Chapter 2

Architecture Landscape

By Mårten Ericson, Bahare Masood Khorsandi, et al.[1]

DOI: 10.1561/9781638282396.ch2

Published in *Towards Sustainable and Trustworthy 6G: Challenges, Enablers, and Architectural Design* by Ömer Bulakçı, Xi Li, Marco Gramaglia, Anastasius Gavras, Mikko Uusitalo, Patrik Rugeland and Mauro Boldi (eds.). 2023. ISBN 978-1-63828-238-9. E-ISBN 978-1-63828-239-6.

Suggested citation: Mårten Ericson, Bahare Masood Khorsandi, *et al.* 2023. "Architecture Landscape" in *Towards Sustainable and Trustworthy 6G: Challenges, Enablers, and Architectural Design*. Edited by Ömer Bulakçı, Xi Li, Marco Gramaglia, Anastasius Gavras, Mikko Uusitalo, Patrik Rugeland and Mauro Boldi. pp. 11–39. Now Publishers. DOI: 10.1561/9781638282396.ch2.

now
the essence of knowledge

---

[1] The full list of chapter authors is provided in the Contributing Authors section of the book.

2.1 Introduction

The network architecture evolution journey will carry on in the years ahead, driving a large scale adoption of 5th Generation (5G) and 5G-Advanced use cases with significantly decreased deployment and operational costs, and enabling new and innovative use-case-driven solutions towards 6th Generation (6G) with higher economic and societal values. The goal of this chapter, thus, is to present the envisioned societal impact, use cases and the End-to-End (E2E) 6G architecture. The E2E 6G architecture includes summarization of the various technical enablers as well as the system and functional views of the architecture.

The design of the 6G architecture is based on the analysis of the societal, economic, regulatory, and technological trends, which are discussed in Section 2.1.2. A summary of the use cases envisioned for 6G is also introduced in Section 2.1.3. Accordingly, a set of architectural principles has been drawn, upon which the presented architecture is built. Herein, the main highlights of the 6G system design are provided, while the details on the various network domains are given in the subsequent chapters.

In Section 2.2, the overall architecture description discusses the new stakeholders in the mobile network ecosystem, and how the architectural work is taking into account their requirements in all the domains of the network. Specific design principles that need to be factored in for the new architecture are also described. Section 2.3 discusses the components of the security architecture, which are required and must be applied to have security as a design principle for the 6G architecture. A deep dive into the Management and Orchestration (M&O) architecture is then presented in Section 2.4. Section 2.5 outlines the summary of this chapter and presents the outlook.

2.1.1 The Societal Impact of 6G

Since the invention of mobile telephony half a century ago, wireless network technology has undoubtedly transformed the everyday lives of billions of people on the planet, and profoundly shaped the economy and the evolution of human society to date. The mobility of communication and of access to information has allowed completely new ways of interacting, working, and evolving our communities. For each generation of wireless technology, the applications and usages have become increasingly ingrained in our societies and have become an established backdrop to our modern lives. 6G will continue to impact our societies and will enable that communication is always possible and information is always available.

2.1.2 Trends and Evolution Towards 6G

Today, when the world is facing several unprecedented challenges in parallel and the prosperity of human society and the long-term survival of mankind are in peril, access to information and the possibility to communicate everywhere are a must. From climate change to global pandemics, social inequalities, misinformation, and distrust in democracy, addressing any challenge that impacts today's global economic, societal, and political agendas requires further and sustainable digitalization of the global economy and society. Infused by emerging and disruptive digital technologies on the horizon, wireless networks are and will be the keystone for enabling such a transformation. The network evolution during this and the next decade will enable a large scale adoption of use cases to sustainably combat our challenges and enable higher economic and societal values at a significantly decreased operational cost.

As the Internet revolution played out over the past decades, with mobile broadband altering our interactions, professions, and habits in unforeseen ways, the true social impact of 6G can only be ascertained in hindsight. Nevertheless, the kernel of its potential can be considered through the current societal and economic trends towards 2030 and beyond, which will be analysed in the following sections. In addition, regulatory and technological trends that are critical for the design and deployment of future networks will be discussed, ensuring the vision and the research work encompass all the essential elements and will lead to a future network design that is deeply rooted in reality and profoundly benefits humanity in the mid-to-long term.

Societal trends towards 2030 and beyond

In 2015, 17 interlinked Sustainable Development Goals (SDGs) were collectively identified by the General Assembly of the United Nations (UN) [1]. Since then, all sectors of society have been called for working towards and delivering on these goals with a timeframe of 2030 and beyond. The Information and Communication Technology (ICT) and wireless network industries have positively contributed to many of the goal areas so far (e.g., to combat poverty and CO_2 emissions), and the potential of further contributing and successfully progressing towards the goals is huge. In developing future networks towards 2030, there is a consensus among major stakeholders from industry, academia, and policy makers around the world: network technology shall support and further accelerate this change for a better and sustainable world, and the network industry will increase its share of contributions and responsibilities to society, enabling significantly increased efficiency in the use of resources and facilitating new and sustainable ways of living in the next decades [2–9].

Economic trends towards 2030 and beyond

Wireless network technology has long been regarded as an important engine for driving global economic growth. As projected in [10], network technology that encompasses 5G and beyond will potentially trigger \$13.2 trillion in global sales across ICT industry sectors by 2035, representing 5% of global real Gross Domestic Product (GDP), while 6G value chain will be able to generate 22.3 million jobs globally by 2035. This estimation did not even include the impact of connectivity on non-ICT sectors. As recognized in [11], "the next era of industry will be one where the physical, digital and human worlds are coming together," facing great economic and societal challenges towards 2030. Future networks will be a key enabler for such a revolution with advanced technological capability and human-centric design. New use cases will offer new growth opportunities assuming existing business models, and they can also drive and inspire new business models in an evolving revenue ecosystem.

Regulatory trends towards 2030 and beyond

While the telecommunications sector has been liberalized and privatized in the 1990s, sector regulation continues to be important in conjunction with efficient spectrum access rules, aspects of electromagnetic field (EMF), and assurance of level playing field with platform and cloud operators beyond telco context. Towards 2030, this trend will continue. For example, spectrum management is at the heart of future networks and any wireless technology development, and governments and regulators will have new opportunities due to a wide variety of spectrum bands with highly distinct deployment characteristics and spectrum access models with different levels and needs of spectrum sharing. Another rising issue is EMF exposure. The deployment of 5G technology has started in different areas of the world, and in some regions (including Europe), concerns over EMF exposure fuel the opposition of the public to its rollout [12, 13]. The exposure to EMF is and will be regulated, based on guidelines from the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [14]. Since the beginning of telephony, regulations have played an important role in shaping innovation and the operation of the telecommunications industry, for example, setting the industry to be monopolies in the 1960s, liberalizing the sector with privatization in the 1990s, and setting up new regulations for 5G local and private networks. Future networks will likely combine a range of radio access network (RAN) technologies from macro cells to small cells with very high-capacity short-range links. This calls for refining regulations to resolve inconsistent local approval processes and frequency band assignments to enable dense small cell deployments.

Technological trends towards 2030 and beyond

Previous generations of mobile networks have incessantly increased the performance and capacity to connect and communicate, facilitating global mobile communication and an intertwined global economy accessible at our fingertips. The efficiency gains provided to industries facilitate complex global logistics chains, and the interactive media have engendered a plethora of novel services and industries. This trend is not foreseen to abate in the foreseeable future but is rather expected to expand and encompass even further aspects of our societies.

Technology evolution towards cost reduction and improved efficiency

- **Reimagined network architecture:** As the applications grow more demanding and diverse, the complexity of the deployments and management of the system increases, and the possibility to flexibly and dynamically scale and control the network resources in an efficient way becomes more important. In 5G, the core network (CN) was reimagined into a service-based architecture (SBA), which leverages the virtualization of network functions to only instantiate the functions needed at each instance. Current trends in network architecture point to an extension of the SBA further out into the RAN allowing more flexible and autonomous operation of the network. A new network architecture paradigm for the 6G era is driven by a decomposition of the architecture into platform, functions, orchestration, and specialization aspects [15]. Future network platform will be associated with an open, scalable, elastic, and agnostic heterogeneous cloud, which is data-flow centric and will include hardware acceleration options. Functionally, the convergence of RAN and CNs will help reduce architectural complexity. At the same time, options of flexible offload, extreme slicing, and flexible instantiation of subnetworks will drive the increased level of specialization of the architecture. Of high relevance for the open provision of services and the monetization of resources will be the transformation of orchestration architecture; cognitive closed loops and automation are likely to become pervasive. All future deployment scenarios will rely on a superior transport network and network fabric that is flexible, scalable, and reliable to support demanding use cases and novel deployment options, such as a mixture of distributed RAN and centralized/cloud RAN enabled by AI-powered programmability [2]. The network architecture shall provide the capability to facilitate all the AI operations in the network.

- **Improved network capacity:** The ever-increasing demand for network capacity necessitates the provision of additional bandwidth. The potential to utilize the higher frequency bands, such as the sub-THz (100–300 GHz) range, is currently being explored. However, the radio propagation is significantly attenuated at these frequencies, and the reduced diffraction makes the connection more susceptible to blockage. Coupled with the reduced power efficiency and increased noise at higher frequencies, this compounds to several technological challenges that need to be overcome to provide sufficient coverage.
- **New devices and interfaces:** Future networks will be connected to multitudes of devices and interfaces beyond mobile phones or computers, enabling novel human–machine/machine–machine. New human–machine interfaces created by a collection of multiple local devices will be able to act in unison [3]. In addition, the ubiquity and longevity of Internet of Things (IoT) devices will be further enhanced through zero-cost and zero-energy devices where printable, energy harvesting devices can be deployed anywhere.
- **Network of networks:** In order to capture local and specialized network and sub-network needs, 6G network-of-networks will cover multiple scales of – physical and virtual – networks. The evolution of private and 5G non-public network (NPN), such as campus networks, will expand to support many machines and process with strict requirements on quality of service (QoS) and connectivity, employing edge processing for further automation. With

digital twins (DTs), massive data harvesting from local sensors builds up capillary sub-networks handled by gateways, while in parallel the wide-area network must handle mobility and coverage.

- **Trustworthy networks:** As more and more aspects of our lives, societies, and industries become reliant on mobile connectivity, it becomes imperative to ensure the performance, reliability, and security of the networks so that the services can be used as intended, when needed, without undue connection disturbances or access to private data. This will require the network architecture design to consider the security implications at every step, to avoid a patchwork of solutions after the fact.
- **Sustainable 6G and 6G for sustainability:** As one of the major challenges facing our societies today, the sustainability of our environment, industries, and the society at large must be ensured to be able to reach the sustainable development goals set by, e.g., the United Nations. For 6G, this entails addressing both the first-order effect of the network, referring to the direct environmental impacts of the manufacturing and operating of the networks in terms of energy consumption, CO_2 emission and usage of scarce resources, as well as the second-order effect, referring to how the networks enable improvements in sustainability with, e.g., improved efficiency in industries, or a transition from business travels towards virtual business meetings. However, there are also higher-order effects, also known as rebound effects, that must be considered, where the improved functionality of the mobile networks induces a novel behaviour of the users, which could, e.g., increase the total energy consumption. Moreover, societal sustainability should be addressed, with new services enabled by 6G meeting societal needs and demands [16].

Disruptive technologies that will shape future connectivity

- **Convergence of communications, localization, imaging, and sensing:** With the use of wider bandwidth signals coupled with high band spectrum (>100 GHz) as well as the incorporation of simultaneous localization and mapping (SLAM) with communications at lower frequencies, future networks will be designed integrating high-precision localization (with centimetre-level accuracy), sensing (both radar-like and non-radar-like), and imaging (at millimetre-level) capabilities. This requires the development of highly novel approaches and algorithms to co-optimize communications, sensing, and/or localization.
- **Network intelligence:** The evolution of artificial intelligence (AI)/machine learning (ML) has progressed in the past decades and may bring major disruptions to future networks. Their applications are currently designed for specific tasks, but as the development progresses, more general-purpose applications

emerge. As this development occurs in parallel with and in conjunction with the development of the mobile networks, it is foreseen that there may be several synergies between them. By leveraging on the mobile access, the AI agents can operate in a distributed fashion, gathering, analysing, and acting upon data available across different localities on a much larger scale. At the same time, the AI functionality can be utilized to optimize and enhance the network operations to improve the performance and reduce the operating costs by impacting the design of air interface, data processing, network architecture, and management towards computing for achieving superior performance [3, 7]. It will become essential for the E2E network automation dealing with the complexity of orchestration across multiple network domains and layers [15]. This may also bring forth fundamental changes in how the mobile networks operate, when there are AI agents both managing and operating the networks, as well as transmitting and receiving the information being communicated, and the fundamental tenets of the network architecture design may need to be revisited. For instance, the AI agents may be able to optimize the network behaviour in near real time, which would necessitate the ability to reprogram the network functions. This programmability would go beyond the configurability available today and would allow the modification and introduction of novel functionality into already deployed equipment.

- **Digital twin:** A DT is a digital replica of a living or non-living entity, physical object, or process. The virtual representation reflects all the relevant dynamics, characteristics, critical components, and important properties of an original physical object throughout its life cycle. The creation and update of DTs relies on timely and reliable multi-sense wireless sensing (telemetry), while the cyber–physical interaction relies on timely and reliable wireless control [17] over many interaction points where wireless devices are embedded.

2.1.3 Use Cases: Revolution or Evolution?

In previous generations of mobile networks, the use cases were straightforward: how to provide voice and, later, data communication with increasing bit rates to mobile devices. For the 5G, the use cases were broadened beyond enhanced mobile broadband (eMBB) to include massive machine type communication (mMTC), requiring low data rates with very low power consumption to enable connectivity to billions of simple devices, as well as critical machine type communication (cMTC), later termed ultra-reliable low-latency communication (URLLC), instead requiring extreme reliability and low latencies [18].

With 5G Advanced, extended reality (XR) has been introduced as a prominent use case, which encompasses both virtual reality (VR) and augmented reality (AR).

In XR, different on-body or head-mounted devices can be used to experience the digital world either fully immersed (VR) or overlaid onto the physical world (AR).

With the recent development and deployment of the 5G networks, the current needs in the developed markets appear to be satiable with current technology at least at peak performance, primarily necessitating a network densification to meet the capacity and latency demands.

In 6G, it is foreseen that the incumbent use cases will continue to be prevalent, with access to mobile broadband extended even further, by incorporating non-terrestrial networks and satellites to cost-efficiently reach remote and underserved areas.

Considering again the example of XR use cases, this XR use case is projected to increase in relevance as the devices improve in performance and form factor, and improvements in the network can transition this use case from stationary use near a hotspot towards mobile outdoor use. To ensure the performance in terms of data throughput and low latency, while maintaining the small form factor, it is expected that the XR use case will have to leverage on computational offloading, where significant amounts of the data processing are completed in the network instead of on the device. Similar to this XR example, other 5G use cases will evolve towards extended range of usage, thanks to the developed capabilities offered by 6G, reaching more people and devices and allowing for usage in more extreme conditions.

When it comes to revolutionary use cases, the introduction of novel functionality, such as joint communication and sensing, integrated AI functionality, or energy-neutral devices relying on ambient energy harvesting, could enable unforeseen usages and applications of the future 6G networks. The development of "6G for sustainability" use cases, in collaboration with different sectors and verticals, could also open the way to revolutionary usages. Relying on 6G as a tool to contribute to the reduction of the environmental footprint of other sectors could indeed lead to new roles for 6G and mobile networks, beyond the traditional market of previous generations. Although the International Telecommunication Union Radiocommunication Sector (ITU-R) is working on defining the usage scenarios for 6G, a few possible extensions to the previous usage scenarios can be envisioned, e.g., further enhanced mobile broadband (FeMBB), ultra-massive machine-type communications (umMTC), extremely reliable and low-latency communications (eURLLC), long-distance and high-mobility communications (LDHMC), and extremely low-power communications (ELPC) [19, 20].

6G use cases

The societal and economic trends are driving the identification of relevant use cases for 6G. The Hexa-X project provides a vision on the role of 6G in the evolution

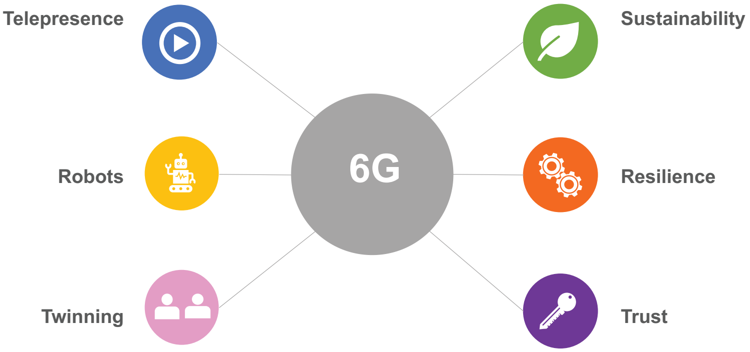

Figure 2.1. Generic use-case families for 6G.

of society [21–23], accounting for these trends and setting the baseline for the identification of use cases. Combining the sets of use cases identified by the various European projects provides an overview of the envisaged usage enabled by 6G. These different use cases can be clustered into broad and generic use case families, encompassing both evolutionary use cases and revolutionary ones, building on new functionalities. These generic use case families can be considered from the perspective of the type of end-user usage involved, as shown in Figure 2.1, such as:

- **Telepresence:** Immersive experience is a central theme for various use cases, with different degrees of immersion, from the evolution of XR experienced with 5G but with increased mobility, reliability, and scale to a fully immersive experience, fully merging physical and digital worlds, with various application areas, both professional and personal (travel, gaming, sports, etc.). This will leverage both the expansions and evolutions of existing technologies, providing connectivity as well as incorporating novel functionalities such as localization, sensing, and computational offloading.
- **Robots:** In parallel with the development of 6G, the evolution of robots and autonomous systems will continue, and robots are envisioned to become part of everyday life, both in professional and personal settings. They will collaborate and interact with each other, but also with humans. The generalization of robots will increase productivity but will also offer solutions to assist humans in their daily lives, meeting societal demands such as care of disabled persons. Although many aspects of this use case may be served by existing technologies, the increased demands for concurrent reliability, high bitrate, and low latency necessitate novel approaches.
- **Twinning:** The concept of DT will be extended in 6G, generalizing the use of the full digital representation of an environment to enhance control,

management, and maintenance of different flows and objects to various activity sectors. To capture, store, analyse, and distribute the digital representation of the environment, it will require a seamless network of unprecedented scale, incorporating sensing, computational offloading, and connectivity with low latency to numerous devices at the same time.

The generalization of these new services will also call for a new generation with increased capabilities to support large deployments.

Other use-case families can be identified according to the research challenges and values addressed:

- **Sustainability:** 6G can be a solution, for various verticals, to enable new use cases contributing to the reduction of their environmental impact (agriculture, industry, logistics, smart city, etc.). 6G can also help meeting societal demands by facilitating access to key institutions and enforcing human rights, such as access to healthcare, education, and reduction of inequalities.
- **Resilience:** Various 6G use cases are built upon resilient infrastructure, guaranteeing the delivery and quality of service despite the complexity of the network and possible situations and events. A resilient 6G network can be an asset to improve and develop key usages (e.g., in the automotive sector) or to develop new usages (e.g., facilitating public protection).
- **Trust:** A high level of trust in 6G networks is a prerequisite to various use cases, involving sensitive information or operations.

Other use-case families can be identified, related to capabilities offered by the network, either related to the management and operation of the network. New use cases can also be enabled, thanks to new capabilities introduced by 6G, such as sensing, positioning, AI processing, or compute capabilities.

Each use-case family encompasses a wide range of usages, from evolutionary ones, extending and enriching the 5G usages with new capabilities, to more disruptive ones, opening up new horizons where 6G could benefit and transform society. 6G use cases can also be evolutionary, relying on improvement of existing technologies, but also revolutionary when introducing new capabilities, such as sensing, AI, and compute capabilities as well as novel devices and interfaces.

6G requirements

Like the use cases, requirements for 6G can also be categorized into the evolution of key performance indicators (KPIs), e.g., higher throughput, lower latency, and revolution of novel KPIs (Figure 2.2). These novel KPIs explicitly focus on the E2E view required by novel 6G use cases, such as E2E dependability or service

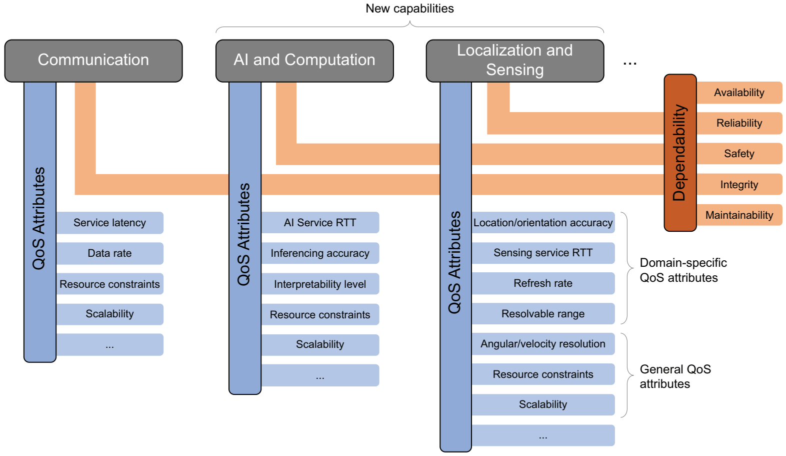

Figure 2.2. Classification of 6G KPIs.

availability. With the envisioned novel capabilities of 6G systems, such as ultra-precise 6D localization, sensing, and artificial intelligence functionality, additional KPIs for these capabilities need to be considered. KPIs for novel capabilities are discussed in [23].

In addition to KPIs, the social and economic trends towards 2030 motivate additional indicators for the fulfilment of key values, such as sustainability, inclusiveness, trustworthiness, and flexibility. To this end, the key value indicators (KVIs) and a methodology for value representation is introduced and described in [21, 22], and [23], with further alignment across different projects towards a unified methodology happening in the 6G-IA [24].

The main point in this methodology is that the use cases introduced at the beginning of this section can contribute to the key values, and a KVI is used to illustrate this. When feasible, it is proposed to use the target level of the UN SDGs as a preferred framework for identifying and detailing the value impact. In some cases, a KVI quantification may be challenging, and then a connection to a KPI can be made to grade or assess a value creation potential and contribution from a use case. For the key value of trustworthiness, a “level of trust” as a KVI is explored, and for flexibility, an association is made to proxies such as scalability requirements/KPIs.

A KVI analysis of a selected set of use cases is included in [23].

2.2 The Need for a New Architecture

This section presents the overall direction that the 6G architecture should move towards to fulfil the trends and technology evolutions. This is done by defining a set of architectural principles and followed by a high-level E2E architecture view.

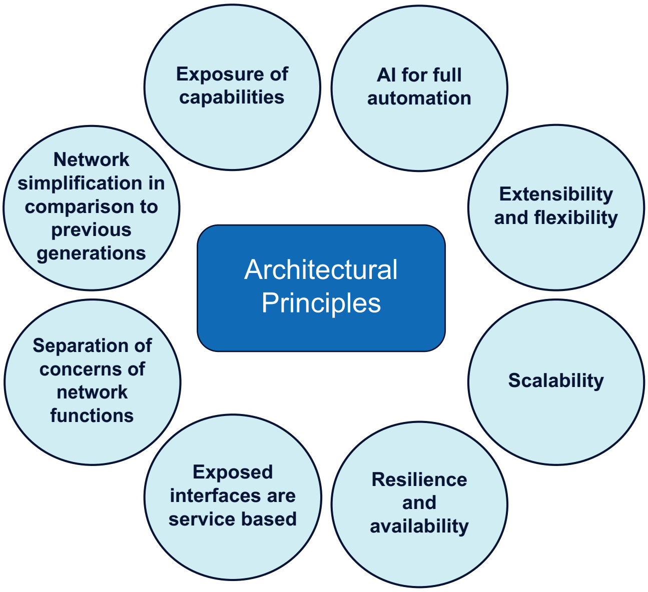

Figure 2.3. 6G architecture principles guiding the architecture design [1].

2.2.1 Architectural Principles

To serve as a guideline when developing the 6G architecture, eight different architectural principles are defined [24, 26]. The order or the numbering of the principles does not indicate the level of importance. Figure 2.3 shows a summary of the eight different principles.

Principle 1: Exposure of capabilities

The architecture solution shall expose new and existing network capabilities to E2E applications and management, such as predictive orchestration. The analytic information can, for example, be performance for predictions, such as latency and throughput, or it can also be localization and sensing information.

Principle 2: AI for full automation

The architecture should support full automation to manage and optimize the network without human interaction. The closed-loop network automation assumes the use of AI/ML.

Principle 3: Extensibility and flexibility

The ability of the network to adapt to various topologies without loss of performance while still enabling easy deployment. This can, for example, be the ability to adapt to new traffic demands, spectrum situations, private networks, and ad-hoc mesh networks.

Principle 4: Scalability

The network architecture needs to be scalable both in terms of supporting very small to very large-scale deployments, by scaling up and down network resources based on needs.

Principle 5: Resilience and availability

The architecture shall be resilient in terms of service and infrastructure provisioning using features, such as multi-connectivity and removing single points of failure.

Principle 6: Exposed interfaces are service based

Network interfaces should be designed to be cloud-native, utilizing state-of-the-art cloud platforms and IT tools in a coherent and consistent manner.

Principle 7: Separation of concerns of network functions

The network functions have a bounded context, and all dependencies among services are through their application programming interfaces (APIs) with a minimal dependency with other network functions, so that network functions can be developed, deployed, and replaced independently from each other.

Principle 8: Network simplification in comparison to previous generations

The network architecture should be streamlined to reduce complexity by utilizing cloud-native upper-layer RAN and CN functions with fewer (well-motivated) parameters to configure and fewer external interfaces.

2.2.2 End-to-end Architecture

Figure 2.4 depicts a high-level view of the envisioned 6G architecture and highlights the key technical enablers. The various building blocks are organized into three layers: **Infrastructure, Network Service (NS), and Application.**

The **infrastructure layer** comprises RAN (addressed more in Chapter 3), CN, and transport networks, which contain radio equipment, switches, routers, communication links, data centres, cloud infrastructure, and so on. The infrastructure layer provides the physical resources to host the NS and application layer elements.

The envisioned 6G infrastructure layer should also contain RAN improvements, such as extremely low latency, high reliability, high availability, high data rate, high capacity, affordable coverage, and high energy efficiency. Extremely high data rate links will be required in some very high-performance applications anticipated in 6G, e.g., immersive smart cities (a use case from telepresence use case family) and fully merged cyber-physical worlds (a use case from twinning use case family) (see Section 2.1). Most of those are related to highly advanced online imaging, including holographic communications as well as providing extreme data rates for high-capacity cells. In those cases, a throughput of 100 Gbit/s or even significantly higher can be required. This means bandwidths of several tens of GHz would be required to provide this. The architecture design, in particular the infrastructure layer, needs to ensure that such data rates can be brought to local small-scale base stations that will serve end users. More details can be found in Chapter 3.

Furthermore, due to the introduction of new use cases and their strict requirements, e.g., immersive smart city [22], the infrastructure layer envisioned for 6G should be able to accommodate new enablers, such as localization and sensing (addressed more in Chapter 4). Joint communication and sensing (JCAS), also known as integrated sensing and communication (ISAC), will be one of the main differentiators of the vision for 6G architecture with respect to 5G communication systems. Sensing not only includes positioning but also encompasses other novel functionalities that were not present in 5G, such as radar-type sensing and non-radar-type sensing using communication technologies, which in turn leads to new services, such as sensing as a service (SaaS), and landscape sensing [23].

The deployment of mobile networks has become increasingly complex and diverse with every new generation. The 6G network of networks should easily and flexibly adapt to new topologies to meet the requirements of both extreme performance and global service coverage well beyond what 5G is capable of. The 6G architecture incorporates different (sub)network solutions into a network of networks. The 6G network should also be able to support very small to very large-scale deployments, by scaling up and down network resources based on needs (see Chapter 5). 4G brought the so-called heterogeneous network (HetNet) solutions, i.e., how networks with both wide-area macro- and small-cell pico-base stations should cooperate. The extension of the radio spectrum into mmWave in 5G added yet another aspect to flexible deployment. 6G deployments will include nodes using even higher sub-THz spectrum (e.g., in the 100–300 GHz frequency range) with limited coverage as well as nodes at low frequencies with seamless coverage. Furthermore, the number of network solutions for capacity and coverage is also expected to increase in the 6G timeframe. These include solutions such as distributed multiple-input multiple-output (D-MIMO) networks, non-terrestrial networks (NTN), campus networks, mesh networks, and cloudification of the network elements. Thus, 6G will be a network of networks.

Even with the new 6G solutions mentioned, the increased use of mobile broadband and digital solutions may require a more densified network, in order to cope with the increased capacity needs. This could lead to an increase in overall emissions unless energy efficiency continues to be addressed.

The envisioned 6G architecture will employ a number of key sustainability enablers to complement the 6G sustainability targets; it is fundamental to jointly take into account all the sustainability aspects of networking, including hardware, planning, deployment, operations, and the entire equipment life cycle. These aspects can be effective in achieving sustainability in all layers and levels of the architecture, namely ***at deployment levels*** that include architectural and hardware innovations, ***at management and orchestration levels*** that target network operation efficiency maximization, ***at service/application layers***, such as application-aware networks, and ***at cross-layer sustainability enablers*** that include innovations in two or more layers. Detailed information on these enablers can be found in Chapter 6.

The **NS layer** is envisioned to be cloud- and micro-service-based with functions and microservices expanded from central cloud to the edge cloud (see Figure 2.4).

One of the key technology enablers of the NS layer is the introduction of the extreme edge cloud (see Figure 2.4)). Extreme edge cloud covers part of the network with high heterogeneity of devices with a wide variety of technologies, in terms of both hardware and software. These devices could be personal devices (smartphones, laptops, etc.) and a huge variety of IoT devices (wearables, sensor networks, connected cars, industrial devices, connected home appliances, etc.). The concepts of edge and extreme edge computing become more and more relevant for the 6G architecture and services. Microservice-based implementation can provide improvements towards a softwarized, intelligent, and efficient 6G architecture. Chapter 5 describes the enablers for an intelligent network. The ultimate target for the 6G architecture is to enable autonomous and adaptable networks, with no (or minimal) human intervention, leveraging cognitive, closed-loop control network functions that can be instantiated on an on-demand basis, even across network domain boundaries. In this sense, an intelligent 6G architecture should be able to define the underlying mechanisms to support embedded AI for 6G and ensure dynamic adaptability of the network architecture to new use cases while keeping the infrastructure and energy costs at acceptable and sustainable levels.

Another important aspect of a more flexible and intelligent network is programmability, addressed in detail in Chapter 7. Programmability can be a tool to introduce new features, especially to deployments that have a limited footprint due to limited hardware types and specific requirements. Over the last decade, programmability is significantly enhanced thanks to the software-defined networking (SDN) paradigm as well as the ongoing trend towards softwarization and cloudification. For 6G architecture, this trend is expected to continue in order to allow third-party developers to interact with the network in new ways, and 6G architecture is expected to ensure reusability and flexibility.

Furthermore, with a cloud-native approach, the RAN and CN architectures can be streamlined, e.g., reduce some complexity by removing multiple processing points for a certain message and removing duplication of functionalities among functions [30].

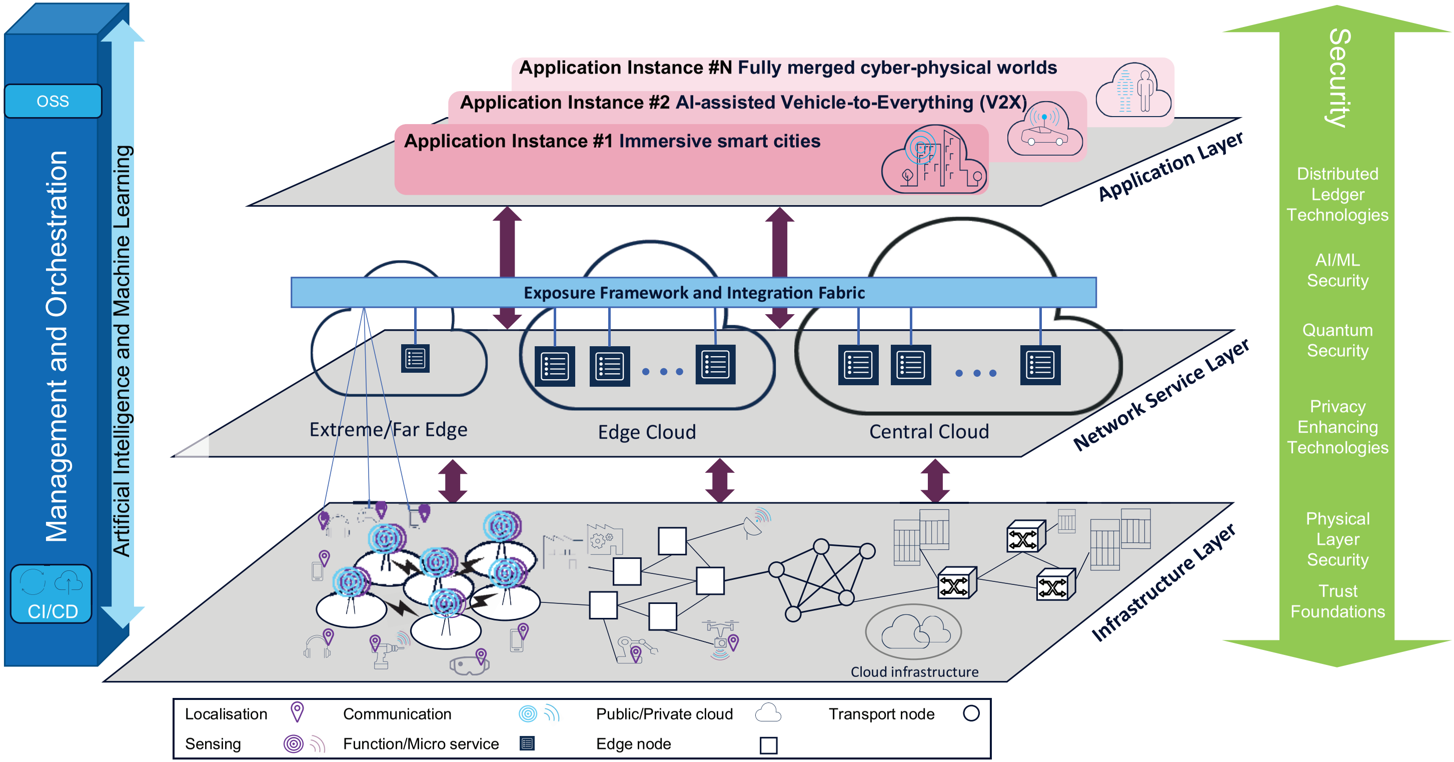

Figure 2.4 End-to-end system view of the 6G architecture [23].

Cloud-native technologies can enable the creation of cloudlets at the edge of the network, with application-to-application and function-to-function communications, which are capable to satisfy a large number of interconnected assets with flexible mesh topologies. Another important aspect of the NS layer is the *exposure framework and integration fabric*. It establishes a communication channel that enables seamless interoperation and networking across different domains.

The 6G architecture will be able to support the strict requirements of various use cases that have been envisioned for the next generation of mobile networks (see Section 2.1.3). In particular, use cases belong to massive twining and telepresence use-case family, e.g., immersive smart city [22] that can be a digital replica of a real traffic scenario of the city, the automated train operations, the control of the utilities (energy, water, gas, etc.), air quality and more are some of the aspects of the implementation of massive twining to city environments. An interactive 4D map can be used to plan utility management, such as public transport, garbage, piping, cabling, buildings, and heating, or to connect many parts of a factory that can be inspected and steered in detail. Similarly, AI-assisted vehicle to everything (V2X) is another example of use cases that can provide high level of safety and security for any transport system, especially road transport due to the prevalence of accidents. This motivates the need to further explore the potentiality of the AI algorithms for enhanced automotive services provided by future 6G networks, and it requires a solid architectural foundation.

Network M&O is gradually moving towards increasing the levels of automation and fully automated closed-loop control. This is supported by the parallel adoption of advancements in AI/ML technologies. The aim of this shift is to provide a framework to optimally support reliability, flexibility, resilience, and availability and addressing changes in the infrastructure, requirements, and failures. More details on the 6G M&O architecture envisioned for 6G can be found in Section 2.4.

Security and privacy mechanisms are integral parts of the overall architecture, affecting all network layers as well as the M&O domain. Figure 2.6 highlights the 6G security technology enablers across different layers [31].

Privacy-enhancing technologies are important on all layers where sensitive data are gathered or processed, and clearly also in the management domain. Similarly, AI/ML security is relevant for all functions making use of AI/ML, in the sense of specifically protecting this use, but also refers to AI/ML-driven security mechanisms, e.g., in the management domain [32]. Finally, distributed ledger technologies are relevant wherever it is required to establish "distributed trust," i.e., trust that is not anchored in a centrally trusted authority, as it may be the case in inter-domain management.

Figure 2.5 shows one possible functional view of the envisioned 6G architecture, which is depicted on the E2E system view of the architecture. It is hierarchically

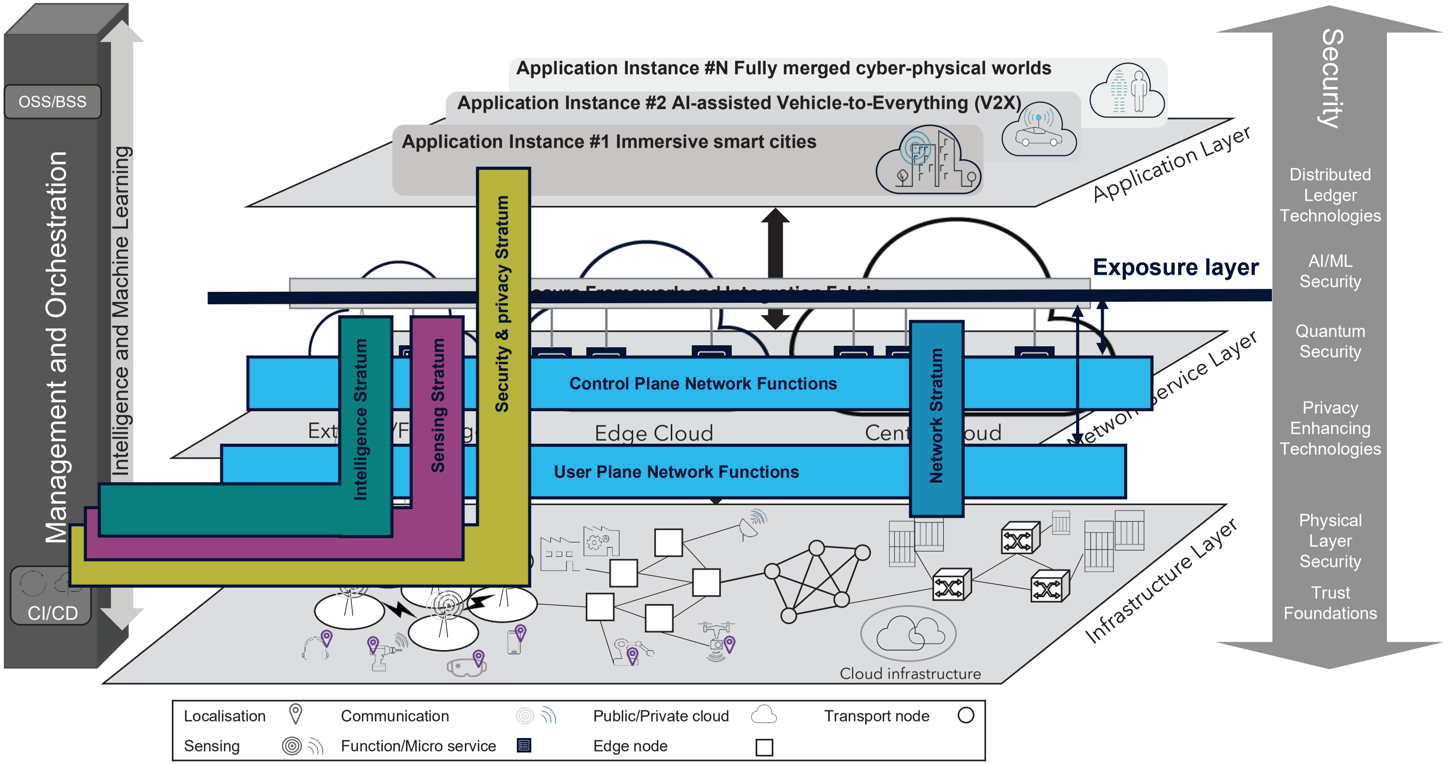

Figure 2.5 Functional view of the proposed 6G reference architecture with the focus on the stratums.

composed of the set of planes that traditionally build the mobile network architecture and has done so since the earliest releases of the 3rd generation partnership project (3GPP) standards. In this context, and by borrowing and extending the terminology from the 3GPP system, a stratum is defined as a set of coordinated functions that is running in different planes or domains of the network. For the proposed functional architecture, four stratums on *Network*, *Sensing*, *Security & Privacy*, and *Intelligence* have been introduced.

Network stratum is consisted of network functions in control plan (CP) and user plan (UP) that are responsible for delivering the expected QoS, efficiently allowing user equipment (UE) to exchange data with the network. CP and UP entail novel access technologies, which may also include the ones leveraging sub-terahertz bands and visible light communications; AI-native air interface, arranged in specific ways (e.g., cell free networks [33, 34]), and even including extreme edge functions like the ones that are managing and reconfiguring intelligent metasurfaces.

Traditionally, the non-access stratum included functions from the UE, UP, and CP. The **network intelligence stratum** encompasses and coordinates functions in all networks, ranging from the intelligent operation of network functions to their autonomous management and orchestration. The network intelligence stratum gathers data and analytics from the **infrastructure layer**.

The infrastructure can be extended to include environmental aspects (i.e., the environment where the infrastructure is deployed, and functions are executed) to allow a tight interaction between the network and the surrounding space. Properly steering beams at very high frequencies or using unmanned aerial vehicle (UAV) to extend the network's coverage requires a **sensing stratum** that can efficiently coordinate functions, harvesting data from fixed landmarks or dynamic laser/light imaging, detection, and ranging (LIDAR) scans, or even using the UP wireless technology as an additional source of sensing, possibly in an energy harvesting fashion.

The last stratum is the **security & privacy stratum**, which manages the cyber security and data privacy aspects of the network. This stratum coordinates functions in all the planes and domains of the network up to the vertical service provider one, which also benefits from the enhanced 6G security and cooperates with it to minimize the attack surface, while allowing the service customers to have full control over the data (including the network one).

Clearly, this richness in the available network functions, which have to be arranged and properly configured according to the network slices they belong to, poses new challenges to the **management plane** of the network, see Section 2.4.

This interaction is possible thanks to the **enhanced exposure interface** between the network and the vertical service providers on the **application layer**, through the use of network applications, which can leverage on data, functions, and procedures offered to support and enhance the user experience. Through the exposure interface, the traditional barrier between operators and service providers is removed, allowing a white-box customization of the vertical services.

2.3 Security & Privacy Architectural Components

Figure 2.6 shows the overall architecture, visualizing the applicable security and privacy components in all areas, and highlighting the specific 6G security technology enablers. While the focus lies on the technology enablers as new architectural components, a holistic 6G security architecture must also comprise today's well-proven security mechanisms, as far as they are still relevant in 6G. On this basis, Figure 2.6 summarizes these components, without the aspiration of exhaustiveness and depth of detail.

Figure 2.6 distinguishes among non-virtualized equipment (for radio access and optical transport), the cloud infrastructure, and the software running on it, including the virtualization layer, the logical network layer, and the management and orchestration functions, including security and risk management and inter-domain management. In each part, the figure shows the most relevant security and privacy building blocks or architectural components, with the new 6G security technology enablers highlighted in red, and the more traditional building blocks, like for example "*Secure SW*," in blue.

Many building blocks apply to multiple areas, e.g., "*Secure SW*" applies to the non-virtualized radio and optical equipment (as far as this equipment comprises software), to the virtualization layer, and to all the software running on it, including M&O functions. As another example, "*Trust foundations*" apply to all hardware, i.e., the radio and optical equipment as well as the cloud infrastructure. On the other hand, some building blocks appear in dedicated places only, like "*Distributed ledger technologies*" appearing at inter-domain management only, but this does not preclude the potential applicability of the building block in other areas. Also, when a building block appears in an area, this does not imply that the building block is always applicable. For example, certain non-virtualized radio access equipment may not have access to sensitive data, so no privacy-enhancing technologies may be required here. As another example, obviously not all transport equipment is required to support quantum key distribution.

The traditional security building blocks may be mostly self-explaining, but note the following:

- "*Secure SW*" refers to software with a low (close to zero) degree of vulnerability. "*Secure HW/FW*" has the same meaning for hardware or firmware. An

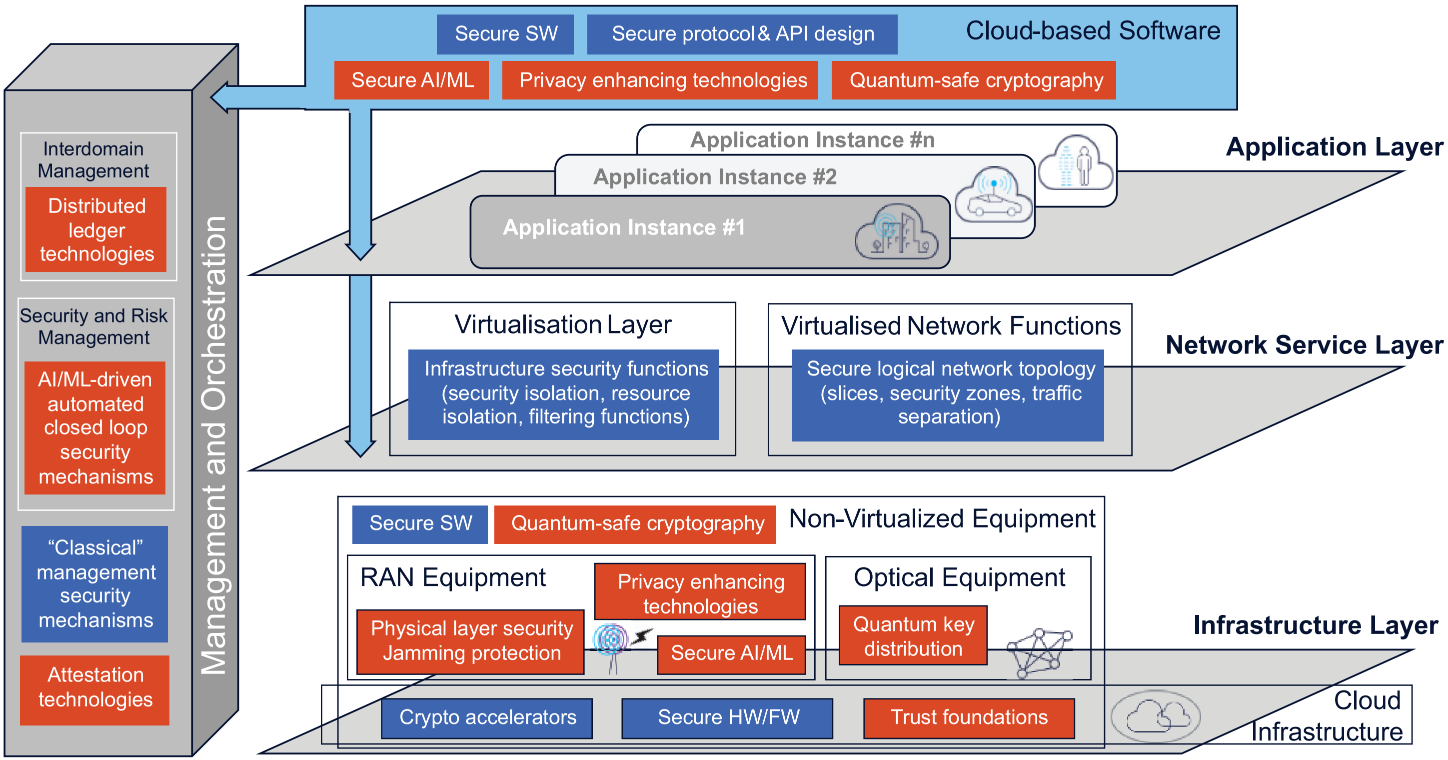

Figure 2.6 Overview of the essential 6G security architectural components [33]. The new 6G security technology enablers highlighted in red, and the more traditional building blocks are in blue.

example is the robustness of a processor against leaking information between different processes running on this processor in a (quasi-) parallel manner.

- "*Secure protocol and API design*" refers to robustness not only against external attackers (which is typically achieved by the use of cryptography), but also against erroneous or malicious behaviour of authorized peers.
- "*Classical management security mechanisms*" comprise well-established mechanisms, such as access control, role-based access, secure logging, isolation of management functions/traffic from all other traffic, etc.

Further details on the components of the security and privacy-preserving technologies are provided in Chapter 8.

2.4 Service Management and Orchestration

Service M&O deals with the deployment and operation of the NSs supplied through the mobile network operator (MNO) to their customers, preserving all of the contractual aspects associated to those services. It addresses the provision of services, QoS and quality of experience (QoE) fulfilment, or fault reporting, among others. In previous generations of the mobile communications systems, the customers of the MNOs have been mainly individuals consuming voice and messaging services. However, the market situation is much more complex now, including new data services and corporate customers, such as vertical industries, digital operators, hyper-scalers, or large-scale content providers, among others. It is anticipated that this trend, in terms of heterogeneity of stakeholders and provided services, could continue and even experience growth within the coming years.

To cope with this complexity, it is needed to enable the services M&O systems with the required capabilities to provide the necessary orchestration resources. Specifically, the following main capabilities have been identified for the future 6G M&O systems.

The adoption of the cloud-native principles also in the M&O system. This would be aligned with the E2E architectural concepts in Section 2.2.2, but from the M&O perspective, it would involve three main aspects: (i) the priority on using micro-services, i.e., light-weight self-contained, independent, and reusable components from different suppliers; (ii) the implementation of the *service mesh* concept, regarding the communication among the network components; and (iii) the enabling mechanisms for the NSs to be deployed/updated using "continuous" DevOps-like practises, e.g., implementing CI/CD workflows with a high automation degree.

Unified M&O across multiple domains that could be owned/administered by multiple stakeholders and featured with heterogeneous technology resources. This entails the definition of converging interfaces, the mechanisms to dynamically check and expose the different resources and capabilities from each domain, and the access control procedures for consuming the various primitives and services.

Increased degree of automation to strongly reduce manual interventions regarding the functionalities of service and network planning, design, provisioning, optimization, and operation/control, leveraging closed-loop and zero-touch responses. The M&O system needs to be able to identify, detect, or predict potential issues, triggering automatic reactions.

Adoption of data-driven and AI/ML techniques in the M&O system. AI/ML techniques could cover numerous optimization aspects and lifecycle actions concerning the services M&O, including resource allocation and slice sharing at provisioning time, service composition, scaling, migration, re-configuration, and re-optimization of NSs, among others.

Intent-based approaches for service planning and definition. In order to help with the extended complexity, the M&O system would implement automated mechanisms for translating service specifications and commands based on high-level intents, which might be expressed even in natural language (e.g., relying on AI/ML techniques).

To meet these main challenges, the M&O system is seen as a common functionality impacting all layers of the E2E architecture: from the infrastructure up to the applications (see Figure 2.7). In this regard, an initial high-level M&O architectural design for the future 6G networks has been produced. This architectural design takes the previous 5G architectural view from the 5G PPP Architecture Working Group as a baseline [34, 35] represents the structural view of this architecture, with the main building blocks grouped in different layers.

The NSs and slices at the service layer (top in Figure 2.7) are executed on the infrastructure layer (bottom) through the network functions at the network service layer (middle). All these elements (network functions, services, and slices) are designed and provided from the design layer (right).

A new layer, named the *design layer*, has been included to represent the M&O-related operations involving third-party software providers. This is intended to introduce the well-known DevOps-like practises (e.g., continuous integration and continuous delivery/continuous deployment (CI/CD)) in the telco-grade environment. Also, hyperscalers, private networks, and the extreme edge domain have been explicitly included as part of the infrastructure layer. New control loops have been included: (i) the “DevOps control loop,” representing the automated continuous iterations (e.g., CI/CD) between the MNO scope (grey colour) and the external design layer (light blue colour); and (ii) the “infrastructure control loop,” meant to automate the infrastructure discovery processes and the related monitoring methods targeting the extreme edge asset integration (which can be potentially asynchronous in terms of connection/disconnection of devices, so requiring special

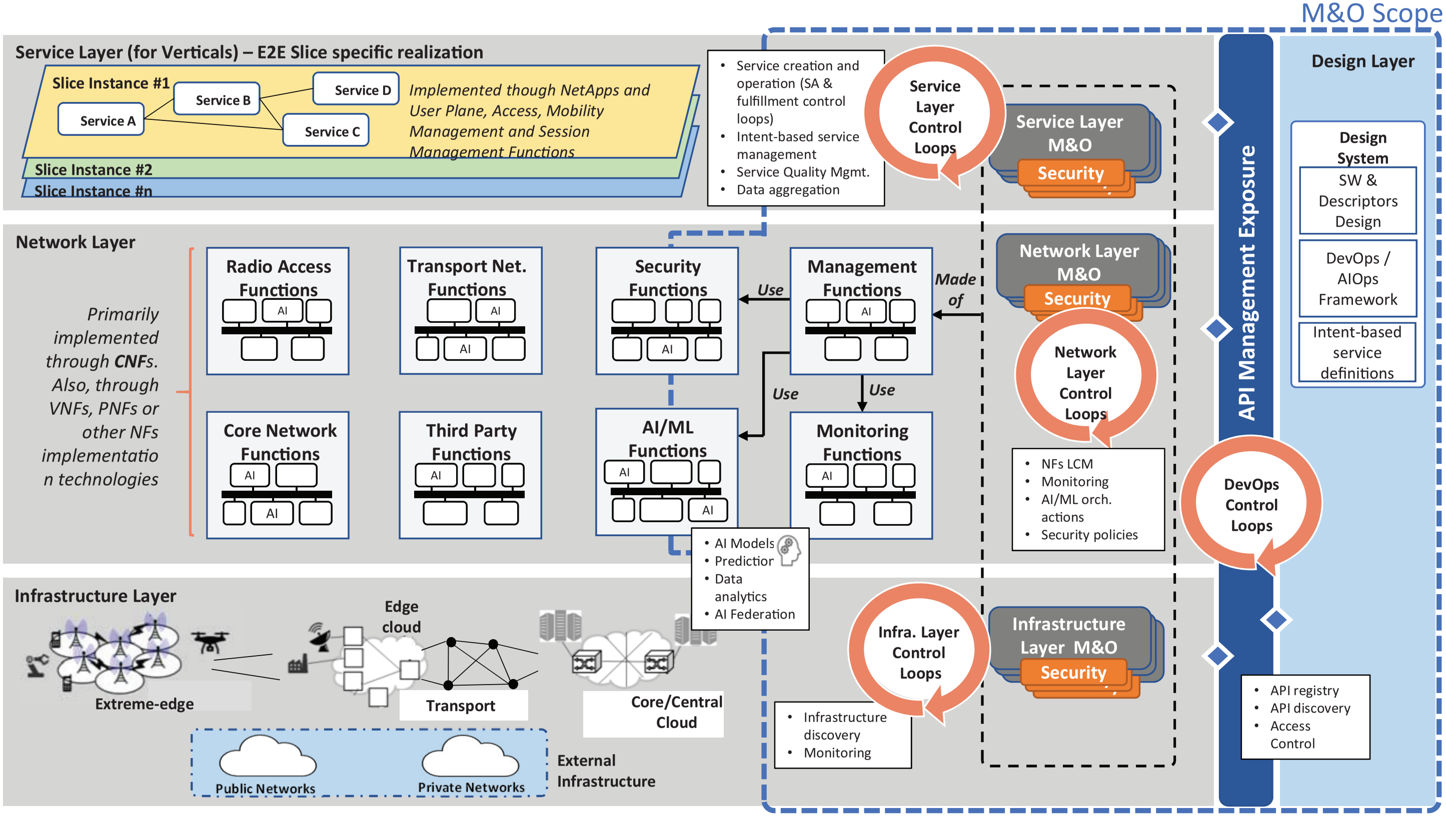

Figure 2.7 Proposed 6G management & orchestration system – structural view [34].

processes for their management). As in the baseline architecture in [35], NFs are associated in different groups at the network layer (e.g., radio access functions, CN functions, M&O functions, AI/ML functions, etc.). However, following the cloud-native practises, these functions would be primarily implemented through containerized NFs (CNFs), although also through virtualized NFs (VNFs), physical NFs (PNFs), or other NF implementation technologies (e.g., to ensure backward compatibility). It should be noticed here that, although some functions work only as managed resources (e.g., CN functions or third-party functions), others are specific M&O resources (e.g., the monitoring functions or the management functions themselves); however, other functions are *hybrid*: they can support M&O resources (e.g., certain security-related or AI/ML functions) or work as *pure* managed resources (e.g., certain AI as a Service (AIaaS) functions or security functions not in the M&O scope). Functions in the network layer are generic, i.e., instead of referring specific functions (e.g., communication service management function (CSMF), media resource function (MRF), NFV orchestrator (NFVO), etc.) as in [35], just generic blocks are provided. This is intentional, in order to consider the new functions that would be probably defined for the future 6G stack. A new set of AI/ML collaborative components have been distributed across the network covering both managing and managed scopes. M&O functions can be instantiated in the three different layers (service, infrastructure, and network layers), including specific security-related functions. Finally, and also aligned with the cloud-native approach, a new cross-layer API management exposure block has been included to communicate the different network elements in the different network layers. In short, it mimics the behaviour of the zero-touch service management (ZSM) *cross-domain integration fabric*, enabling the so-called *capabilities exposure* of the network of elements in the various architectural layers. It makes possible communicating the various M&O resources within and between administrative domains, although it could be applied more broadly to represent potential federated interactions.

2.5 Summary and Outlook

This chapter discusses the current architectural trends and technologies for the future 6G network. Motivated by the surge of new requirements stemming from societal trends and use cases, a set of architectural principles has been introduced, and new architectural and technical enablers needed for the 6G architecture have been identified. A high-level view of a possible E2E system of the 6G architecture as well as a functional view is described. Thereafter, a description on how the enablers fit into the system view is given, which is also an overview of the content in this book. The chapter dives into the security and privacy area in a bit more detail and gives an overview of the 6G security and privacy architectural components. Finally, the main capabilities needed for a future 6G M&O systems are discussed.

References

[1] United Nations (UN), "Transforming our world: the 2030 Agenda for Sustainable Development," 21 October 2015. Accessed: April 6, 2023. [Online]. Available: https://sdgs.un.org/2030agenda.

[2] Ericsson, "6G – Connecting a cyber-physical world," February 2022. Accessed: April 6, 2023. [Online]. Available: https://www.ericsson.com/4927de/assets/local/reports-papers/white-papers/6g--connecting-a-cyber-physical-world.pdf.

[3] Nokia, "Communications in the 6G era," 9 September 2020. Accessed: April 6, 2023 [Online]. Available: https://onestore.nokia.com/asset/207766.

[4] GSM Association, "2022 Mobile Industry Impact Report: Sustainable Development Goals," September 2022. Accessed: April 6, 2023. [Online]. Available: https://www.gsma.com/betterfuture/wp-content/uploads/2022/11/2022-SDG-Impact-Report.pdf.

[5] M. Matinmikko-Blue, S. Aalto, M. I. Asghar, H. Berndt, Y. Chen, S. Dixit, R. Jurva, P. Karppinen, M. Kekkonen, M. Kinnula, and P. Kostakos, *White paper on 6G drivers and the UN SDGs*, University of Oulu, June 2020. Accessed: April 6, 2023. [Online]. Available: http://urn.fi/urn:isbn:9789526226699.

[6] G. Fettweis, "6G – Just a better 5G?: 2020 5G World Forum keynote series," 18 November 2020. Accessed: April 6, 2023. [Online]. Available: https://ieeetv.ieee.org/2020-5g-world-forum-keynote-gerhard-fettweis.

[7] N. Demassieux, "6G. Why?," In *EuCNC 2020*, Dubrovnik, Croatia, 2020. Accessed: April 6, 2023. [Online]. Available: https://www.eucnc.eu/wp-content/uploads/2020/07/2020-05-29-6G.-Why-Nicolas-Demassieux-EUCNC-VDEF.pdf.

[8] Samsung, "The Next Hyber-Connected Experience for All," 14 July 2020. Accessed: April 6, 2023. [Online]. Available: https://cdn.codeground.org/nsr/downloads/researchareas/20201201_6G_Vision_web.pdf.

[9] NTT DOCOMO, "White paper 5G Evolution and 6G, version 5.0," January 2023. Accessed: April 6, 2023. [Online]. Available: https://www.docomo.ne.jp/english/binary/pdf/corporate/technology/whitepaper_6g/DOCOMO_6G_White_PaperEN_v5.0.pdf.

[10] Raconteur, "The economic impact of 5G," 2020. Accessed: April 6, 2023. [Online]. Available: https://www.raconteur.net/infographics/the-economic-impact-of-5g/.

[11] European Commission, "A New Industrial Strategy for Europe," 10 March 2020. Accessed: April 6, 2023. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0102.

[12] Arcep, "Networks and the Environment," 8 September 2020. Accessed: April 6, 2023. [Online]. Available: https://en.arcep.fr/fileadmin/cru-1677573101/user_upload/37-20-english-version.pdf.

[13] The Connexion, "Lille issues 'moratorium' on 5G technology," 11 October 2020. Accessed: April 6, 2023. [Online]. Available: https://www.connexionfrance.com/article/French-news/Lille-issues-moratorium-on-controversial-5G-technology-pending-2021-Anses-report.

[14] International Commission on Non-Ionizing Radiation Protection, 2023. Accessed: April 6, 2023. [Online]. Available: https://www.icnirp.org/.

[15] V. Ziegler, H. Viswanathan, H. Flinck, M. Hoffmann, V. Räisänen, and K. Hätönen, "6G architecture to connect the worlds," In *IEEE Access*, vol. 8, pp. 173508–173520. Sep. 2020.

[16] Orange, "Orange inaugura tienda en el metaverso," 13 September 2022. Accessed: April 6, 2023. [Online]. Available: https://blog.orange.es/innovacion/orange-inaugura-tienda-en-el-metaverso/.

[17] R. Minerva, G. M. Lee, and N. Crespi, "Digital twin in the IoT context: A survey on technical features, scenarios, and architectural models," In *Proceedings of the IEEE*, vol. 108, no. 10, pp. 1785–1824, 2020.

[18] European Telecommunications Standards Institute (ETSI), "About ETSI," 2023. Accessed: April 6, 2023. [Online]. Available: https://www.etsi.org/about.

[19] M. Rasti, S.K. Taskou, H. Tabassum, and E. Hossain, "Evolution toward 6g multi-band wireless networks: A resource management perspective,“ In *IEEE Wireless Communications*, vol. 29, no. 4, pp. 118–125.

[20] Z. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. Ding, X. Lei, G. K. Karagiannidis, and P. Fan P, "6G wireless networks: Vision, requirements, architecture, and key technologies," In *IEEE Vehicular Technology Magazine*, vol. 14, no. 3, pp. 28–41, Jul 2019.

[21] Hexa-X, "D1.1 – 6G Vision, use cases and key societal values," 28 February 2021. Accessed: April 6, 2023. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5d9f611f1&appId=PPGMS.

[22] Hexa-X, "D1.2 – Expanded 6G vision, use cases and societal values – including aspects of sustainability, security and spectrum," 30 April 2020. Accessed: April 6, 2023. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5dc8b611b&appId=PPGMS.

[23] Hexa-X, "D1.3 – Targets and requirements for 6G – initial E2E architecture," 28 February 2022. Accessed: April 6, 2023. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5e90431aa&appId=PPGMS.

[24] 6G Infrastructure Association, Vision and Societal Challenges Working Group, Societal Needs and Value Creation Sub-Group, "What societal values will 6G address?," May 2022. Accessed: April 6, 2023. [Online]. Available: https://5g-ppp.eu/wp-content/uploads/2022/05/What-societal-values-will-6G-address-White-Paper-v1.0-final.pdf.

[25] Hexa-X, "D5.1 – Initial 6G architectural components and enablers," December 2021, Accessed: April 6, 2023. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5e652c1f2&appId=PPGMS.

[26] M. Ericson, S. Wänstedt, M. Saimler, H. Flinck, G. Kunzmann, P. Vlacheas, P. Demestichas, D. Rapone, A. De La Oliva, C. J. Bernardos, and R. Bassoli, "Setting 6g architecture in motion–the hexa-x approach," In *2022 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*, June 2022.

[27] Hexa-X, "D3.2 – Localisation and sensing use cases and gap analysis," September 2022. Accessed: April 6, 2023. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5e648d02a&appId=PPGMS.

[28] Hexa-X Deliverable "D5.2 – Analysis of 6G architectural enablers' applicability and initial technological solutions," October 2022, Accessed: April 6, 2023. [Online]. Available: to appear in https://cordis.europa.eu/project/id/101015956/results.

[29] Hexa-X Deliverable "D2.1 – Towards Tbps Communications in 6G: Use Cases and Gap Analysis" June 2021. Accessed: April 6, 2023. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5df2529fd&appId=PPGMS.

[30] E. U. Soykan, L. Karaçay, F. Karakoç, and E. Tomur, "A Survey and Guideline on Privacy Enhancing Technologies for Collaborative Machine Learning," In *IEEE Access*, vol. 10, pp. 97495–97519, Sep 2022.

[31] N. Rajatheva, I. Atzeni, E. Björnson, A. Bourdoux, S. Buzzi, J. B. Dore, S. Erkucuk, M. Fuentes, K. Guan, Y. Hu, and X. Huang, J. Hulkkonen, J. M. Jornet, M. Katz, R. Nilsson, E. Panayirci, K. Rabie, N. Rajapaksha, M. J. Salehi, H. Sarieddeen, T. Svensson, O. Tervo, A. Tolli, Q. Wu, and W. Xu, "White paper on broadband connectivity in 6G," In *arXiv preprint* arXiv:2004.14247. April 2020.

[32] H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson, and T. L. Marzetta, "Cell-free massive MIMO versus small cells," In *IEEE Transactions on Wireless Communications*, vol. 16, no. 3, pp. 1834–1850, Jan 2017.

[33] M. B. Khorsandi, R. Bassoli, G. Bernini, M. Ericson, H. F. Fitzek, A. Gati, H. Harkous, H. Hoffmann, I. L. Pavon, G. Landi, and D. Lopez, "6G E2E Architecture Framework with Sustainability and Security Considerations," In *2022 IEEE Globecom Workshops (GC Wkshps)* Dec 4, 2022.

[34] Hexa-X Deliverable "D6.2 – Design of service management and orchestration functionalities", Apr. 2022. Accessed: April 6, 2023. [Online]. Available: to appear in https://cordis.europa.eu/project/id/101015956/results.

[35] 5GPPP, "Architecture Working Group – View on 5G Architecture", Version 4.0, August 2021. Accessed: April 6, 2023. [Online]. Available: https://5g-ppp.eu/wp-content/uploads/2021/11/Architecture-WP-V4.0-final.pdf.