 6G). Furthermore, the COVID-19 pandemic has amplified the social and economic significance of ICT infrastructure, e.g., e-working, e-commerce, and e-health.

In order to enable sustainable progress for society, it is key to have a **human centric approach** to how technology and related services are changing our lives and the environment. **End-user engagement** is also increasingly important for a smoother acceptance of new technologies like 6G, which are expected to have ubiquitous presence, carry vast data about the person and her environment, and imply continuous digital interaction.

The above will impose great challenges on the design of the evolving communication infrastructure. For instance, radio access network densification, support of multiple logical networks over the same HW infrastructure, mass deployment of edge and cloud components as well as massive increase of sensors will cause a significant increase of **energy consumption**, potentially enhanced footprint of greenhouse gas (GHG) emissions. Currently, ICT already contributes around 2,5% of the global GHG emissions [2-12]; unfortunately, that figure tends to grow in light of the ever-growing demand of new and enhanced services. Therefore, 6G needs to be designed even more as an **energy optimized system** including smart solutions (i.e., integrating AI to achieve optimizations), less energy demanding new radio technologies, as well as business models that foster energy efficiency. In parallel, it is also important to stress that the evolution of 5G beyond the 3GPP Release 18 and especially 6G will have an even more important role in enabling services that will lead to a more **sustainable** future. It can be envisaged that a system, to be qualified as 6G, will need to operate in a way that is compliant with strict sustainability criteria; this may create opportunities for new certification procedures.

At each new generation, communication systems get more powerful and complex, thus calling for larger financial investments to deploy and operate them [2-13]. Therefore, to attain appropriate Return on Investment (ROI), new systems like 6G will be mostly directed to richer areas, and in the mid-term this trend can be detrimental from the societal and financial viewpoints. Such an example is the constant upgrade of the investments in urban areas, compared to the lower volume of investment done in less-densely populated, sub-urban and rural ones; this trend, experienced whenever a new system, e.g., 4G and 5G, is launched, hinders the deployment of new services, in addition to the widening of inequalities. In this respect, **6G** should be created to encompass efficient solutions, suitable for various environments and situations. This **will foster inclusion and contribute towards the reduction of the (currently growing) digital divide**.

Moreover, the **convergence of 6G,** an integral part of **ICT, with operation technologies (OT)** raises the prospect of disassociating the location of manufacturing, industrial equipment, assets, and processes, from the actual location of the human operators. This will introduce unprecedented changes in our way of life as it will redistribute the existing balance between urban and rural areas, potentially redefining the role of cities by reversing the urbanization trend.

Furthermore, as systems evolve into more and more intelligent, powerful, and dynamic ones, **trust** on those systems becomes more and more crucial. In the context of network design, trust is not only associated with security (e.g., the procedures of authentication, authorization, non-repudiation), but also relies on further aspects, namely, functional criteria (e.g., the behaviour of the system and the way it manages data), and non-functional criteria (e.g., the performance, the resource consumption and the costs of deployment and operation). Indeed, an important system-component and key enabling technology of our times is AI. **Trustworthy AI** can be an essential factor that will lead to a 6G infrastructure that can be trusted. This opens new streams for research and development, for embedding new capabilities into 6G infrastructures.

Currently, there is a trend of rising open marketplaces hosted on hyper-scale internet-based retail platforms, which leads to the decline of revenues in highstreet retail that is mainly based on physical presence and customer visitation. Such a trend is further accelerated during COVID-19 pandemic and by the lockdown restrictions which may cause **death of the highstreet** if no countermeasure is taken. To stay competitive highstreets are therefore moving into the cyber-physical domain, with the target of evolving into an immersive and quality of life enhancing environment, holding consumers in a mixed retail, catering, and entertainment like highstreet of the future, e.g., the planned NEOM future city [2-14]. 6G is expected to provide cost-efficient and effective means to achieve that target.

To support those developments, it is of utmost importance to train the looked-for workforce with **core skills** on Science Technology Engineering and Maths (STEM). In addition, 6G is expected to require broader and cross-fields knowledge and therefore successful innovations will also benefit from diversity of thoughts, thus leading to an increased emphasis in Social Sciences and Arts related skills to be added to the traditional STEM ones.

The recent announcement of a 4G system being commissioned for utilisation on the **Moon** hints towards the new frontiers into which communications systems may emerge [2-15]. Communications to satellites and the International Space Station (ISS) are being commoditised as more and more private industrial players enter, whilst travels to Moon and Mars are gaining again attention. 6G should therefore offer key architectural concepts and spectrum capabilities that can enable network deployments beyond the GEO systems of today. Greater engagement from bodies like the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA) in specifying global standards can be anticipated in the 6G era.

2.3 Policy context

"In the 21st century, those who control digital technologies are increasingly able to influence economic, societal and political outcomes" [2-16]. Global policy makers more and more consider digital technologies as critical and essential means for the autonomy of their countries and as the foundation of countries' **sovereignty**. In the continuously evolving geopolitical context, the EU is updating its political and industry strategy with respect to digital technologies and seeks to bolster its digital sovereignty that rests on three pillars: computing power, control over data and secure connectivity [2-17][2-18]. The target is neither to seek total independence nor to isolate the EU from other parts of the world, rather to develop strong European technology offers and alternatives that meet European political interests and values, as well as economic and societal goals. A central key is then to develop secure infrastructures such as 6G and to secure European sovereignty in critical technologies and systems in next decades [2-19].

The EU is currently in a privileged position regarding communication networks, as it **hosts two out of the four major telecommunication vendors and three global satellite operators**, meanwhile European companies own over one quarter of essential patents related to the 5G standard as of 2019 [2-20][2-21]. Such global leadership position is however under threat amid rising concerns on security and supply chain disruption as stressed by the COVID-19 outbreak. In particular, the EU is currently lagging in terms of cloud platforms, end devices microelectronics, and photonics in the communications domain [2-20] and therefore cannot currently fully provide on its own end-to-end solutions. Despite of presence of strong telecommunication players, the EU only holds 3.5% of the global electronics production in this market. This may be attributed to the absence of a strong fabless ecosystem and the lack of design capabilities and fabrication technology leadership in very advanced CMOS processes, i.e., technology nodes below 10 nm. 6G is strategically important to European technological sovereignty in the coming years, and pure market dynamics may need to be complemented by a set of actions steered by a European industrial policy [2-22].

The joint declaration by EU member states in December 2020 on a European initiative on processors and semiconductor technologies (EPI) [2-23], and the recently announced ‘GAIA-X A federated data infrastructure for Europe’ initiative [2-24] are very recent first and promising steps towards that direction.

The EU develops, within a certain framework (e.g., legal, social), products, systems and services which are built to operate according to its set **values** [2-25]. The EU has a deep-rooted tradition in developing wireless systems and will continue being a big market for such technologies moving towards 6G. In the light of these aspects, it is important to make sure that the EU will interact with other areas of the world, promoting the adoption of its values, from the perspective of both the society and the environment, and for guaranteeing a level playing field, in which all human beings can hope for a better future.

2.4 Business

Defining **the enterprise of the future** and understanding the way it interacts with 6G is critical for an efficient value creation. A new landscape will emerge for the enterprises as a result of the convergence that 6G will allow in the fields of connectivity, robotics, intelligent transport systems, cloud, and secure commerce and trust, which will tune-up with new community collaboration approaches to create new and agile business models. 6G is the catalyst and the central means of this looked-for convergence which will radically reshape the way enterprises operate and make business.

So far, digitization has primarily affected the activities that act as prerequisites or are complementary to the actual production, e.g., the workers in front of a computer at a desk. The aforementioned ICT and OT convergence fostered by 6G will lead to the emergence of prosumers, while the remote connection and remote interaction will allow for a broad implementation of the **‘deskless’ workers concept** for the benefit of several verticals. Such workers will carry out their tasks by means of new digital tools or apparatuses which will enable them to perform their activities asynchronously, i.e., they will decide where and when the tasks are executed. Furthermore, the workers will cease to be passive users of applications and, thanks to the introduction of adaptive systems and exploiting modular and interoperable middleware platforms, will be able to co-code and continuously improve and change systems, according to their experience, expertise, and dynamical needs.

An important effect of 6G will be **universal digital replications of real-world entities**. As 6G systems will bring further potentials, diverse vertical sectors call for digital twinning, e.g., manufacturing, transportation, management of critical infrastructure, smart city management, climate change and environment management, practically covering all facets of our lives. The ever-increasing requirements for low latency and high reliability creates prospects for new business and revenue streams.

In the 40 years history of the wireless industry, we have seen the deployments of centralized national-scale public networks operated by few and structured in a cellular configuration. With the widespread deployment of 5G on the road towards 6G, we will gradually enter a new era where a **massive number of distributed cell-free networks** will be operated and utilized by a whole new ecosystem of millions of players. Moreover, the need to remotely operate the converged ICT and OT platforms makes it mandatory to optimize the end-to-end performance of the converged fixed-wireless connectivity infrastructure. An important differentiation of 6G with 5G is that global, instead of local, solutions are sought. Tectonic changes are therefore expected in the market structure and associated business models. Likewise, an evolution of regulation will be needed, as already mentioned above. For instance, a multi-level net neutrality evolution has the potential to unleash new business models and innovative specialized application services while ensuring fair competition and open access to any kind of public 6G specialized connectivity.

6G is a complex system technology [2-26]; accompanying markets and **business models** will be affected, and strategies and governance will both resist and utilize the unavoidable dynamics. In 6G, these dynamics will be reinforced by the introduction of many new “nodes/things/entities” in the network, which self-organize in a distributed fashion with high density. This dynamism makes necessary to consider new connectivity modes over an end-to-end path that can overcome the high costs associated with the overprovisioning paradigm. The growing 6G reliance on SW and virtualization will increase the network “entities” capability to dynamically reconnect at a high pace also business wise; technologies and platforms offering service set-up and restoration in the order of seconds are necessary. Thus, the evolution of 5G markets towards 6G ones is subject to high uncertainty, however, we can assume that patterns will emerge, and that strong self-reinforcing effects may lead to dominant technologies and commercial players. This of course represents business opportunities for the single player, as well as potentials for unfortunate societal and market scenarios. Both from a business and societal point of view, it is necessary to understand the market dynamic and forces introduced by 6G to facilitate innovation, societal improvements, and economic profit and growth.

A recent **forecast** [2-27] suggests that by 2035 the mobile communication sector will reach a global economic output of $13 T (5% of all global real output) and its associated industry will invest $235 B annually and generate 22 M jobs. Economists are now postulating that new concepts for Capitalism (2.0) are emerging as a result of relentless pursuit of **GDP** growth and distortion of economies. Such new concepts will affect economic KPIs in techno-economic models which anticipate and value innovations and assess value propositions in 6G investments. Corporate governance models that are receptive to a broader stakeholder view will force innovation in corporate investment, enterprise shareholders are re-evaluating the approach to investment criteria beyond the established ESG (Environmental, Social and Governance) KPIs. The responsible investment agenda movement is challenging and creating consensus around broader Sustainability and Impact visions, for which ESG lacked focus. There is evidence of increased pressure from shareholders coming through a higher volume of resolutions in recent shareholder meetings of publicly listed companies; “patient capital” will set the criteria for success in coming years.

3 Why do we need 6G?

3.1 Introduction

6G is the mobile network generation that will help us to tackle the challenges we will face in 2030 and beyond. Mobile communications are becoming pervasive and will play an even bigger role in our day-to-day lives than today. This means that 6G will have to achieve a lot more goals than just providing fast mobile Internet access. An overview of these goals is listed below, with more information on each of these goals in the subsequent sections.

- The convergence of physical, human, and digital worlds in 6G will require support for digital twinning, immersive communication, cognition, and **connected intelligence**.
- To provide flexibility, **programmability** should be at the heart of 6G.
- 6G needs to support **deterministic** end-to-end services.
- 6G needs to provide integrated **sensing** and communication, which will enable high accuracy localization and high-resolution sensing services.
- 6G will play an ambitious role towards **sustainability**, to reduce its footprint on energy, resources, and emissions and improve sustainability in other parts of society and industry.
- 6G needs to become a truly **trustworthy** infrastructure that will become the basis of societies of the future.
- To ensure that 6G can be inclusive for all people across the world, it needs to be scalable and **affordable**.
- 6G needs, where needed, to significantly **stretch** the KPIs that 5G can achieve now.

3.2 Convergence of digital, physical, and personal domains

With 6G we should expect to approach a fully connected world, where the physical world is represented in high detail in the digital domain, where it can be analysed and acted upon. The network would provide the links between the domains by devices embedded everywhere, as well as provide the infrastructure and the intelligence of the digital domain. Humans would be placed in the middle of this cyber-physical continuum, with our bodies as well as our intelligence connected. Three classes of interactions will be made possible by this domain convergence:

- **Twinning of systems between domains.** Sensors and actuators can tightly synchronize domains to achieve digital twins of cities, factories, even our bodies. This will enable rich data mining and highly efficient control, but data integrity and security must be ensured.
- **Connected intelligence.** The network will serve as the key infrastructure offering high-capacity links with low end-to-end latency, and secure compute functionality available throughout the network. Trusted AI functions can operate in and on the network. Virtual representations of persons and physical devices can exchange information with each other in the digital domain, which implies a new way of identifying virtual representations.
- **Immersive communication.** People can extent their senses through the digital domain. High-resolution visual/spatial, tactile/haptic, and other sensory data should be exchanged with high throughput and low latency to create an immersive experience of being somewhere else. To achieve this, high-throughput links with deterministic end-to-end latency needs to be coupled with new devices are required.

- **Cognition.** It is not sufficient to represent humans as physical objects in the digital domain. It is also important to be aware of their intentions, desires, and mood. For instance, an existing way to find out what humans want is to use AI-assisted voice recognition tools. Cognition brings all these sensor inputs together with knowledge about preferences, earlier choices, and e.g., a person’s mood.

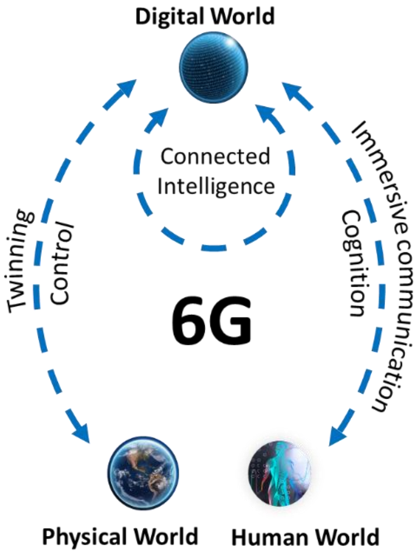


Figure 3.1: Convergence of digital, physical, and personal domains.

3.3 The 6G data revolution and the need for programmability

5G networks pave the way to support massive number of end devices and multiple logical networks with the introduction of network slicing. The gradual shift to the full digitization of the real world is expected to create vast amounts of data.

Current European plans for the design of 6G networks [3-1] consider addressing a few topics like [3-2] a) an efficient interworking of communication networks with IoT devices, b) the support of distributed and advanced edge computing solutions, as well as c) the design of networking protocols more adequate for cloud support for the operation of the network (e.g., with the usage of a service-based/ cloud native architecture) and the collection and management of the collected data. Furthermore, some level of User Equipment programmability should also be explored by exposure of APIs of the wireless devices, enabling customization of the air interface without the need to standardize too many details for each use case and/or speed up time to market for new features.

The processing of data is a rather complex process where AI and ML are expected to play a crucial role. The native support of AI/ML can provide innovative solutions not only to the optimization of the network functions but also to the operation of the end devices and the telecommunication and vertical services and applications. Such solutions are expected to influence the design in 6G of the network architecture and network functions, as the collection and processing of huge amount of data requires improvements in terms of network capacity and communication throughput. Moreover, the management of data stored in high performance and distributed computing facilities poses new requirements in terms of *trusting the accuracy and consistency of* *the collected data*. Finally, security and privacy will have to be further investigated right from the beginning of the work on 6G, so as adequate and evolved end-to-end mechanisms can be deployed.

3.4 Supporting deterministic end-to-end

Many future (distributed) remote-control and XR (Tactile Internet [3-3]) applications require to run on tight and deterministic end-to-end latency constraints. A packet arriving too early can be delayed at the receiving end. A packet arriving too late is a lost packet. Hence, increasing the latency jitter can increase the packet loss rate.

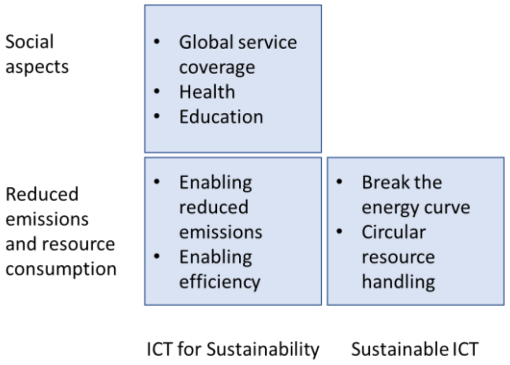
Control systems acting on one or swarms of interactive mobile robotic devices can relax their bandwidth and latency requirements by orders of magnitude, using model predictive control (MPC). Stochastic MPC [3-4] has also been shown to be an effective measure to overcome stringent requirements. An example on applying this in a wireless setting on platooning, large gains are achievable to reduce the requirements on packet losses or latency constraints [3-5].

Hence, it will be of utmost important to learn from Tactile Internet applications which are being tested and rolled out within 5G within the next 5 years. Only then will we be able to learn precisely which improvements on jitter, packet error rate, as well as latency are truly necessary for 6G.

3.5 Integrated sensing and communication

6G will expand into even higher frequencies and will employ massive antenna array technologies, following the trend initiated in 5G Systems. These technologies will not only be exploited for providing ubiquitous communication but also for other purposes, notably such as sensing the environment (e.g., THz imaging) and achieving centimeter-accuracy localization [3-6][3-7]. Localization and sensing will exist together with communication and will share the resources in time, frequency, and space; they will be intelligently bonded through a mutual-beneficial relationship. 6G will also take advantage of the Age of Information (AoI), which measures the freshness of status updates for applications that require remote monitoring and control [3-8]. However, AoI is impotent in getting the information semantics that captures the time/space varying importance of the information exchange, and its dynamic evolution. Therefore, 6G systems will introduce new means to harvest and interpret the “context” of the communication; related aspects will encompass high-precision localization in addition to the time of communication and the AoI [3-9][3-10]. In 6G intelligent context-aware networks, deployment, operation, and energy usage will be minimized subject to the information gathered from sensing and localization without human intervention [3-11]. THz frequency imaging and spectroscopy will support real-time and perpetual data on the human body through non-intrusive, contact-free, and dynamic measurements [3-12] in e.g., digital health technology. In 6G simultaneous localization and mapping (SLAM) methods will enable the implementation of advanced cross reality (XR) applications and navigation of autonomous vehicles and drones [3-13]. Lastly, in 6G sensing as geolocation, radar, and spectroscopy will ensure a precise image of the setting, passive and active sensing will continuously convey to each other and process the information [3-14].

3.6 Ensuring sustainability



	ICT for Sustainability	Sustainable ICT
Social aspects	• Global service coverage • Health • Education	
Reduced emissions and resource consumption	• Enabling reduced emissions • Enabling efficiency	• Break the energy curve • Circular resource handling

Figure 3.2: Sustainability and ICT.

Sustainable development is at the top of the European agenda and EU policies give recognition to its economic, social, and environmental dimensions that should be tackled together. When talking about sustainability and ICT, we must differentiate between sustainable ICT and ICT for sustainability.

Sustainable ICT aims to reduce the footprint of ICT in energy, resources, emissions, in essence, ensures that ICT is doing its share as part of a sustainable society. A key challenge for 6G will be to break the energy curve, i.e., to suppress the increase in energy consumption with increasing traffic. KPIs on energy consumption per data bit as well as total consumption will be complementary. KPIs for circular resource handling will be considered in the context of ICT to address other perspectives.

ICT for sustainability defines what ICT can do to transform industries, communities, etc., by delivering connectivity and intelligence through 6G. The aim is to minimize energy and resource consumption, reduce emissions and enhance social aspects, which require enhancement in the world. The first part is related to the ICT for Sustainability ambition, whereas the latter considers Sustainable Development Goals set forth by the United Nations. KPIs will be necessary to measure the extent of emission reductions or resource consumption, along with the available Sustainable Development Goal target metrics.

3.7 Society depends on 6G

The 2030s will become known as the start of the age of broad use of personal mobile robotics. The cellular generations 1G and 2G provided telepresence of voice services, and 3G and 4G added the telepresence of data. With 5G the advent of the Tactile Internet commenced, i.e., telepresence and control of real and virtual objects via a cellular network will become possible. Just as 1G and 3G were dominated by business customer use of the new services, 5G is experiencing this as well. We now talk about 5G delivering new services for “vertical industries”, with less focus on consumers. 2G and 4G, however, delivered the consumer cell phone and the consumer smart phone. To follow the same line therefore 6G must deliver the functionality to become the infrastructure to enable the broad use of network controlled personal real and virtual robotics [3-15].

- Privacy enablement: deliver network functionality to keep the location of terminals private (e.g., for automated driving)

- Trustworthiness by design: As cellular networks are becoming the main infrastructure for societies, we must ensure that all network functions as well as the operating systems and hardware platforms can be continuously formally verified, building a truly trusted 6G.
- Societal fairness: To ensure that all societies can join the 6G enabled world, coverage must be enabled for remote regions. The total 6G infrastructure's energy consumption must return to 4G levels, independent of the number of terminals.

In summary, 6G will become the basis of societies of the future. It must address pressing societal needs and deliver new functionality at the same time. The 6G development and deployment must be achieved while considering human factors and end-user engagement in order to evolve into a truly human-centric society.

3.8 Affordability, scalability

To ensure that 6G can be inclusive for all people across the world, it needs to be affordable and scalable with a great coverage everywhere.

One way to achieve an affordable and scalable 6G system is to make sure that the system is global, i.e., the same system is utilized worldwide. While in the current phase of fundamental research and exploitation of technical components, various local initiatives exist, at some point it is important that global standards continue to be the main driver of 6G (e.g., 3GPP). The transition from 3G to 4G, consolidated with 5G, has proven that global standards is a successful way to make technology accessible. That of course does not prevent the involvement or multiple standard groups (e.g., 3GPP and O-RAN), as long as there is a very clear cut between their responsibilities.

In addition to global standards, it is also important that 6G has an architecture design that is manageable by reducing the number options (i.e., options without a real market potential). In other words, 6G standardisation should aim for a proper number of manageable interfaces with relevant business impact.

For 6G, affordability and scalability have to consider that operators must invest in network equipment and operate the network. With the use of higher frequencies, more and more base stations will be needed to provide coverage everywhere. A significant increase of the number of pico-cells – e.g., one per room – is only possible if the cost of these base stations can be lowered to compensate.

Finally, also mobile devices will have to be affordable. Low-cost devices should be available where only basic functionality is needed (e.g., with sensors). And yet here too the fundamentals apply that too many different technology options will increase overall cost.

3.9 Stretching KPIs

Over the last decade we have seen a 50% to 100% yearly growth in mobile data traffic volume. [3-16]. There is no reason to assume that the next decade this growth of mobile data will slow down. We can expect a continued increase of the number of connected devices (sensors, connected cars, home devices, body cams, etc) combined with ever increasing demands from new applications and services. This implies that 6G will have to cater for a mobile data traffic volume that is up between 100x to a 1000x larger than 5G.

Note that this growth of mobile data traffic volume cannot result in a comparable growth in energy consumption. To keep energy consumption of 6G comparable to 5G, overall energy use per terminal, base station, network node must come down and energy efficiency per transported and processed data needs to improve in line with the growth of mobile data traffic volume.

One of the biggest promises of the next decade is that immersive communication, holographic telepresence and AR/VR will become our default way of communication. It is commonly agreed that the ideal quality for such immersive experience will require 8k video resolution per eye. To support this kind of applications we expect that 6G will have to deliver end user experienced data rates up to 10 Gbits/s.

The increasing number of mobile devices does not necessarily mean that the mobile device density increases. However, 6G will likely use smaller cells in which the device density can be higher. 6G should support peak densities of up to 10 devices per m^2. Furthermore, when the mobile data traffic for each device increases, the required capacity will also increase. For scenarios such as spectators in a stadium with augmented reality glasses or workstations on an office floor, capacities in the range of 150 $Tpbs/km^2$ will be needed, which means 10x the capacity requirements of 5G [3-17].

The following graphic shows an overview of the main 6G goals, plus the KPIs where 6G will be improving 5G.

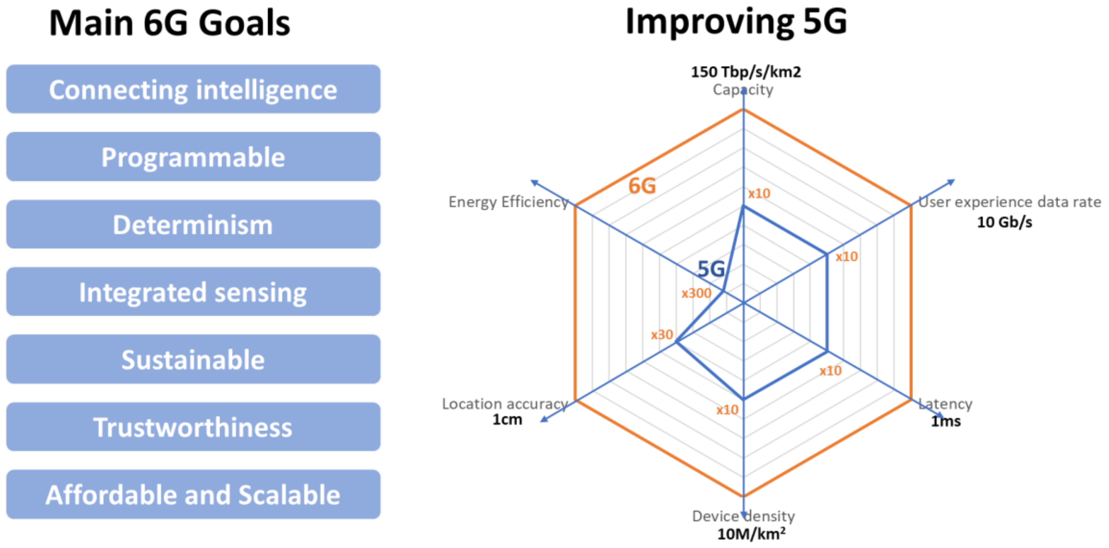


Figure 3.3: 6G goals.

4 Envisaged key technologies for 6G

This section will highlight the envisaged key technologies for 6G, ranging from system network architecture and control, edge and ubiquitous computing, radio technologies and signal processing, optical networks, networks and service security, non-terrestrial networks communication, as well as devices and components (see below the figure showing these technology areas with strong impact on different 6G requirements and KPIs). For more details about the envisaged key technologies for 6G, the readers are referred to the SRIA, the relevant chapters and the references therein [4-1].

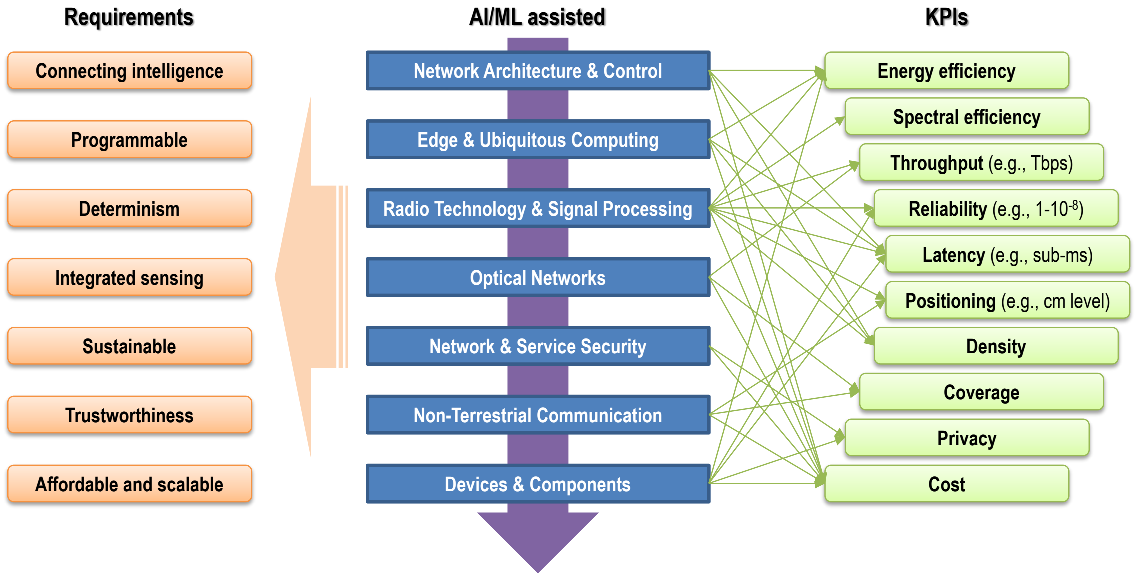


Figure 4.1: Technology areas with strong impact on different 6G requirements and KPIs.

4.1 System network architecture and control

6G technology research shall be such to pave the way for efficient, sustainable, smart and trustworthy distributed computation. The intertwining of communication and computation algorithms requires a communication/computation co-design that falls under the scope of in-network AI governance (incl. AI-based allocation and instantiation of network functions; management of collaborative AI components across the network; design of distributed AI mechanisms based on e.g., Federated Learning (FL); or the deployment of AI-output/decision justification mechanisms leading to explainable AI).

From a *service* management perspective, AI/ML will be needed to maintain operation cost-effectiveness of envisioned complex 6G services such as the interaction on human-digital-physical worlds and Internet of Senses. Besides, the proliferation of multiple virtualization technologies, including virtual appliances, microservices, containers, serverless functions and their interoperability will increase the complexity in network operations. Thus AI/ML mechanisms will become crucial to automate decision making processes.

AI/ML will also enable the implementation of predictive orchestration in 6G, for instance, to achieve near-optimal placement decisions (including placement of Virtual Network Functions considering e.g., device geographic density), service and network slice configuration or maintenance based on the real-time needs and resource availability. This would allow to accomplish a zero-touch approach. 6G Orchestration will target the continuum from end devices, to edge, to RAN (where new architectures and user-centric paradigms such as cell-free networking need to be considered), and cloud/core. Prediction of a future state of a device should be taken for service self-adaptation, to ensure lowest possible latency, energy efficiency and other key performance targets, as well as migration among available devices, edge, and cloud resources for adequately supporting mobility of data producers and/or consumers.

For such an AI-driven system operation to be feasible at all, every component in the *infrastructure component* and every *service component* must become and remain controllable by the *tenant* (e.g., mobile network operator). Infrastructure components include (i) physical devices with different capabilities (e.g., compute servers, network gear, sensors/actuators) and life spans (e.g., battery-driven, eco-powered, plugged in; (ii) mobile or fixed network elements (e.g., terrestrial, satellite- or train-mounted base stations); (iii) virtual appliances running on physical devices, characterized by a sudden appearance or disappearance in dense clusters and, potentially, in big number of instances (e.g., within data centers); (iv) services consumed by third parties (e.g., leased lines, transport services).

All *services* provided by the tenant, including user, control and management plane functions, are provided from that infrastructure. In particular, the aforementioned AI/ML functions *per se* will be instantiated and run on top of that same infrastructure. Additionally, such infrastructure will be intrinsically multi-tenant. Even though sharing the resource pool does not imply that every physical device is to be shared, a one-to-one service-to-infrastructure mapping assumption can be considered obsolete.

All this calls for a *very versatile, pervasive and autonomic resource control*. It must feature the capability to maintain the controllability of all available resource components regardless of:

- component nature, the resulting network topologies, densities and addresses;
- usage loads and fluctuations;
- own operational decisions of the operator, of the used AI/ML functions, controllers, etc. It is imperative to handle self-inflicted errors (e.g., cut-off of resource subbranches, discrepancies between the controller views and the actual resource situations, etc.), which will be impossible to avoid in any larger distributed system like the above;
- operational decisions of third parties, both of the same-level operators, using the shared resources in parallel, and of the providing operators, i.e., of the owners of the underlying resources.

Hence, autonomic, distributed mechanisms are required in all infrastructure and service components for the organization and maintenance of such resource control. Additional autonomic mechanisms are required for the multi-tenant and multi-purpose operations of that resource pool, most notably distributed runtime *conflict resolution* and *resource scheduling*.

4.2 Edge and ubiquitous computing

The development and importance of edge computing is driven by multiple factors like massive IoT, Industry 4.0, Smart Cities, and new AI/ML based distributed applications. At the same time, the increase of computing resources at the network edge provides an enabler to support such use cases. The main goals of edge and ubiquitous computing are to reduce delays and increase responsiveness as well as to reduce the volume of data flows between user / IoT devices and centralized cloud computing resources (devices can also offload processing to the network, this allowing them to be simpler, smaller, and use less power). Furthermore, the new paradigms in composing services as a chain of microservices or functions is leading to cases where virtualized network functions can be distributed over core and edge computing resources. Finally, far edge computing where computing resources are pushed to the very edge of the network, is completing the diverse distributed computing environment. While this development has started with earlier mobile network generations, in 6G networks the importance of the edge and ubiquitous computing will be greater since the transition of whole telecom architecture towards distributed (micro)service-based architecture, and 6G promises like "zero delay" will make local processing the only viable option in these scenarios.

In 5G networks, edge computing technologies are going to develop in evolutionary ways utilizing various computing platform technologies developed for open and cloud computing environments. In practice, this means adaptation of virtualization technologies like containers and container orchestration as well as service composition models like SaaS (Software as a Service), FaaS (Function as a Service), etc. On the other hand, edge computing and especially far edge computing require better management of heterogeneous resources and location of service instances. Furthermore, limited resources at the edge as well as the need for improved energy-efficiency, call for lightweight virtualization and more detailed orchestration methods. This means that many improvements and modifications to current cloud specific methods are potentially needed and it is not necessarily clear that everything can be efficiently brought under the same orchestration in this evolutionary approach.

It is envisioned that computing and networking resources (in-network computing) will merge to a single computing continuum stretching from user / IoT devices to centralized cloud. In such a case, all services and resources would be naturally managed in a single integrated way, including not only application, service and data plane resources and functions, but also the control plane functionalities of telecommunication system. This would naturally require lots of development in computing platforms and virtualization technologies. However, this would offer a much more versatile and efficient platform for 6G networks and thus methods are needed for the collection of distributed data for AI/ML and caching for timely utilisation at the edge and in the core. Finally, this kind of development would also mean that edge computing as an independent concept would fade away.

4.3 Radio technology and signal processing

5G provides support for services like eMBB, mMTC, URLLC, and their associated KPIs. However, 6G networks are expected to deal with more challenging applications (e.g., holographic telepresence), and meet far more stringent requirements, such as Tbps data throughput, sub-ms latency to the networking layer, extremely high reliability with packet error rate as low as 10^{-8}, increased device density, extreme energy efficiency/ultra-low energy consumption, very high security, cm-level accuracy localization, etc. Some of those challenges could be tackled by using more electromagnetic spectrum in the Terahertz (THz), sub-THz, infrared and visible light bands. Complementarily, the centimeter and millimeter spectrum currently utilized for 5G and other legacy systems needs to be re-farmed and efficiently reused, and co-existence issues among mobile or non-mobile systems be carefully addressed. Considering the challenges imposed by the law of physics on THz spectrum, the design of commercially viable THz communication systems will require to jointly study waveform and modulation, radio channel characterization, beamforming and feasibility of hardware together. The radio building blocks (waveform, modulation and coding, non-orthogonal multiple access, full-duplex, massive MIMO (mMIMO) which is usually distributed, etc) need to be further developed to meet stringent 6G requirements. Among others, investigations are needed on, e.g., intelligent reflecting surfaces (IRS), integrated positioning, sensing and communications (to e.g., enable a widespread use of robotics in industrial applications), random access for massive connections, wireless edge caching, etc. Moreover, ML and AI as a tool has been successfully utilized in many applications. Yet, its application in radio interface design needs to be carefully studied.

Specifically, for 6G air interface design, the following key enabling technologies should be investigated:

1. Spectrum reutilization: 5G typically uses “low-bands” (< 2 GHz) and “mid-bands” (2-8 GHz) for eMBB, URLLC & mMTC, and “high-bands” (> 24 GHz) for eMBB and URLLC applications. Allocated frequency spectrum and its availability is one of the main factors that determines the system capacity. However, radio spectrum is a very scarce resource. Especially lower frequency bands are precious and tightly regulated. In order to satisfy the high bandwidth demands of upcoming 6G systems, it is crucial to efficiently reutilize the existing low-, mid- and high-band spectrum resources (e.g., jointly utilizing licensed and unlicensed spectrum, using e.g. cognitive radio-based solutions).

2. Millimeter-wave (mmWave) communication: Compared with low- and mid-bands, mmWave has a much bigger available bandwidth which is a very valuable asset for 6G. Currently, mmWave roughly below 50 GHz has been considered for 5G NR and it is anticipated that further mmWave bands (e.g., above 100 GHz) will be needed for 6G. mmWave technology provides a good solution for backhaul, fronthaul and access networks. As it can support high data rate, mmWave is applicable to autonomous driving, smart factories, etc. Especially for 6G requirements, further challenges need to be overcome such as efficient transmit and receive beamforming design, modulation coding scheme implementation with low power, low cost, and high throughput, etc.

3. Optical Wireless Communication (OWC): Despite the small cell concept and new radio frequency spectrum allocation, the exponential growth in mobile traffic may lead to congestion in the radio frequency part of the electromagnetic spectrum. Using OWC in the infrared and visible light spectrum (which is about 2600 times the size of the entire RF spectrum of 300 GHz), can alleviate that and complement traditional RF communications especially in dense indoor deployments. Some further advantages of OWC are combined illumination and data communication, availability of off-the-shelf optical devices, provisioning of geofencing and geolocation improvements, lack of multipath fading, cm-level positioning in indoor environments, etc. Main challenges include, e.g., blockage due to the near line-of-sight transmission of light, interference mitigation to ensure that a UE can achieve high SINR, and OWC network development and integration into 6G. Light communication can be employed for connecting core network through wireline/optical fibre and/or wireless backhauling, cable TV networks, free-space optical networks, and non-terrestrial networks (e.g., airborne or spaceborne vehicles based links, see Section 4.6), etc.

4. Terahertz (THz) communication including semiconductor technologies and new materials: Technology to enable communications in the THz bands (0.1–10 THz, where 100–300 GHz are also considered as upper mmWave band) is also envisioned as a key to satisfy the need for much higher data rate requirements, e.g., Tbps. THz radios will evolve from the large phased-arrays at mmWave region but will face more obstacles in efficient implementation due to the physical constraints of modern semiconductor and packaging technologies. New materials (like graphene) may play a role when they become mature for mass production. Before that, the solutions will rely on novel RF architectures, continuous development on antennas, packaging and semiconductor processes in a careful balance between performance and cost. Other challenges in this area include, e.g. new THz channel models, new waveform and modulation schemes, new experimental platforms and testbeds, novel MAC protocols, modelling and mitigation of non-linearities and phase noise, ADCs/DACs for tens of Giga samples/sec with reasonable power consumption, beamforming schemes for meeting 6G requirements in terms of coverage, mobility and robustness; efficient realizations of MIMO antenna arrays and transmit/receive chains, regulation and standardization of THz bands, etc. New paradigms in terms of the design of single chain radios working across multiple bands simultaneously can assist to achieve system performance goals. Hybrid optical processing can also improve efficiency.

5. Massive and ultra-massive MIMO: The concept of mMIMO has been introduced and studied in the context of 5G. Especially for higher frequencies, due to the shorter wavelength, a large number of antennas can be packed in a small area, leading to the concept of mMIMO and ultra-mMIMO, as well as mMIMO doubly at both base station and UE. Another way to improve wireless communication is to change propagation characteristics of wireless channels, e.g., through intelligent reflecting surfaces (IRS) or large intelligent surfaces (LIS). The current cell-/ network-centric approach can be changed to the user-centric one where the cluster serving a particular UE can be determined dynamically by choosing a subset of APs nearby. Its combination with distributed mMIMO operations leads to so-called cell-free mMIMO. In this concept, all APs are able to serve UEs cooperatively without any cell restrictions, with the possibility of coherent transmission and reception, and almost uniform services across the network can be offered. To efficiently realize distributed MIMO, we need to address beam management, practical approaches to non-coherent operation in higher bands, and full digital beamsteering. The cost should be evaluated considering both mMIMO and transport as E2E solutions. Another arrangement with many antennas deployed on a large area, i.e., the facade of a building, leads to the concept of extremely large mMIMO. Yet, many challenges remain, such as channel modelling; feeding and control of each antenna element; real-time estimation and feedback of a large number of channel elements; synchronization; scheduling of very large numbers of terminals; architecture and functional split options; integrated access, backhaul and fronthaul in mesh configurations; user-centric, dynamic and scalable AP clustering and load balancing; distributed space-time-frequency coding to exploit all diversity sources; FDD operation; and mobility support.

6. Waveform, multiple access and full-duplex designs: CP-OFDM (cyclic-prefix OFDM) waveform has been adopted in xDSL, Wi-Fi, 4G and 5G. Strict synchronization is required for CP-OFDM to maintain orthogonality. Other waveforms, e.g., filter bank multi-carrier, universal filtered multicarrier, or generalized frequency division multiplexing, have been proposed for different application scenarios. In high mobility scenarios with large Doppler spreads, orthogonal time frequency space modulation has also been introduced. Complementarily, relaxing the orthogonality constraint may lead to a more efficient and flexible use of the wireless channel. For example, non-orthogonal multiple access (NOMA) or rate-splitting multiple access (RSMA) can result in larger achievable rates and provide means for grant-free access. Besides, waveform design can extend to the radar domain to offer the potential for combined radar and communications capabilities. Furthermore, advanced self-interference and cross-link interference cancellation techniques can potentially double the spectral efficiency and enable in-band full-duplex transceivers that offer a wide range of benefits, e.g., for relaying and bidirectional communication. Hardware-friendly waveforms with optimized parameters e.g., having low envelope fluctuations are needed for reducing the negative impact of hardware constraints present at THz frequencies, such as low peak output power, strong nonlinear distortion and high phase noise.

7. Enhanced coding and modulation: Channel coding aims to correct transmission errors and thus is key to ensure "reliability". However, it is one of the most complex baseband processing blocks. Modern channel coding schemes such as Turbo, LDPC and Polar codes with excellent performances made their way into several communication standards, incl. 2G, 3G, 4G and 5G. For instance, 5G supports up to 20 Gbps throughput and a reliability as high as $1\text{-}10^{-5}$. Future 6G KPIs and use cases pose new requirements on codec design, so that research is needed on advanced channel coding and modulation schemes close to Shannon limit, aiming at extremely high throughput, extremely high reliability, very low power consumption and low encoding/decoding latency, such as Tbps throughput channel decoder, modulation with shaping loss removed, etc.

8. Integrated positioning, sensing, and communication: Context-awareness is essential for many existing and emerging applications requiring integration of positioning, sensing, and communication capabilities. High-accuracy location awareness has been identified as a key enabler for many applications including autonomous cars, factory of the future, smart cities, virtual/augmented reality, and public safety (e.g., V2X vulnerable road user discovery). Integrated positioning, sensing and communication will enable a smart network management for improved spectral and energy efficiency, as well as reduced latency. Future wireless systems operating at higher frequencies, with larger bandwidth, more antennas, a denser network and D2D links, and possibly dedicated infrastructure, will facilitate radio positioning with cm-level accuracy. But how to design such a system? How could positioning be utilized for better communications efficiency? Radar may be able to sense the environment, recognize human gestures and sense different material, providing cost-efficient alternatives to existing technologies, but how should radar and communication converge in 6G? This field is very promising for a better society but, as of today, not at all mature. Significant research challenges need to be addressed before sensing can be standardized in 6G infrastructure and networks, including waveform design, interference management (e.g., self-interference/full-duplex), spectral resource sharing, hardware reuse, time sharing between positioning and communications, performance guarantees in passive mode, information theory and estimation theory limitations, leveraging AI/ML and edge computing techniques, cost and energy efficiency, to name a few.

9. Random access for massive connections: 5G can already support mMTC with a large number of connected devices. In future networks, however, millions of devices will be connected and, for many of them, only very sporadic data will be generated. How to coordinate such a network without spending the whole network resource and node energy needs to be carefully investigated. Moreover, access protocols whose reliability is based on retransmissions would pose severe challenges as the number of devices becomes very large. Hence, grant-free approaches in which devices transmit their (usually short) packets without any resource negotiation with base stations, possibly limiting or avoiding retransmissions, look promising. Complementarily, devices embedded everywhere would need to be powered by some form of energy-harvesting and run on energy-efficient protocols.

10. Wireless edge caching: On-demand video streaming and Internet browsing are characterized by asynchronous content reuse; highly predictable demand distribution; delay tolerant, and variable quality. For such applications, the current mobile systems often have some issues, e.g., the wireless capacity of macro-cells is not sufficient, and/or wired backhaul to small cells is weak or expensive. In such cases, wireless edge caching provides an efficient solution. Caching can reduce network load and interferences, and consequently increase spectral and energy efficiency, and decrease communication latency. But caching is usually implemented in the core network, how to efficiently implement it for wireless (e.g., combining with multiuser MIMO physical layer schemes) needs to be studied.

In addition, 6G radio technologies need to be carefully researched to cope with future broadcast/ multicast services, which could be – differently from 5G – taken into account from the very first release, to enable a cost-efficient and scalable mass content delivery platform for TV sets, connected cars, smartphones, tablets and wearables. 6G represents a great opportunity for the convergence of mobile broadband and traditional broadcast networks. In Europe, the 470-694 MHz band is used for the provision of terrestrial broadcasting services at least until 2030, a timeline well aligned with the first 6G release. Especially, 6G wideband broadcasting, which should support infrastructure from low-power low-tower to high-power high-tower, can reduce the transmit power by around 90% and contribute to the green deal initiative while keeping the capacity provided by existing digital terrestrial television systems.

4.4 Optical networks

6G will bring a new era in which billions of things, humans, and connected vehicles, robots and drones will generate Zettabytes of digital information. Smart optical transport connectivity will be the foundation of this new era: always available, intrinsically secure, green, and with flexible scaling. Delivering the required performance, resilience, and security levels, while satisfying cost, energy efficiency and technology constraints, presents a formidable research challenge for the next decade. 6G will continue to rely on progress in the optical infrastructure in terms of higher capacity, lower latency, increased programmability, enhanced reconfigurability, increased environmental hardening and significantly reduced power consumption.

Disruptive approaches are needed to approach Shannon's limits and push Moore's limits out further. All dimensions in space and frequency are needed to be exploited, opening new optical wavelength bands and space division multiplexing. It will lead to the development of novel packet/optical switching architectures. This includes study on hybrid use of electronic and optical switching as well as studies on the scalability of guaranteeing deterministic end-to-end QoS performance for a large number of flows/applications. The inherently low power consumption of optics can be directly used to reduce power consumption overall, if optical functions replace more power-hungry electronics.

A tighter integration between optical and wireless technologies and a converged network infrastructure will foster the adoption of a common transmission and switching platform supporting various switching granularities that range from packet to timeslot and wavelength channel level. In addition, advances in photonic integration will pave the way for a raft of new IT and networking devices in which optical, RF and digital electronic functions can be combined, e.g., in multi-chip modules (MCM) comprising highly integrated CMOS dies and high-speed optical engine chiplets on the same package substrate. The potential for novel materials to emerge into this component domain should be investigated.

All these technological advances in optical networks, including an increased programmability and remote configurability at the device level, also require advances in network control, automation, and autonomicity. However, smart connectivity requires additional solutions and innovations for optical network automation beyond simple programmability to truly self-driving networks. Moreover, the complexity of the underlying optical technology, resulting in a large number of interdependent configuration parameters, requires cognitive networks powered by streaming telemetry, real-time network measurements, AI and ML. Hacking and espionage, but also natural catastrophes, terrorism or sabotage threaten our critical infrastructure. Therefore, the design of optical network equipment needs to employ modern security and reliability paradigms (security by design) and apply modern software technology.

Another relevant aspect for the optical technology will be defining solutions that find the right balance between high programmability and extreme performance (e.g., high bandwidth and latency) from one side, with low cost at the other side. Maybe just downsizing traditional optical equipment will not allow meeting the suitable target cost required for 6G especially in the radio access areas characterized by high levels of density of equipment. Novel technology such as integrated silicon photonics could be a relevant solution to address such challenges.

4.5 Network and service security

Cybersecurity solutions depend on the nature of the target system. As an immediate consequence, cybersecurity must evolve as the system does. While 6G is envisioned as highly distributed computing and connectivity architecture, the softwarization and automatization of critical management functionalities (via e.g., intelligent distributed AI/ML-based control and service orchestration) create an attack surface far more wide and complex than in current 5G domain. The system is not only vulnerable for direct cybersecurity attacks, but also the misbehavior of automatized functionalities needs to be identified and their impact should be minimized. Guaranteeing the dependability and trustworthiness of the system will be one of the major challenges. Solutions such as zero-touch micro-segmentation and slicing needs to be guaranteed, and distributed AI/ML functions and models need to be hardened to avoid malfunctions and cyberattacks and guarantee their trustworthiness and security (e.g., to avoid model poisoning and membership inference attacks in federated-learning distributed architectures). Major factors impacting research directions in the context of Networks and Services towards 6G include dynamic changes with unprecedented time and space distribution (static and perimetric approaches failure), introduction of deep technologies (implying a new attack surface), as well as changes in (potentially) critical usages and expectations.

Beyond classical approaches, security in 6G systems shall explore disruptive strategies such as

- Virtualization, from basic functions to end-to-end virtual perimeters using slices.
- Softwarization, making smart usage of flexibility and programmability of orchestrated security closely integrated with orchestrated systems and services.
- Concepts such as deception or moving target defense.
- Holistic approaches encompassing the whole life cycle, from original component/code developments to introduction of technologies (e.g., AI Quantum).
- Cloudification: delivery of security “as a service”, define/operate service attributes for SNS. Integrated in the service-based overall paradigm.

Security quantification in a 6G context should deal with complexity and fragmentation, and mandates the exploration of mechanisms to identify, evaluate, certify, and monitor the level of security. Based on such quantification, trust can be given to providers and services enabling the growth of the sector by answering the diversity of demand from mass market to specific B2B verticals.

Despite commonalities with other digital services, some data centric or green issues remain a specific challenge for future 6G systems. As such Human Centric privacy, relevant trustable AI or simply orchestrated operations across parties or impact and sustainability of solutions will be key to shape an acceptable digital future.

The research for security solutions should also take into consideration the performance, ease of management and energy consumption, when targeting to guarantee the security and trustworthiness of 6G telecom and service/application platforms.

4.6 Non-terrestrial networks communication

The Non-Terrestrial Network (NTN) architecture vision described in the Strategic Research and Innovation Agenda [4-1]. and its integration into 6G networks calls for the research and development in the following areas:

1. Architecture design as a single access network: Design of an architecture with no distinction between terrestrial and NTN elements that can be therefore orchestrated to provide cost-efficient network configuration by dynamically moving functionality creating a flexible network topology. Three main enablers need to be developed, namely, softwarization of the NT access network, virtualization, and disaggregation.

2. Constellation with hierarchical design: Hierarchical constellations will consist of nodes flying at different altitudes and communicating among them through horizontal inter-node links, i.e., among nodes at the same altitude, and vertical inter-node links, i.e., among nodes flying at different altitudes, or terrestrial nodes.

3. Smart NTN with computing and storage in the sky: Flying nodes will become smart edge nodes of the 6G network. Processing, storage, and communication in the sky needs to be enabled in support of the realization of non-terrestrial clouds and space information networks (SIN).

4. Resource optimization with infrastructure as a resource: Beyond the bandwidth, time, power, and space dimensions, resource optimization needs to address the infrastructure itself as a resource to be configured according to the service requirements.

5. Dynamic spectrum management, coexistence and sharing: Dynamic spectrum coexistence and sharing between the terrestrial and NTN segments, as well as among the different layers of the architecture, e.g., GEO and NGSO nodes, space- and air-borne nodes, need to be developed.

6. New spectrum beyond THz: The use of new spectral bands use, up to optical communications, needs to be investigated, in close collaboration with the terrestrial counterpart (see Section 4.3). This includes the characterization of propagation conditions and development of channel models encountered by the NTN elements both in inter-node communications and in non-terrestrial to terrestrial communications.

7. Radio access technologies with flexibility and adaptability: Waveform design shall jointly address the non-terrestrial and terrestrial channel characteristics, such as Doppler effects introduced by the NGSO nodes, the delay, and latency aspects of the higher altitude nodes, and the need for efficient support of channel estimation. The integrated access network needs also to support discontinuous backhauling in scenarios where a flying base station cannot assume a continuous connection to the core network, e.g., in LEO or vLEO incomplete constellations.

8. NTN components with beyond current technologies: Software-defined payloads, new antenna design and technologies, and new components at THz and beyond.

9. AI for exploitation of NT dynamics: Autonomous and intelligent network management system shall be appropriately developed, exploiting the predictable dynamics component of the NT segment.

4.7 Special purpose networks / sub-networks

Driven by the capability to meet ultra-reliable and low latency requirements, we are beginning to see the use of 5G in vertical industries for industrial automation. The trend will likely further expand resulting in increasing demand for 6G for verticals with application to special purpose networks or to even smaller range ‘sub-networks’ that can generally operate in a stand-alone fashion but may benefit from connectivity to the wide area network [4-2]. Examples of sub-networks that will benefit from 6G performance enhancement will range from in-body sub-network, in-robot to in-car and sub-network of swarm of drones (see Figure 4.2). For example, in-body subnetworks can be used for the control of life critical functionalities such as heart-bit (wireless pacemaker) or insulin pump in diabetic patients, while in-vehicle sub-networks can support wirelessly the CAN bus and automotive Ethernet operations, for engine control, anti-lock braking and assisted driving. The usage of low power short range highly specialized sub-networks allows offloading micro/macro infrastructures from the most demanding applications, paving the way to a cost-effective support of high-performance services.

Whereas in-body networks may require extreme reliability and latency in conjunction with very high density of sensors, swarms of drones will rather require extension of non-terrestrial networks (NTN) related requirements such as link budget optimization and ad-hoc cooperation between flying objects. Energy optimized short-range sub-networks with wireless zero-energy devices (such as passive radio frequency identification tags) will allow for a battery life of up to ten years; at the same time, also specialized wide area use cases such as for environmental monitoring may require sensor devices with very long battery lifetime.

Sub-networks will be a key driving factor for 6G architectural change due to sub-networks' local topology in conjunction with the specialized performance attributes required such as extreme latency or reliability. Sub-networks are defined to work in stand-alone mode as well as connected to wide area connectivity 3GPP network. Such an approach will enable the offloading in both directions as well as enhanced schemes for discovery; at the same time, scope of functionality and protocol stack complexity can be adjusted accordingly.

The air interface design for subnetworks should be tailored to the needs of the specialized applications. In particular, sub-millisecond latencies and extreme reliability can be achieved by using large subcarrier spacings (e.g., above 120 kHz), ultra-short transmission intervals, blind packet repetitions and channel hopping for the sake of harvesting frequency and interference diversity. While the basic foundation of such technology components is already known since 5G, it is our understanding that they should evolve further to cope with the more extreme requirements. Also, air interface should be designed to be robust to jamming as this is one of the main potential threats to the support of ultra-reliable services. In the case of dense deployments, such as robots in a cluttered factory or vehicles in a congested road, interference management is of paramount importance for ensuring sufficient signal quality in the operational bands. Interference management should exploit local sensing capabilities at each subnetwork, together with, when available, extra information on the current frequency allocation in neighbour subnetworks provided by the wide 3GPP network.

Figure 4.2: Example of Sub-network Use cases (in-body and in-vehicle), from [4-3].

4.8 Opportunities for devices and components

Progresses in all aspects of the wireless network are highly dependent on electronic technologies, components and devices that are used for implementation. This includes the whole range of components such as processors, memories, analogue, RF, DACs and ADCs, antennas, packaging and optical components.

In the RF domain, technologies in the sub-10GHz, mm-wave and THz to be used in 6G networks face their own specific challenges. First, sub-10GHz challenges lie in the areas of transceiver architectures and circuits towards ever better linearity, phase noise, faster, more power efficient and higher resolution converters, more antenna channels, multi-band. The choice of the right CMOS technology node (going to 7, 5, 3 or 2nm, migrating from FinFETs to gate-all-around transistors, use of GaN for TX power), together with cost and power constraints exacerbate the challenge. Ultra-low power devices need µWatt performance, calling for progress in energy harvesting and back scattering transceivers. Second, millimetre-wave challenges are in the areas of MIMO/Hybrid beamforming architectures for large and very large arrays, semiconductor technologies and medium resolution, high speed converters. Packaging and interconnect are very challenging at these frequencies, metamaterials offering opportunities for nice disruptions. These challenges are growing further for the THz band (i.e., >100 GHz) where progress is needed in CMOS, SiGe and III-V semiconductor (AsGa, InP, GaN, ...) and potentially novel technologies, circuits, packaging, broadband beamforming (including true time delay), large arrays, on-chip antennas, ultra-broadband baseband (5 to 10GHz) and associated converters. These technologies may also contribute to or benefit from mm-wave and THz sensing, both active and passive, such as imagers, radars, etc.

The challenges in the optical domain are in the ever-increasing demand in throughput (3.2 TBauds transceivers by 2030), increased use of coherent (i.e., QAM) transmission even for short distances, monolithic integration of optical components and CMOS processing, photonics devices, new on-chip components such as laser sources and optical phase-locked loops. Cost and especially power is a major issue towards greener infrastructures.

On the digital processing side, research is needed to bridge the gap between high-efficiency ASIC and high-flexibility programmable devices. Memories are expected to increase in capacity by a challenging 1.4x factor every year. For extreme efficiency, in-memory computing is seen as a promising technique to squeeze power to a minimum. For AI, significant progress is needed to reduce the power, both at the server side (green servers) and the edge device (very low power). To that aim, Neural Processing Units (NPUs) can be leveraged. Bio-inspired spiking neural networks is an emerging architecture offering orders of magnitude reduction in power, but it is far from mature.

Hardware for security needs research to increase reliability, offer graceful degradation and automatic recovery, and robustness to quantum computing attacks. For hardware security, there is also the need of novel multi-processor system-on-chip architectures (MPSoC). As modern MPSoCs often rely on untrusted third-party IP blocks to minimize design cost, the trustworthiness of the overall system must be ensured. The untrusted components need to be properly isolated and their behavior verified. Such a system may also be supported with ISA extensions and with microkernel OS.

4.9 Summary and future trends

Numerous technologies need to be researched for the upcoming 6th Generation of mobile system. Radio themes (spectrum usage, mMIMO, random access, channel modelling, etc, especially in

THz communications) will be needed to globally expand network capacity by approaching Shannon's and Moore's limits. Moreover, sounding techniques, mixing communications and environment mapping, will be essential for many societal scenarios. Higher layers will also require specific research, such as novel switching architectures and new routing protocols, efficient containers and container orchestration, with reliable software virtualization, with fast instantiations and mobility, as well as a breadth of challenges on the security domain (quantification, fact checking services based on AI, secure software engineering and operational procedures, etc). The development of system architectures spanning all types of resources, regardless of their nature (compute, networking), realization (virtual/physical) and position (remote/local), dynamically adding and removing resources as they come and go (churn) will also be needed. What will be required is to integrate a massive number of embedded devices everywhere, high-capacity links, and a diverse set of access types, through a compute continuum, into one network meeting the high expectations of the future and importantly improving quality of life.

Another essential tool will be AI/ML mechanisms for the optimization of the physical and higher layers, using both online and offline strategies. This can be achieved by adapting to the deployed wireless environment, mitigating hardware impairments, and achieving lower computational complexity. Online learning for quick, robust and predictive environment-aware transceiver reconfiguration may be one of the breakthroughs. Data-driven transceiver design in a novel “end-to-end” fashion, in contrast to the conventional “block-per-block” design, can be more efficient. AI/ML can be employed to optimize various radio interface functionalities, e.g., multi-antenna transmission, cell-less system setup, channel prediction, synchronisation, demodulation, decoding, beam alignment/management/recovery and overall radio resource management.

Besides, Radio Access Networks (RAN) is undergoing architectural transformation, disaggregation and virtualization of RAN functions to support service heterogeneity, coordination of multi-connectivity technologies, and on-demand service deployment with accelerated and distributed processing power. Disaggregated, micro-services based RAN architecture, combined with AI/ML as well as open and standardized interfaces allows for RAN functions and services to be flexibly selected, deployed and optimized for the specific use case. 3GPP and O-RAN alliance are both working on multivendor "horizontal" split points i.e., interfaces between different RAN layers and units, e.g., front haul, distributed and centralized units for user and control plane. O-RAN introduces an open near real-time controller i.e., RAN Intelligent Controller (RIC) for the purpose of RAN programmability and service optimization. With an open architecture, RIC embeds intelligent, AI/ML based capabilities, and allows on-boarding of RAN control applications for near-real time fine grain performance optimization and policy tuning.

Ultimately, 3GPP and open RAN concepts allow RAN equipment and software from different vendors to communicate and interoperate (e.g., through the abstraction of software from hardware) [4-4] and further disaggregation into a distributed unit and a centralized unit in 5G networks. This, however, may increase integration complexity as well as compromise overall network performance accountabilities. Multi-vendor decomposition and supply chain may increase the threat surface for malicious attacks as well as the operational complexity of the network. In addition, large scale adoption of Open RAN concepts in 6G may require sorting out inherent energy consumption issues as raised by the use of general purpose processors to run virtualised RAN functions. All these and other issues related to the disaggregation and proliferation of the number of standardized and open interfaces need to be analyzed and mitigated, before 6G can unequivocally adopt Open RAN concepts.

Finally, the exploitation of properties from quantum mechanics promises unprecedented performance in quantum sensing, communication, security, and computing. Such capabilities will remain underutilized in the absence of a development of quantum networks and their integration with classical ones. 6G networks will likely face the dawn of such integration to unleash quantum sensing/communication/computing capabilities on the one hand, as well as to exploit quantum capabilities for efficient resource utilization.

5 6G Architecture

The fifth generation of mobile wireless communication (5G) began adopting the Internet principle of service-oriented architecture (SOA) and moving away from the single-client-single-server model. Similarly, many Internet services have moved from monolithic services towards collaborating microservices, at both application- and network-service level, while the service provisioning has changed towards virtualization on cloud infrastructure instead of dedicated server hardware [5-1]. However, this approach was limited to the control plane and the core network (CN) and the management plane with service-based management architecture (SBMA), without going the full path towards an end-to-end Service-Based Architecture (SBA), still relying on dedicated hardware operating logically separated radio access network (RAN) nodes. With 6G, it is expected that the SBA could expand through the whole network through all planes and end-to-end, encompassing CN, RAN, and terminals, allowing much greater deployment and operational flexibility, supporting network-of-networks and system-of-systems concepts for easier subsystem integration and scalability.

5.1 6G architecture outlook and analysis

5.1.1 Vision

The 6G architecture should be flexible and efficient in order to enable easy integration of everything, i.e., a network of networks, including nodes using above 100 GHz frequencies [5-2], joint communication and sensing, NTNs and terrestrial communication and encompassing novel AI-powered enablers as well as local and distributed compute capabilities [5-3]. In particular, the integration of NTN components (e.g., LEO, MEO, GEO, and overall air-/spaceborne assets possible interconnected) offers extended and supplementary coverage for connectivity as well as distributed storage and compute services. To realize that new smart service and connectivity platform across verticals and the associated value chains [5-4], the architecture must be able to integrate mission-critical networks with reliability, availability, and resilience beyond 5G's URLLC, which needs to account for the flexible infrastructure provisioning for end-to-end service guarantees.

5.1.2 Main principles of the future mobile communications system

The main principles of a future mobile communication system should be the ability to handle a **higher degree** of **flexibility** and **functionality** [5-4], [5-5]. This will enable 6G to support **new use cases with dedicated/special networks/verticals**, while offering both public and private smart networks and services in mixed environments supported by advanced and adaptable functionalities. Dedicated communications concepts are being developed for a wide range of application areas (e.g., business verticals or services) such as logistics, manufacturing, agriculture, energy networks and digital schools. The architecture solutions for the increased flexibility and functionality should not increase the overall complexity of the different network layers and system functions. Further on, the visible complexity to the user/developer/app needs to be reduced such that the final user, the developer and the app can use simple primitives with clear features and error conditions, without constraining the flexibility and the features. This will require **softwarization, full cloud-native architecture and further developed SBA** [5-6], as well as **software and hardware disaggregation** [5-1].

Capabilities that were previously only possible outside the network through cloud solutions will now be integrated into the 6G system, such as the ability to process and store data (compute-and-forward), as well as allow the use of **AI everywhere** in the network [5-7], where it can be beneficial. That is, 6G must support a framework to efficiently collect the necessary information for the learning, i.e., the data aggregation. The "AI everywhere" principle will be used to enhance network performance (UE predictions, load balancing, etc.), but also to provide AI-as-a-Service (AIaaS) in a federated network, so that a user can obtain AI capabilities by buying the AI service and submitting relevant data to the latter. Another important principle is the **reliability**. Since MBB is becoming more and more critical to the society and to be able to support new verticals, the architecture of 6G must support reliability, availability, and resilience beyond 5G, both in terms of service and infrastructure provisioning [5-8]. Related to reliability is digital inclusion and global service coverage. The 6G architecture shall enable coverage of remote places, e.g., in rural areas, transport over oceans or vast land masses, enabling new services and businesses that will promote economic growth based on the convergence of different previously segmented communication means, e.g., local networking, mesh networking, PAN, NTN and mobile systems into one single communication system abstraction available and usable from both end devices as from the cloud platforms involved.

5.2 Towards 6G architecture

The evolution of the mobile systems so far can be categorized in two different dimensions:

- The evolution of the underlying infrastructure, i.e., of systems providing resources and services.
- The evolution of the actual mobile systems architecture, which already today mostly uses resources provided by different infrastructures (transport, data centers, radio sites, etc.).

5G has shown that a change from a dedicated, physical device driven infrastructure to a partly virtualized infrastructure justifies changes in the mobile system architecture. We discuss the evolution along these two dimensions and introduce an overall architecture as illustrated in Figure 5.1 in the following sections.

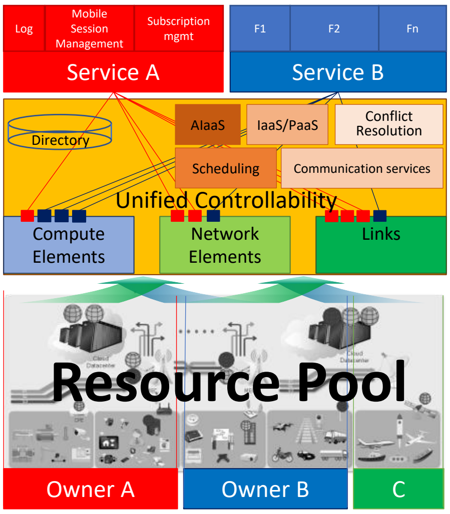


Figure 5.1: 6G as a smart service execution platform.

5.2.1 Infrastructure evolution

In the infrastructure dimension, the desire to provide more diversified services and the increased sustainability awareness ("green ICT"), together, call for a radical increase in the degrees of freedom and flexibility of the (costly) nation-wide infrastructures [5-4], [5-9]. Reuse and universality will be key for the future infrastructure. Hence, we expect the infrastructure to evolve in two directions:

- Diversification of the types of considered resources in the infrastructure towards networking, storage, and compute resources of different realizations, ranging from classical physical nodes and dedicated HW accelerators to virtual instances (e.g., booked and used as a service).
- Extension of the virtualization scope and of its capabilities: infrastructure virtualization and programmability are expected to extend over all available resources, i.e., using the current taxonomy, it should propagate from the CN into the RAN, including base stations,

nodes and terminals. Besides, future virtualization should feature fusion capabilities, i.e., it should become able to finally break out from the boundaries of per-node virtualization to seamless multi-node or subsystem virtualization.

These two directions will have the potential to transform the current fixed ICT infrastructures into dynamic compositions of different types of resources. Future resources will be more heterogeneous (both compute and networking), should be understood as potentially transient (virtual/physical, stable/unstable, powered/battery-driven/powerless, stationary/mobile, etc.) and scattered across the physical domain boundaries (remote/local) and the related deployment dimensions (e.g., the transient nature of NTN/Aerial systems). The scope of resource composition forming the usable infrastructure will extend further downlinks towards terminals, therefore allowing seamless embedding of the ICT systems into their physical environments (through a controlled exposure of I/O, sensors, and actuators, e.g., in the terminals). Vertically, to uphold the overall system scalability, it is crucial to abstract whole subsystems of potentially high complexity through relatively simple resource node and service abstractions in order to enable seamless resource sharing and coordination between heterogenous systems such as, e.g., terrestrial and NTNs, transport and compute domains, data centers and RAN, user terminals and operator networks, etc., while guaranteeing their independent development and evolution.

Overall, in the future, the infrastructure used by mobile telecommunications systems will be per se a flexible on-demand provision. Shown in Figure 5.1 as “Resource Pool”, in general, such a virtual infrastructure will be allocated across the administrative boundaries of independently operating, separate owners (e.g., Owners A, B, C in Figure 5.1) of used resources; in general, it will not be confined to one single authority domain, and it will not have a clear, stable boundary (in Figure 5.1, e.g., Service A uses resources beyond the resources belonging to Owner A). Several such “allocations” will be overlappingly running at different layers on top of the overall physical resource footprint, diversifying load profiles [5-1], rendering physical boundaries inadequate and resulting in various conflicts at the respective realization level, e.g., overbooking of available resources or concurrent contradicting requests from different services [5-1].

The illustrated situation calls for a pervasive, extremely capable resource control, compared to e.g. the work done by the IETF ANIMA WG [5-10], able to interconnect (glue) and reach all these resource types, regardless of their nature, geographical and topological positions, to robustly deliver data or commands within their semantic constraints between the latter and to dynamically represent these resources as simple and stable abstractions (e.g., Network/ Compute/ Links in Figure 5.1). Using this initial glue (shown as “Unified Controllability” in Figure 5.1), such novel infrastructures will become full-service platforms, natively offering capabilities beyond the mere end-to-end transport. Such capabilities will range from multiparty QoS-aware transport for efficient service invocation to Cloud-like storage and compute primitives, also known as infrastructure- or platform as a service (IaaS or PaaS); they will cover resource programmability services and provide e.g., AIaaS [5-1], [5-11]. Such level of flexibility should be provided at very low cost compared to the contemporary alternatives. This will require to investigate novel technologies for the transport and infrastructure management paradigms, which will require progress on:

- **novel resource control plane scheme with signaling, transport, routing and information distribution mechanisms** to cope with the strong heterogeneity in network density, peculiarities, and the node dynamics [5-12],
- integration of suitable **distributed secure computations** [5-13] schemes to limit trust assumptions about the respective executing system,
- **autonomic and distributed conflict resolution** [5-13], correctness enforcement [5-14] and **distributed resource scheduling** [5-15] schemes to increase the resource efficiency without jeopardizing complexity and scalability, and,
- **distributed AI**, to avoid single points of failure, to bring learning closer to the event

sources and to be able to harness the available yet scattered compute power.

Using the resulting mechanisms and solutions, the Unified Controllability (cf. Figure 5.1) will create an impression of an elastic end-to-end infrastructure with stable API-like interfaces for transport, compute, AI instrumentations and programmability of different abstractions, qualities and automation levels to the service layer (both in development and runtime environments).

5.2.2 Mobile system architecture evolution

The future mobile system architecture per se will be influenced by the novel service requirements and expected novel capabilities and the push from the programmable elastic system underneath.

We expect the emergence of new types of functions within the user plane (in particular, user compute functions, AI-related APIs to both service providers and end users, APIs to positioning, sensing and orientation), in the control plane (e.g., control of compute tasks and allocations, of data injected in the AI models) and in the management plane (AI-based network operations for operators, intent-based programmability with well-defined return values, going up to novel interfaces for easy extensions of the running system through user-owned functions, at least at the user plane level). The future mobile system (e.g., Service A in Figure 5.1), including all planes, will run as set of microservices evolving on top of the Unified Controllability layer in Figure 5.1.

The flexibility of the modern infrastructures will need to be preserved and upheld in the mobile system architecture, now allocated as a service chain, e.g., as described by the IETF SFC WG [5-16]. Explicit mentions of nodes (with identities or addresses) may not be needed. Reference points should foresee dynamic capability discovery and well-defined yet extensible data structures. Fixed interfaces should be generally replaced by service invocation logic, without prescribing any endpoints and without making too strong assumptions regarding execution properties. Indirection capabilities and parallelism/concurrency should be considered everywhere, without jeopardizing security. Hence, instead of relying on, e.g., explicit ID, addressing or physical separation measures for invocation, data-driven access control and transaction logic [5-13], proof of traversal and of possession should be considered.

More generally, the actual mobile system will increasingly look like a computer program executed within the programmable infrastructure. Using high level programming languages, compilers and interpreters, we expect intent-based expressions [5-10] of needs and constraints of services to be translated to microservice-based and data-driven allocations. The latter will run (in parallel to other allocations) within a distributed telecommunications system runtime provided and upheld by the previously described pervasive resource control layer.

5.2.3 Cross-layer issues

While functional properties are generally provided from within the allocated mobile service, the presented split as in Figure 5.1 between flexible, generic ICT infrastructure and mobile system services will raise questions as to the enforcement of the required extra-functional properties.

Whenever dedicated infrastructure provisions are available, they should be used in order to increase the efficiency (e.g., power or compute efficiency by using dedicated HW accelerators, high reliability through allocation on reliable components only, or security by using trustworthy, verified components). However, to maintain infrastructure universality, such provisions should never be service-dedicated and, generally, exposed over the same infrastructure API. The required mobile service properties should not be directly translated to infrastructure requirements, as overblown expectations towards the infrastructure are a known cost factor and an obstacle to deployment. In particular, the envisioned support for critical services should not result in the whole ICT infrastructure becoming critical. Most importantly, this refers to the reliability, security, resilience, and privacy properties.

To become executable on different underlying systems without jeopardizing their own extra-functional properties, the allocated services should be able to enforce all of the latter by dynamically evaluating the capabilities of the used infrastructure parts and by compensating the lacking provisions through their own, virtual means. Such means include dynamic, whenever necessary AI-driven [5-14], decision making and insights from the cloud-based service realizations and private end-to-end messaging systems. Regardless of how and where the properties are enforced, transparency in the realizations, accountability for actions and explicit controllability of data flows are expected. Explainable AI mechanisms are a crucial requirement.

5.3 6G Architecture vision summary

The latest, 5th generation of the mobile telecommunication system (5G) has significantly increased both performance and flexibility of the provided service for users and service providers alike. With its new radio (NR), 5G has introduced new radio modes (URLLC and mMTC, in addition to an improved MBB access). The new 5G core network (5GC) can accompany this radio flexibilization through the support for slicing, enabling operators to set up different flavors of core network functions and to add novel network functions to flexibly control user sessions in a variety of ways from the same core network. Such creation and addition of new serving instances is explicitly supported by the dynamic resolution of the serving instance by dedicated functions e.g., network repository functions (NRF) in the novel SBA of 5GC [5-6]. This is not only useful to be able to provide flexible core network services but also to better fit to novel types of realizations of the core network, which today often use virtualization with dynamic orchestration in the resource layer.

However, while 5G represents an important opening towards new service engineering practices compared to 4G, it only applies these principles on a per-domain basis largely reusing the domain boundaries of 4G (i.e., terminal / RAN / CN). Consequently, the end-to-end session in 5G employs different architectural patterns and, partly, adheres to different realization principles or assumes different types of realizations underneath. For instance, 5G primarily considers wireless resources, while cloud or transport resources are not handled directly by the 5G system but are left to the realization system. This partly undermines the end-to-end flexibility: while the functionality can be quite flexibly defined from within the 5G definitions, the resource footprint requires “out-of-standard-scope” considerations, jeopardizing interoperability.

In 6G, we expect direct integration of different resources from networking to computation and sensing. For that reason, we extend the scope beyond the RAN and CN to the terminals and data centers and insist on a full, end-to-end resource awareness of the 6G system. In this way, the functionalities and services can be provided as microservices where needed, while ensuring fully trustworthy services.

The envisioned main differences between 5G and 6G network architecture can be summarized in the following table:

	5G	**6G**
TYPE OF SERVICE	Point to point QoS transport	Point-to-multipoint transport, including configurable logical network overlay topologies with managed quality properties and net-app awareness, with compute services, sync services, AI services
TYPE OF RESOURCES	Communication	Communication + compute + sensing
ARCHITECTURE SCOPE	RAN+CN	Terminal + RAN + CN
CLOUD-NATIVE	Only CP in 5GC	E2E and cross-plane (User plane / Control plane / Management plane)
MICROSERVICES	No	Yes, E2E, all planes
RESOURCE AWARENESS	Only air interface	Yes, all employed resources, including compute, transport, wireless
TRUSTWORTHINESS	Trustworthy nodes	Trustworthy adaptive services/ network of networks
AI/ML INTEGRATION	Over-the-top	Natively integrated
ADMISSION CONTROL	Access control	Execution control
DEVICE/NODE DISAGGREGATION	CU/DU, IAB	Fully flexible

6 Conclusions and recommendations

6G is expected to play a key role in the evolution of the society towards the 2030's, as the convergence between the digital, physical, and personal domains, will increasingly become a reality. It shall also play a role in supporting the objective of Europe to become climate neutral in 2050, as expressed in the European Green Deal. This will greatly contribute to the United Nations Sustainable Development Goals.

One of the biggest promises of the next decade is that immersive communication, holographic telepresence and AR/VR will become our default way of communication. With 6G we should expect to approach a fully connected world, where the physical world is represented in high detail in the digital domain, where it can be analysed and acted upon. The network would provide the links between the domains by devices embedded everywhere, as well as provide the infrastructure and the intelligence of the digital domain. Humans would be placed in the middle of this cyber-physical continuum being fully interconnected.

6G will therefore become the basis of societies of the future. To this end, it must address pressing societal needs and deliver new functionalities at the same time. Privacy by design, trustworthiness by design, and societal fairness, shall be the foundations of the 6G infrastructure.

Digital technologies are more and more considered as critical and essential means for ensuring as one of the foundations of countries' sovereignty. Developing strong European technology offers and alternatives, that meet European political interests and values, as well as economic and societal goals, is key. Secure and trustworthy European-based 6G infrastructures will help on the one hand to ensure the sovereignty of Europe in terms of critical technologies and systems, and on the other hand to make sure that European primary values such as privacy, trust, transparency, accountability, security, and societal interests are considered. At the same time, it is important that the EU continue to interact with other areas of the world, promoting the adoption of its values, from the perspective of both the society and the environment, and for guaranteeing a level playing field, in which all human beings can hope for a better future.

Global standards and renewed regulations shall play a key role in the development and deployment of 6G and subsequently of services developed using 6G technologies in Europe and beyond, in many vertical sectors. It is one of the keys to ensure a sustainable and affordable 6G network available everywhere, to everyone.

To achieve those ambitious objectives, AI/ML mechanisms will become crucial elements in 6G, e.g., to automate decision-making processes, and to accomplish a zero-touch approach. Research will be required in key technologies required for 6G, i.e., system network architecture and control, edge and ubiquitous computing, radio technology and signal processing, optical networks, network and service security, non-terrestrial networks communication, and device and components.

In terms of architecture, 6G will address both the evolution of the underlying infrastructure, i.e., of systems providing the basic resources and services, and the evolution of the actual mobile systems architecture, which already today mostly uses resources provided by different infrastructures (transport, data centers, etc.). From the perspective of the infrastructure, where reuse and universality will be key, a radical increase in the degrees of freedom and flexibility of the (costly) nation-wide infrastructures is required to provide more diversified services and achieve the increased sustainability awareness. On the other hand, the future mobile system architecture will be influenced by the novel service requirements and expected novel capabilities, and the push from the programmable elastic system underneath.

Whenever dedicated infrastructure provisions are available, they should be used in order to increase the efficiency (e.g., power or compute efficiency by using dedicated HW accelerators, high reliability through allocation on reliable components only, or security by using trustworthy, verified components). To become executable on different underlying systems without jeopardizing its crucial extra-functional properties, the mobile system architecture should be able to enforce all of the latter by dynamically evaluating the capabilities of the used infrastructure parts and by compensating the lacking provisions through its own, virtual means.

On top of these technical challenges, the rest of the section aims to provide a fairly high-level time-plan for 6G such as initial deployment and the foreseeable opportunities and obstacles (mainly intended for regulation, but also for business) and how to deal with them at European level.

6.1 Timeline

Initial efforts on identifying future service needs for the next decade, as the ones performed by ITU-T with the Focus Group on Network 2030 [6-1], have fostered the definition of evolutionary steps from 5G networks being deployed nowadays. Complementary to that, beyond-5G solutions are starting to be developed framed on research and innovation activities on different geographies. Examples of that are the set of projects granted on the ICT-52-2020 call from Horizon 2020 programme [6-2], with Hexa-X as the Flagship project. It is expected that these early experiences, together with other industrial initiatives recently triggered, such as NGMN [6-3], will provide valuable inputs to standardization bodies fostering the development of advanced 6G solutions. Remarkably, ITU-R has just formed a vision group on IMT towards 2030 and beyond (6G) targeting to complete its task by end of 2023.

From 3GPP standards development point of view, there are yet features and capabilities from existing 5G solutions that require full specification, and which are expected to be completed in forthcoming 3GPP Release 18, targeting end of 2023. Next releases, by mid of the decade, i.e., 2025, are expected to be focused on 5G evolution, in parallel to the analysis of 6G, and finally on the proper 6G specification. The following figure illustrates the overall roadmap for 6G development.

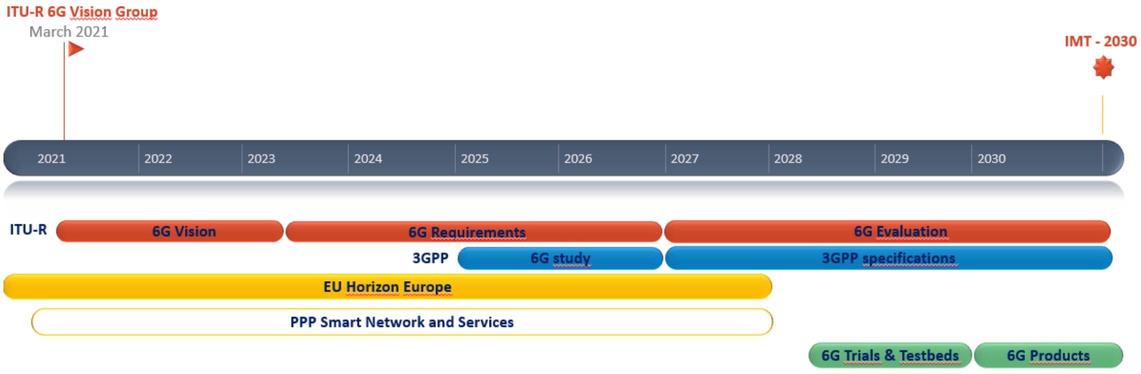


Figure 6.1: Overall roadmap for 6G development.

As to 5G NR NTN (Non Terrestrial Networks) roadmap, it is expected that first products and technologies availability will be closely aligned to the finalization of 3GPP Rel. 17 (planned for March 22) with the necessary completion of development and validation phases for roughly 12-18 months. As such it is reasonable to assume that first 5G NR NTN systems may be operational around end of 2023. Then, the migration from legacy and existing proprietary radio protocols (e.g., DVB-based) towards 3GPP ones will take around 5-10 years. On the other hand, the more revolutionary stream of NTN technologies i.e., targeting new or partly explored frequency bands (e.g., >50 GHz and beyond THz) will be capitalized on a longer term, i.e., after 2025.

6.2 Regulation

The ultimate completion of 6G requires full interoperability between all entities on all levels (see for instance EIF[1], technical, semantic (data), organizational, legal.) The cloudification of the network and the services and the participation of more actors in offering services over 5G and 6G networks requires an **extension of the current regulation of responsibilities**, that currently only affects MNOs. Considering that 6G networks will grow in complexity exponentially, this will create new challenges for security, identity validation, lawful interception, forensic analysis etc. Volatility of logical entities in the network/services with no guaranteed persistence of data creates big challenges to inspect and audit communications when criminal or illegal actions need to be analyzed by digital forensics. Such an ecosystem will definitely require a common certification process taking in account the growing number of vendors that will develop for an ecosystem (across Europe), plus a lean process which would allow Verticals to sell their Services from anywhere to everywhere. Litigation in the chain should include these technical aspects along with others like litigation on taxes paid. Additionally, AI/ML based sophisticated automation to deliver services in 6G networks will require additional regulation based on Ethic principles.

The deployment of 6G Services using new 6G capabilities may require further **clarification for what concerns the applicability of net neutrality rules and of the data protection regulation (ePD and GDPR).** Boundaries on data ownership and privacy between all elements of the complex systems delivering 6G services need to be clearly defined to protect citizens. It is expected to see competition of 6G services for physical resources that will need to be arbitrated **by appropriate guidance on Net Neutrality regulation**. This will bring new business models and SLAs.

Security will need to be adapted to much more dynamic network models. AI/ML assisted security will need further development to respond to new security threads introduced by dynamicity of 6G services and Networks. This will require new professional skills and more professionals trained on these technologies will be needed across private and public companies.

The European Commission Radio Spectrum Policy Group (RSPG) recommends that EC and Member States actively support 6G research and development and, when needed, ensuring EU harmonized spectrum as well as the flexible usage of new THz harmonized spectrum in order to support fixed wireless access and wireless backhauling [6-4]. This is aligned with 6G demands in terms of new **additional spectrum** above 100GHz for terrestrial This trend will be also confirmed in the case of NTN technologies where more concrete exploitation of frequency bands beyond 50 GHz and even going above THz will be targeted for RF-based system. In addition to that, NTN systems building on free-space optical communication can make use of even higher frequency bands (i.e., 150-300 THz). Changes in the new rules for assignment represents an opportunity to

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[1] https://ec.europa.eu/isa2/eif_en

take into account the requirements of other actors beyond MNOs, specially following these RSPG recommendations for flexibility [6-5].

6.3 Business

As the cradle of wireless and mobile communications, Europe has a strong position in telecommunications infrastructure. Ericsson and Nokia together represent a 30.4% global market share and have leading positions in global telecommunications standardization. However, there are many issues that could affect European leadership or even autonomy in 6G, such as the almost non-existing position in consumer telecommunication devices, the lack of European big providers of services for citizens over the networks, the lack of a real common market for network services with a big **fragmentation** in the companies, and the lack of integration or cooperation between companies at European level.

This market situation can have an exponential effect in 6G where Networks and Services will require combination and integration of many more components. There is a high probability that digital and software content will increasingly be developed outside Europe, with a negative impact in terms of economy, sovereignty, and security.

However, the increasing **programmability** of the network and new use cases for B5G and 6G more focused on specific target communities (like industries), could be an opportunity for European companies. Those new business opportunities (industry, infrastructures, transport, territories) will create a new market and services for cheaper, easy, scalable, easy to deploy, easy to tailor to the business specific needs, etc., solutions, which will create opportunities for new local (European, national or even regional) players. And if we can grow thanks to the European market such new players, we could imagine that the next step will be export out of Europe (e.g., Middle-East).

It could also be worth to mention new usages / services which NTN (Non Terrestrial Networks) could bring (in crisis situation, maritime use cases, disaster situation, etc.). In addition, those new usages and services will be critical for Europe, Member States Regions and Territories day to day life and resilience, meaning that this will lead to sovereignty and security issues.

This means that at the European level there should be some regulations and support enable this European, Member States, Regional new players to emerge and to make sure that sovereignty and security requirements are well identified and enforced. This should even be reinforced because the same technologies will also be used more and more in the defense systems of the Member States armed forces. But as European companies have to face a very tough, and sometimes unfair, competition from non-European companies, the EU should continue to significantly support and fund R&T/D activities related to those technologies to make this happen. In the same direction, Europe needs programs to foster Entrepreneurship with Private but also Public participation that requires efforts in % GDP comparable to other markets, complemented with tax policies for startups to avoid relocation of promising businesses because of tax savings.

The goal should not be to aim for a complete autonomy in all areas (since associated economy decoupling is neither feasible nor **desirable to maintain the global standards ecosystem**, e.g., in mobile communication) but to ensure leadership in strategic areas and finding alternate ways of having a secure and trusted access to those technologies where a European supply network cannot be established. By doing so, Europe can speak for itself by providing alternative solutions in the supply chain and thereby gain leverage (since others are as much depending on us on some key topics as we are on them for others). Moreover, such an approach should also create business opportunities by making Europe a sovereign, independent, and reliable source for 6G with, for example, a reliable semiconductor supply chain.

The United Nations made a “universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030”. Digital services are key to fulfil these goals but, at the same time, are part of the equation.

First, sustainability and carbon neutrality will not be achieved if the energy efficiency of such digital services is not globally improved. Holistic approaches are now needed to go beyond the sole minimization of the energy consumption of the various network software & hardware components (potentially issued by different providers), taken separately without considering their intercorrelation. Second, 5G is driving the antenna densification and the wide-spread use of energy intense applications. The induced traffic growth has to be controlled to avoid any rebound effect which would negate efforts towards energy reduction.

Thus, we have to move towards sobriety and eco-conception. Sobriety means **moderation** when producing and consuming services, materials, or energy. Eco-conception means integrating environmental stakes, from conception, production and deployment to termination and recycling. To this end, we need to define new societal and environmental KPIs and adopt a global end-to-end strategy with the various players, directly or indirectly related to the telecom activity (device manufacturers, network operators, application providers, digital services users…). This also means questioning needs and usages, including the net neutrality.

One clear need from the previous discussion is related to the human resources to support 6G in Europe. We need more professionals from engineering schools and high-level university programs in the involved technologies, like communication protocols and software, virtualization and cloud, cybersecurity, microelectronics, quality-testing-verification-certification technologies. More **specific STEM degrees** are required for such fields and more incentives to attract students are needed while including basic but solid humanistic and ethics background. Also, a specific effort is needed to attract female students / develop female talents, as traditionally computer science, telecom, cyber, AI/ML, and more generally digital science suffer from a lack of attractiveness to female students, and therefore creates a very significant gender unbalance.

The overall recommendation is that, to compete with future’s 6G enabled products in defence, automotive, white goods, industrial machinery, consumer goods, etc, Europe needs a world-class competence resource pool in wireless and wireline communications, microelectronics (at least in design), photonics, and software in industry as well as in academia, strengthen by a proactive Regulation adaptation to create strategic and business opportunities for EU companies.

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A2. Abbreviations and acronyms

3GPP	3rd Generation Partnership Project
5G IA	5G Infrastructure Association
5G PPP	5G Public Private Partnership

A3. List of Contributors

Document Editors

- Bernardos, Carlos J. – Univ. Carlos III, Spain
- Uusitalo, Mikko A. – Nokia Bell-Labs, Finland

Section Editors

- Anton, Carles – CTTC, Spain
- Artuñedo, David – Telefónica, Spain
- Demestichas, Panagiotis - WINGS-ICT Solutions, Greece
- Fettweis, Gerhard – TU Dresden, Germany
- Frascolla, Valerio – INTEL Labs, Germany
- Hecker, Artur – Huawei, Germany
- Kaloxylos, Alexandros – 5G-IA, Belgium
- Koumaras, Harilaos – NCSR Demokritos, Institute of Informatics and Telecommunications, Greece
- Magen, Jacques – AUSTRALO, Spain
- Merino Gómez, Pedro – Univ. Málaga, Spain
- Norp, Toon – TNO, The Netherlands
- Rugeland, Patrik – Ericsson, Sweden
- Tomkos, Ioannis – University of Patras, Greece
- Tsolkas, Dimitris – FOGUS, Greece
- Xu, Wen – Huawei, Germany

Document Contributors

- Aguiar, Rui – U. Aveiro / Instituto Telecomunicaçoes, Portugal
- Almodovar Chico, Jose – TNO, Netherlands
- André Bourdoux – IMEC, Belgium
- Ayed, Dhouha – Thales Six GTS, France
- Azcorra, Arturo – Univ. Carlos III and IMDEA Networks, Spain
- Bassoli, Riccardo – TU Dresden, Germany
- Benzaid, Chafika – Aalto University, Finland
- Berardinelli, Gilberto – Nokia Bell-Labs, Denmark
- Bernardos, Carlos J. – Univ. Carlos III, Spain
- Bingert, Raphael – STMicroelectronics, France
- Buzzi, Stefano – U. Cassino and Lazio Meridionale, Italy
- C. Filippou, Miltiadis – INTEL Germany, Germany
- Camps Mur, Daniel – I2CAT, Spain
- Chiani, Marco – U. Bologna, Italy
- Condoluci, Massimo – Ericsson, Sweden
- Conti, Andrea – U. Ferrara, Italy
- Contreras Murillo, Luis Miguel – Telefonica, Spain
- Davoli, Franco - University of Genoa, Italy
- de Cola, Tomaso – German Aerospace Center – Germany
- De Peppe, Raffaele – Telecom Italia, Italy

- Díaz, Almudena –Universidad de Malaga, Spain
- Donmez, Yunus – Ericsson, Turkey
- Dotaro, Emmanuel – Thales, France
- Duquerrois, Jean-Michel – Airbus, France
- Ekelund, Björn – Ericsson, Sweeden
- Elbers, Jorg-Peter – ADVA Optical Networking, Germany
- Ericson, Mårten – Ericsson, Sweden
- Fiore, Marco – IMDEA, Spain
- Fitzek, Frank – TU Dresden, Germany
- Fletcher, Simon – Real Wireless, UK
- Flinck, Hannu – Nokia Bell-Labs, Finland
- Gianesello, Frederic – STMicroelectronics, France
- Gomez-Barquero, David – iTEAM-UPV, Spain
- Haliloglu, Omer – Ericsson, Turkey
- Hallingby, Hanne K – Telenor, Norway
- Haneda, Katsuyuki – Alto U, Finland
- Herzog, Uwe – EURESCOM, Germany
- Hoffmann, Marco – Nokia Bell-Labs, Germany
- Huusko, Jyrki – VTT, Finland
- Iovanna, Paola – Ericsson, Italy
- Kyosti, Pekka – U. Oulu, Finland
- Leonardo da Silva, Icaro – Ericsson, Sweden
- Lonsethagen, Håkon – Telenor, Norway
- Mildh, Gunnar – Ericsson, Sweden
- Muñoz, Raul – CTTC, Spain
- Nimr, Ahmad – TU Dresden, Germany
- Parssinen, Aarno – U. Oulu, Finland
- Parzysz, Fanny – Orange, France
- Payaró, Miquel – CTTC, Spain
- Ramantas, Konstantinos – Iquadrat, Spain
- Ramos, Aurora – ATOS, Spain
- Rodrigues, Joao A. – Nokia, Portugal
- Saimler, Merve – Ericsson, Turkey
- Sarajlic, Muris – Ericsson, Sweden
- Seppänen, Kari – VTT, Finland
- Stavdas, Alexandros – U. Peloponnese, Greece
- Svensson, Tommy – Chalmers, Sweden
- Tillman, Fredrick – Ericsson, Sweeden
- Tomur, Emrah, Ericsson – Turkey
- Ustundag Soykan, Elif – Ericsson, Turkey
- Uusitalo, Mikko A. – Nokia Bell-Labs, Finland
- Vajnanarayana, Vijaya – Ericsson, Sweden
- Van der Perre, Liesbet – KU Leuven, Belgium
- Vanelli-Coralli, Alessandro – University of Bologna, Italy
- Vardakas, John – Iquadrat, Spain

- Verdone, Roberto – University of Bologna, Italy
- Wänstedt, Stefan – Ericsson, Sweden
- Wikström, Gustav – Ericsson, Sweden
- Wymeersch, Henk – Chalmers, Sweden
- Zemen, Thomas – AIT, Austria
- Zhang Yue - University of Leicester, UK
- Ziegler, Volker – Nokia Bell-Labs, Germany
- Zou, Yaning – TU Dresden, Germany