Chapter 1

# Introduction

*By Ömer Bulakçı, Mikko Uusitalo, Patrik Rugeland, Marco Gramaglia, Xi Li, Mauro Boldi, Anastasius Gavras, et al.*[1]

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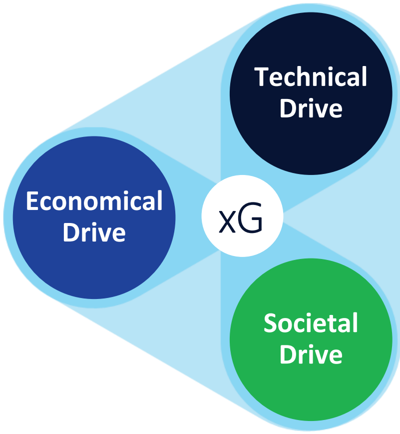
1. The full list of chapter authors is provided in the Contributing Authors section of the book.

## 1.1 Architecting the 6th Generation of Mobile and Wireless Communications System

Since early generations, mobile and wireless communications systems have played a crucial role in the establishment of essential connectivity. This has enabled easy access to information from anywhere and anytime and, thus, has fostered accelerated knowledge build-up and timely value-adding actions based on that beyond telecommunications ecosystems in all sectors of society. The COVID-19 pandemic has additionally proven the importance of the wireless communication infrastructure during these challenging times and has supported global stability as well as faster recovery via maintaining a stable technological environment and seamless societal connection despite quarantine regulations.

Considering such critical role and importance, the relevant technological advancements within and for the telecommunications ecosystem are captured by a non-backward-compatible set of features specified in a new generation of mobile and wireless communications systems. As advancing from a previous generation to the new one requires significant efforts, the need for a new generation shall be

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|---|---|
| **Technical Drive** | • Increase in the mobile data traffic<br>• Diverse Services with Broad Range of Requirements<br>• Rapid growth of wirelessly-connected Devices |
| **Societal Drive** | • Demand for Seamless Connectivity Anywhere & Anytime<br>• Demand for Affordable Access to Broadband<br>• Demand for Sustainable Access |
| **Economical Drive** | • The need for cost-efficient cellular communications<br>• The need for energy-efficient cellular communications<br>• The need for new business areas |

**Figure 1.1.** Drivers for developing new generation of mobile networks.

justified factoring in the technical, societal, and economical drives (see Figure 1.1). These drives are not mutually independent, i.e., one boost in any of the drives can accelerate the whole process. For instance, the need for attaining new business areas also implies the need for supporting a diverse set of induced requirements.

Accordingly, the development of mobile and wireless networks has followed around a 10-year cycle, where, up to the $5^{th}$ generation (5G), previous generations have been designed for particular use case categories. With 5G, an inherent flexibility has been introduced, and the target customer space has been extended from mobile broadband users towards vertical industries with diverse requirements [1]. The framework of network slicing has been introduced to cope with such different requirements. The commercial deployments of the 5G system have been underway since 2019 with an original focus on non-standalone (NSA) architecture, while more and more standalone (SA) architecture has been employed globally. The NSA deployment implies that 5G new radio (NR) is anchored with the $4^{th}$ generation (4G) system, and the 4G core network (CN) is in use. In the case of the SA deployments, where 5G NR connects to the 5G CN, the full potential of the 5G system can be unleased, e.g., by means of the utilization of the network slicing. Moreover, 5G-Advanced enhancements, e.g., extended reality (XR) optimizations, are already being specified in the $3^{rd}$ Generation Partnership Project (3GPP) Release 18 [2].

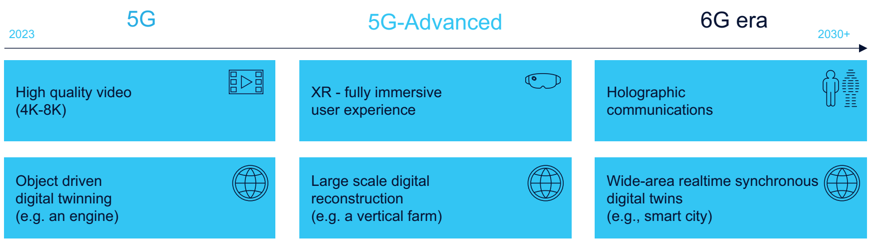


**Figure 1.2.** Example evolution of use case families from 5G towards 6G era.

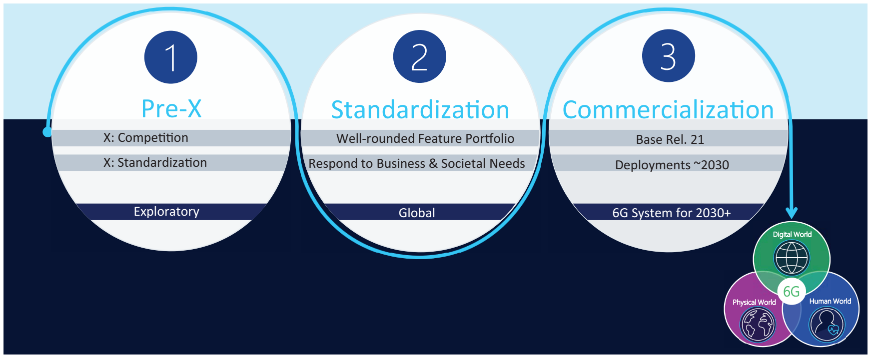


**Figure 1.3.** Three-phase approach to realize the complete value chain of 6G.

While 5G deployments and 5G-Advanced standardization are progressing well, as highlighted in Chapter 9, research into the new generation of mobile and wireless communications systems, i.e., the 6th Generation (6G), has already started. Like in the case for other generations, the creation of 6G has started with the identification as well as prediction of the use cases and the associated requirements (see Section 2.1). An illustration of the evolution of use case families is shown in Figure 1.2. As depicted, digital twinning of objects is already supported by a 5G system, and this support can be expanded via 5G-Advanced. Nevertheless, it is foreseen that a wide-area synchronous digital twinning can be possible only during the 6G era. Accordingly, it can be stated that 5G-Advanced provides the stepping stone towards 6G, where 6G will enable new use cases as well as existing use cases at scale. It is worth noting that the wireless networks are designed to be flexible to address the requirements of new use cases that may not be predicted today.

On this basis, a three-phase approach is being followed to realize the complete value chain of the 6G system, as depicted in Figure 1.3. These phases are outlined in the following.

**Pre-X Phase:** This is the exploratory research phase, where X can refer to competition or standardization. During this phase, the key stakeholders, e.g., academia, vendors, diverse industries, and mobile network operators (MNOs), come together to set the vision, design guidelines, and the foundation for the 6G system. The main motivation for such a phase is the build-up and expansion of the 6G ecosystem. This phase is essential for rapid and efficient standardization process that will follow.

**Standardization Phase:** In this phase, a well-rounded feature portfolio is specified, e.g., radio access network (RAN) and CN by 3GPP, that shall respond to the business and societal needs, as highlighted in Figure 1.1, which have been identified during the Pre-X Phase as well as the standardization phase. It is expected that, differently from 5G specification, many architecture options shall be avoided to enable the full potential of 6G already in the early deployments. Moreover, to make use of the economies of scale and the proven benefits of previous generations, a global 6G standard should be aimed for.

**Commercialization Phase:** Based on the established standardization, which is envisioned to be 3GPP Release 21, the first commercial 6G deployments can be seen around 2030. It should be noted that the 6G system will be designed at least for the full next decade (2030s) and even beyond.

With the seamless execution of all three phases, the promises of the 6G system on the integration of digital, physical, and human worlds can be realized, which can transform the world while maximizing human potential. The details on the standardization and regulatory processes are provided in Chapter 9.

## 1.2 Approach and Timing of the Book

This book is a result of the collaborative work performed at European level during the Pre-X phase of the 6G system's creation. In particular, the main content of the book has been provided by the 5G Public Private Partnership (5G PPP) Phase 3 research projects [3]. 5G PPP Phase 3 projects are categorized under different calls that pertain to specific requirements set by the European Commission (EC); see the corresponding book preface. Among the Phase 3 calls, the most relevant ones for the scope of the book have been the information and communication technologies 20 (ICT 20) and ICT 52 calls, where the former has comprised projects that work on the longer-term vision of 5G, i.e., 5G evolution [4], and the latter has comprised projects that work on the foundation of the beyond 5G/6G system [5]. As part of the ICT 52 call, the Hexa-X project is the system flagship project [6]. Yet, since various enhancements considered for the 5G system by other Phase 3 projects could be employed by 6G with its full potential, such enhancements are also captured herein.


**Figure 1.4.** White papers released by the 5G PPP Architecture WG.

Moreover, a key part of the 5G PPP framework is a set of cross-project working groups (WGs). The outcome of the work from these groups is presented in white papers [7]. As highlighted in the prefaces of this book, the Architecture WG brings the research projects together to build a consolidated view of the architectural efforts, including the overall architecture of mobile and wireless communications networks across different network domains, such as RAN, Transport, and CN, as well as cloud or edge infrastructure.

The outcome of the Architecture WG has been published in a series of white papers and presented during various technical workshops at international conferences and webinars. As shown in Figure 1.4, the latest white paper of the WG is "*The 6G Architecture Landscape – European Perspective*" [8], which is Version 6.0. The first version of the architecture white paper from the Architecture WG was back in July 2016. Since then, this effort has continuously captured the technology trends as developed by the different phases of 5G PPP projects: the first phase (Phase 1) laid the foundation of the network slicing-aware operations we are seeing these days; the second phase (Phase 2) provided the first proof of concepts; and the third phase (Phase 3) has targeted the first large-scale platforms. All these efforts were captured in the subsequent releases of the white paper (Version 2 in January 2018, Version 3 in February 2020, and Version 4 in November 2021). It is worth noting that Version 6.0 is intentionally the next version after Version 4.0 as an indication of the focus on 6G.

Capitalizing on the Version 6.0 of the white paper, this book is a joint effort by the Architecture WG and the Hexa-X project, extending significantly the concise content of the published white paper [8]. Within the framework of the Architecture WG and the joint work, the content of the book has been based on the following projects (in alphabetical order) [3]:

- **5G-COMPLETE**, which aims at revolutionizing beyond 5G architecture, by efficiently combining compute and storage resource functionality over a unified, ultra-high capacity converged digital/analogue Fiber-Wireless (FiWi) RAN.
- **5G-CLARITY**, which brings forward the design of a system beyond 5G private networks to address challenges in spectrum flexibility, delivery of critical services, and autonomic network management using heterogeneous wireless access that integrates 5G, Wi-Fi, and LiFi technologies managed through novel Artificial Intelligence (AI)-based autonomic networking.

- **5G ERA**, which aims at providing third-party application developers with an experimentation facility as a playground to test and qualify their applications.
- **5GASP**, which aims at shortening the idea-to-market process through the creation of a European testbed for Small and Medium-sized Enterprises (SMEs) that is fully automated and self-service, in order to foster rapid development and testing of new and innovative 5G network applications.
- **6G BRAINS**, which brings reinforcement learning into radio-light network for massive connections.
- **AI@EDGE**, which develops a connect-compute fabric – specifically leveraging the serverless paradigm – for creating and managing resilient, elastic, and secure end-to-end slices.
- **ARIADNE**, which proposes to exploit bandwidth-rich D-band, the capabilities of Reconfigurable Intelligent Surfaces (RIS), and powerful Machine Learning (ML) tools in order to realize a novel Communication Theory framework beyond Shannon and design suitable technology enablers for highly reliable and reconfigurable 6G connectivity.
- **DAEMON**, which develops and implements innovative and pragmatic approaches to Network Intelligence (NI) design that enable high performance, sustainability, and an extremely reliable zero-touch network system.
- **DEDICAT 6G**, which addresses techniques for achieving and maintaining efficient dynamic connectivity and intelligent placement of computation in the mobile network.
- **EVOLVED-5G**, which designs and develops an open facility for the long-term support of third-party applications that interact with the network core.
- **Hexa-X**, which is the European 6G flagship research project, defining the vision, and developing technological enablers for connecting the physical, digital, and human worlds.
- **MARSAL**, which targets the development of a complete framework for the management and orchestration of network resources in 5G and beyond, by utilizing a converged optical wireless network infrastructure in the access and fronthaul/midhaul segments.
- **MonB5G**, which targets zero-touch management and orchestration in support of network slicing at massive scales for 5G evolution and beyond.
- **REINDEER**, which develops a new smart connect-compute platform with a capacity that is scalable to quasi-infinite, and that offers perceived zero latency and interaction with an extremely high number of embedded devices.
- **RISE 6G**, which aims at investigating innovative solutions that capitalize on the latest advances in the emerging technology of RISs and offers dynamic and goal-oriented radio wave propagation control, enabling the concept of the wireless environment as a service.

- **TeraFlow**, which aims to deliver a new generation open-source cloud-native Software-Defined Networking (SDN) controller to provide smart connectivity services to beyond 5G networks.

## 1.3 Scope and Structure of the Book

This book highlights the related research work of the contributing 5G PPP Phase 3 projects and presents all the key elements and key architecture enablers and solutions of future 6G network design – a design that is deeply rooted in real needs and can profoundly benefit humanity in the mid-to-long term. Specifically, a high-level view of the 6G End-to-End (E2E) architecture as well as a functional view of the 6G reference architecture are introduced, taking into consideration 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. The key architecture enablers, which will form the backbone of future sustainable and trustworthy 6G network architecture, include all the related technological solutions for building intelligent, flexible, energy efficient, secure, programmable networks and enabling versatile radio technologies, localization, and sensing in the 6G networks.

As 5G PPP Phase 3 consists of the last calls of the Horizon 2020 programme, this book is aimed to lay the architectural foundation for the next European programme towards 6G, i.e., smart networks and services (SNS) joint undertaking (JU).

The rest of this book is structured into the following eight chapters.

**Chapter 2 – Architecture Landscape** draws the envisioned system view of the overall 6G architecture associated with a functional view. The presented architecture is built up considering the key design principles that are populated based on the envisioned use cases, requirements, and trends as highlighted in Section 2.1. The discussions on the management and orchestration (M&O) as well as security and privacy architecture complete the big picture. A brief overview of the architectural enablers is also captured, which sets the guidance for the following detailed chapters enumerated from three to eight.

**Chapter 3 – Towards Versatile Access Networks** presents the envisioned enhancements for the wireless networks, including the efficient utilization of 3GPP and non-3GPP access networks. Such enhancements include the distributed multiple-input multiple-output (D-MIMO) implementation, integrated access and backhaul (IAB) deployments, RIS, multi-access connectivity, and sub-THz access. It is argued that for the limitless connectivity requirement of 6G, D-MIMO can provide expected macro diversity, design flexibility, and interference management; IAB can offer cost-efficient densification without the need of fibre to connect the small cell sites; and RIS can provide means to fine-tune the wireless configuration environments. Multi-access multi-connectivity will remain an important feature for 6G to enhance the wireless link's throughput, reliability, or even latency. In addition, sub-THz bands can help fulfil the requirements of the high data rate applications in short distances or can offer wireless connectivity for the backhaul.

**Chapter 4 – Towards Joint Communications and Sensing** presents the incorporation of sensing capabilities into the mobile networks. These capabilities can be separated into three different categories. First, the 6G network can efficiently collect, store, and analyse sensing data from various different sensors, and provide localization, sensing, and mapping information to applications and users to enhance different 6G services. Second, the localization, sensing, and mapping information can be provided to the radio network itself to improve the communication, e.g., through location or environment-aware beamforming or pre-emptive handover if an impending obstacle is detected. Finally, the purpose of the radio interface itself is reimagined, where the radio signals are used for both communication and sensing, either simultaneously or only using common hardware, potentially providing access to a plethora of transmitters and receivers in a more densified network that can sense and map the environment in a radar-like fashion without the need for dedicated hardware deployment.

**Chapter 5 – Towards Natively Intelligent Networks** presents the recent efforts in the design of an architecture that is natively capable of incorporating all the elements required by network functions empowered by Artificial Intelligence (e.g., data gathering, representation, decision enforcement), as well as some examples of such Network Intelligence Functions and their application in different domains of the network, such as the radio access and the orchestration.

**Chapter 6 – Towards Sustainable Networks** presents targeted metrics as well as the main technological enablers towards ensuring high sustainability in next-generation networks. The chapter focuses on two main principles, "sustainable 6G," i.e., how to make the 6G networks sustainable, and "6G for sustainability," i.e., how 6G can be leveraged so as to ensure sustainability in other markets and value chains. In this context, a broad analysis of the key network sustainability enablers is provided spanning across different levels, i.e., from enablers that include architectural or hardware innovations, and enablers at management/orchestration level or at service/application level that target at network operation efficiency maximization to cross-layer sustainability enablers, which include innovations in more than two layers.

**Chapter 7 – Towards Continuously Programmable Networks** presents design principles and technology enablers towards realizing programmability frameworks, i.e., frameworks that abstract the underlay network infrastructure and capabilities so that the network is dynamically controlled and configured. Standardized solutions and research enablers for such abstraction are indicated, organized in three levels, namely, service/application provisioning level, network and resource management level, as well as network deployment and connectivity level. Indicative approaches include the deployment of common Application Programming Interface (API) managers, the exploitation of P4-programmable switches, the usage of open interfaces of Open-RAN (O-RAN), and the design of Software Development Kits (SDKs) for providing network slices as a service.

**Chapter 8 – Secure, Privacy-Preserving, and Trustworthy Networks** presents aspects related to network privacy and security for information sharing among different tenants and cloud-stored data, as well as end-users' network security. Moreover, it investigates the application of blockchain-based platforms for network slicing by using smart contracts, as well as for industrial Internet of Things networks. Finally, it focuses on trusted execution, trust-as-a-service, as well as trustworthy ML/AI.

**Chapter 9 – 6G Outlook and Timeline** presents the most recent picture about European perspectives on the current status of 6G in terms of standardization, research and regulation initiatives. This final chapter presents also concluding remarks of the book.

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