Edited by
Emmanuel Bertin • Noel Crespi • Thomas Magedanz

Shaping Future 6G Networks

Needs, Impacts, and Technologies

IEEE PRESS

WILEY

Shaping Future 6G Networks

Shaping Future 6G Networks

Needs, Impacts, and Technologies

Edited by

Emmanuel Bertin
Orange Innovation/Institut Mines-Telecom

Noel Crespi
IMT, Telecom SudParis, Institut Polytechnique de Paris

Thomas Magedanz
Technische Universität Berlin/Fraunhofer FOKUS

IEEE PRESS
WILEY

This edition first published 2022

Registered Offices
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd., The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data Applied for

ISBN: 9781119765516

Cover Design: Wiley
Cover Image: © sutadimages/Shutterstock

Set in 9.5/12.5pt STIXTwoText by Straive, Pondicherry, India

10 9 8 7 6 5 4 3 2 1

Contents

Editor Biographies

Emmanuel Bertin (PhD) is a Senior Expert at Orange Innovation, France and an Adjunct Professor at Institut Polytechnique de Paris, France. His activities are focused on 5G and 6G, NFV and service engineering, with more than 100 published researched articles. He received a Ph.D. and an Habilitation in computer science from Sorbonne University. He is a senior member of the IEEE.

Noel Crespi (PhD) holds Masters degrees from the Universities of Orsay (Paris 11) and Kent (UK), a diplome d'ingénieur from Telecom Paris, and a Ph.D and an Habilitation from Sorbonne University. From 1993 he worked at CLIP, Bouygues Telecom and then at Orange Labs in 1995. He took leading roles in the creation of new services with the successful conception and launch of Orange prepaid service, and in standardization (from rapporteurship of the IN standard to the coordination of all mobile standards activities for Orange). In 1999, he joined Nortel Networks as telephony program manager, architecting core network products for the EMEA region. He joined Institut Mines-Telecom, Telecom SudParis in 2002 and is currently Professor and Program Director at Institut Polytechnique de Paris, leading the Data Intelligence and Communication Engineering Lab. He coordinates the standardization activities for Institut Mines-Telecom at ITU-T and ETSI. He is also an adjunct professor at KAIST (South Korea), a guest researcher at the University of Goettingen (Germany) and an affiliate professor at Concordia University (Canada). He is the scientific director of ILLUMINE, a French-Korean laboratory. His current research interests are in Softwarization, Artificial Intelligence and Internet of Things.

For more details: http://noelcrespi.wp.tem-tsp.eu/

Thomas Magedanz (PhD) has been Professor at the Technische Universität Berlin, Germany, leading the chair for next generation networks (www.av.tu-berlin.de) since 2004. In addition, since 2003 he has been Director of the Business Unit Software-based Networks (NGNI) at the Fraunhofer Institute for Open Communication Systems FOKUS (https://www.fokus.fraunhofer.de/usr/magedanz) in Berlin.

For 30 years Prof. Magedanz has been a globally recognized ICT expert, working in the convergence field of telecommunications, Internet and information technologies understanding both the technology domains and the international market demands. He often acts as an independent technology consultant for international ICT companies. In the course of his applied research and development activities he created many internationally recognized prototype implementations of global telecommunications standards that provide the foundations for the efficient development of various open technology testbeds around the globe. His interest is in software-based 5G networks for different verticals, with a strong focus on public and non-public campus networks. The Fraunhofer 5G Playground (www.5G-Playground.org) represents, in this regard, the world´s most advanced Open 5G testbed which is based on the Open5GCore software toolkit (www.open5Gcore.org), representing the first reference implementation of the 3GPP 5G standalone architecture, which is currently also used by many customers for testing against different RAN equipment in different use cases. For three years, he has actively supported the buildup of emerging 5G campus networks based on the Open5GCore considering emerging campus networks as the prime spot for 5G innovation.

His current research is targeting the 5G evolution to 6G, including Core-RAN integration (including O(pen)RAN integration), Satellite/Non-terrestrial Networks and 5G/6G integration, as well as AI/ML based 5G/6G network control and management.

For more details and a longer version look here:

http://www.av.tu-berlin.de/menue/team/prof_dr_thomas_magedanz/

List of Contributors

Zwi Altman
Orange Innovation
Châtillon
France

Alexis I. Aravanis
CNRS, CentraleSupelec, L2S
University of Paris-Saclay
Gif-sur- Yvette
France

Joanna Balcerzak
Orange Innovation
Châtillon
France

Yosra Ben Slimen
Orange Innovation
Châtillon
France

Emmanuel Bertin
Orange Innovation
Caen
France

Nikolaus Binder
NVIDIA
Berlin
Germany

Holger Boche
Institute of Theoretical Information Technology
Technische Universität München
Munich
Germany

Mohamed Boucadair
Orange Innovation
Cesson-Sévigné
France

Juan A. Cabrera
Deutsche Telekom Chair of Communication Networks
Technische Universität Dresden
Dresden
Germany

Renato L.G. Cavalcante
TU Berlin/Heinrich Hertz Institute
Berlin
Germany

Marius Corici
Fraunhofer FOKUS
Berlin
Germany

Noel Crespi
IMT, Telecom SudParis
Institut Polytechnique de Paris
Paris
France

Isabelle Dabadie
Laboratoire de recherche en sciences de gestion Panthéon-Assas (LARGEPA)
Université Paris 2 Panthéon-Assas
Paris
France

Christian Deppe
Chair of Communication Engineering
Technische Universität München
Munich
Germany

Marco Di Renzo
CNRS, CentraleSupelec, L2S
University of Paris-Saclay
Gif-sur- Yvette
France

Frank H. P. Fitzek
Deutsche Telekom Chair of
Communication Networks. Technische
Universität Dresden
Dresden
Germany

Marco Giordani
Department of Information Engineering
University of Padova
Padova
Italy

Imen Grida Ben Yahia
Orange Innovation
Châtillon
France

Thomas Heyn
Head of Mobile Communications Group
Broadband and Broadcast Department
Fraunhofer IIS
Erlangen
Germany

Alexander Hofmann
Department RF SatCom Systems
Fraunhofer Institute for Integrated Circuits
Erlangen
Germany

Jinri Huang
China Mobile Research Institute
Beijing
China

Chih-Lin I
China Mobile Research Institute
Beijing
China

Christian Jacquenet
Orange Innovation
Cesson-Sévigné
France

Alexander Keller
NVIDIA
Berlin
Germany

Markus Landmann
Electronic Measurements and Signal
Processing (EMS) Department
Fraunhofer Institute for Integrated Circuits
IIS. Ilmenau
Germany

Andres Laya
Ericsson Research
Stockholm
Sweden

Thomas Magedanz
Fraunhofer FOKUS
Berlin
Germany

Marie-José Montpetit
Concordia University
Montreal
Canada

Robert Müller
Electronic Measurements and Signal
Processing (EMS) Department
Fraunhofer Institute for Integrated Circuits
IIS. Ilmenau
Germany

Akihiro Nakao
The University of Tokyo
Tokyo
Japan

Zhisheng Niu
Tsinghua University
Beijing
China

Michele Polese
Institute for the Wireless Internet of Things
Northeastern University
Boston
MA
USA

Sahana Raghunandan
Department RF SatCom Systems
Fraunhofer Institute for Integrated Circuits
Erlangen
Germany

Leszek Raschkowski
Wireless Communications and Networks Department
Fraunhofer Heinrich Hertz Institute HHI
Berlin
Germany

Guy Redmill
Redmill Communications Ltd
London
UK

Rafael F. Schaefer
Chair of Communications Engineering and Security
University of Siegen
Siegen
Germany

Christian Scheunert
Chair of Communication Theory
Technische Universität Dresden
Dresden
Germany

Henning Schulzrinne
Columbia Univeristy
New York
USA

Sławomir Stańczak
TU Berlin/Heinrich Hertz Institute
Berlin
Germany

Peter Stuckmann
European Commision
Brussels
Belgium

Soma Velayutham
NVIDIA
Santa Clara
CA
USA

Marc Vautier
Orange Innovation
Cesson-Sévigné
France

David Zhe Lou
Huawei Technologies Düsseldorf GmbH
Munich
Germany

Sheng Zhou
Tsinghua University
Beijing
China

Michele Zorzi
Department of Information Engineering,
University of Padova
Padova
Italy

Forewords

Henning Schulzrinne, Columbia University, USA

The first few iterations of cellular networks, 1G through 3G, were largely telephone networks with mobility added on, including the choice of addressing through telephone numbers, signaling through SS7, and emphasis on interoperable voice services. 4G and 5G started the transition to an Internet-driven architecture, with remnants of the old architecture still clearly visible. But beyond the protocol choices, all existing generations were largely driven by the assumption that networks are operated by a relatively small number of carriers, typically with at least a nationwide service footprint, reliant on licensed spectrum and an assumption of mutual trust. 5G has started to focus more attention on using the same radio technology for both industrial and consumer networks, but the large-carrier mindset still pervades the design, with a tightly-coupled set of protocols and entities. This tightly-coupled model provides some advantages; it bundles a consistent set of features and technologies designed and packaged to work together, relying on a strict user management and authentication framework. However, this model comes also with drawbacks, such as the lack of flexibility to adapt to new technologies or use-cases, and having to rely on three or at most four carriers in most countries.

Since 3G, branding mobile network generations have had both a technical and a consumer marketing role. The generations provided checkpoints for equipment vendors, and made advances in technology that's otherwise largely invisible to consumers relevant and marketable. 5G is probably the first iteration where a transition in technology standards became a matter of national pride and an indicator of national or regional competitiveness, with promises of increases in consumer and societal welfare that may be hard to deliver. However, as the digital divide during COVID-19 illustrated, universal access to affordable broadband, typically at home, mattered more than higher 5G speeds in the downtown business districts and digital transformation is not assured by having nationwide 5G. Thus, technologists and policy makers working on post-5G efforts should be careful in calibrating expectations, given that wireless network technology may not be the most significant hurdle that prevent addressing key societal challenges.

It seems likely that we will see a much larger variety of operational scenarios in the next decade, from traditional vertical-integrated carriers to disaggregated carriers and to private or federated enterprise networks. Any future network architecture needs to be sufficiently modular so that it can scale down to unmanaged home networks and scale up to networks where participants have limited trust in each other. This suggests a much more flexible and much simpler authentication and roaming model than we have had in previous network generations. Here, 6G can probably learn from another wireless technology where “generations” have played less of a role – ubiquitous Wi-Fi.

Developments for IoT during the 5G standardization and deployment phase may also hold lessons that encourage predictive modesty for 6G. Rather than being the universal network that connects billions and billions of IoT devices to create “smart” buildings and cities, cheap home Wi-Fi and new low-cost technologies like LoRa, leveraging unlicensed spectrum, have come to dominate, with carrier IoT offerings falling short of expectations – indeed, retaining boring and obsolete 2G often seems to draw more interest than new 5G ultralow latency capabilities.

Previous generations of cellular networks offered their per-user speed as the headline advantage, but 5G is already showing the limitations of that approach, as few mobile applications are likely to be built that will rely on 1 Gb/s or above speeds. Thus, the key metrics will not be per-user throughput or latency, but cost per base station month, governing deployment cost in low-density areas, and cost per bit delivered, i.e., primarily operational costs. Environmental metrics such as energy consumption or electromagnetic fields (EMF) must also be considered. For many years, capital equipment has only accounted for about 15% of revenues of most carriers, i.e., the vast majority of expenses are operational. This argues for a simple, self-managed, and robust network, with as many commodity components and protocols as possible and as much re-use of available fiber access networks as possible, rather than infinite configurability or elaborate QoS mechanisms. The largest opportunities for improved operational efficiency and reduced complexity are in the control plane, not the data plane, relying for that on machine learning and automation technologies as detailed in this book. However, since 6G will serve as infrastructure, with concomitant reliability expectations, robustness, predictability and explainability of any use of machine learning will be more important than squeezing out the last percentage points of efficiency.

Despite all the changes in technology, the common thread across mobile technology generations has been a dramatic reduction in the consumer unit cost of mobile data, with new applications enabled simply because they became affordable. Thus, 6G will likely only offer a significant value proposition beyond a marketing tag line if it is engineered to minimize operational complexity, maximizes operational automation and ensures high availability. The Wi-Fi experience can offer lessons and might even offer an opportunity for convergence, where 6G radio access is just another PHY, with a common upper-layer stack optimized for a heterogeneous service provider environment that allows a wide variety of industry, academic and government users to rapidly and cheaply create new applications and an even wider variety of entities to offer access to network services. Deciding what to omit from 6G and leave it to other parts of the networking eco system will be as important as deciding what to include.

Research, particularly academic research, should be driven by the urgent needs of society, not just supplying patent-protected “moats” against competition, whether between companies or nations. 6G offers a unique opportunity to the research community to identify the best engineering approaches that enable universal, affordable, secure and reliable networks. This book provides an initial and valuable exploration of these questions.

Henning Schulzrinne
Columbia University, USA

Peter Stuckmann, Head of Unit, Future Connectivity Systems, European Commission

Recent years and in particular the COVID-19 crisis have shown us the importance of resilient and high-speed communications infrastructure. Trust and acceptance in connectivity infrastructure has grown as global societies have discovered its added value and the possibilities for remote working, but also for citizens' daily lives. Business has understood the critical importance of high-speed networks and technologies in maintaining operations and processes. The crisis illustrates both the potential that 5G networks have to provide the connectivity basis for the digital and green recovery in the short to mid-term, and the need to build technology capacities for the following generation – 6G – in the long term.

5G technology and standards will evolve in the next few years in several phases, just as deployment advances. Operators worldwide have launched commercial 5G networks in major cities. This early deployment will build on 4G networks and will aim primarily at enhancing mobile broadband services for consumers and businesses. Huge investments need to be unlocked for the more comprehensive deployment covering all urban areas and major transport paths by 2025. 5G technology is expected to evolve towards new 'standalone' 5G core networks enabling industrial applications such as Connected and Automated Mobility (CAM) and industry 4.0. These will be a first step towards digitising and greening our entire economy. The growth potential in economic activity enabled by 5G and later 6G networks and services has been estimated to be in the order of €3 trillion by 2030[1]. For such critical services, we need to ensure that 5G networks will be sufficiently secure.

R&I initiatives on 6G technologies are now starting in leading regions world-wide, with the first products and infrastructures expected for the end of this decade. 6G systems are expected to offer a new step change in performance from Gigabit towards Terabit capacities and sub-millisecond response times, to enable new critical applications such as real-time automation or extended reality ("Internet of Senses") collecting and providing the sensor data for nothing less than a digital twin of the physical world.

Moreover, new smart network technologies and architectures will be needed to enhance drastically the energy efficiency of connectivity platforms despite major traffic growth and keep electromagnetic fields (EMF) under safety limits. They will form the technology base for a human-centric Next-Generation Internet (NGI) and address Sustainable Development Goals (SDGs) such as accessibility and affordability of technology.

All parts of the world are starting to be heavily engaged in 6G developments. There will be opportunities and challenges concerning new business models and players through software networks with architectures such as Open-RAN[2] and the convergence with new technologies in the area of cloud and edge computing, AI, as well as components and devices beyond smartphones.

Firstly, success in 6G will depend on the extent regions will succeed in building a solid 5G infrastructure, on which 6G technology experiments and, later, 6G deployments can build. In this context, building 5G ecosystems will be of key importance, also because industry R&I investments tend to relocate where markets are more advanced.

---

1 McKinsey Global Institute, 2/2020, Connected World – An evolution in connectivity beyond the 5G revolution

2 More open and interoperable interfaces in Radio Access Networks (RAN)

Secondly, 6G will require taking a broader value chain approach, ranging from connectivity to components and devices beyond smartphones with the massive development of the Internet of Things (IoT) and connected objects like cars or robots. They also exist on the service side, with edge computing integrated in connectivity platforms and cloud computing enabling advanced service provisioning, e.g. for big data and AI.

One important success factor to create and seize such opportunities is to be a standard setter in 6G and the related technology fields. Both future users and suppliers need to shape key technology standards in the field of radio communications, but also in next-generation network architecture to ensure the delivery of advanced service features, e.g. through the effective use of software technologies and open interfaces, while meeting energy-efficiency requirements.

Spectrum resources are another key factor that will determine success in 6G. Whereas bands currently allocated for mobile communications will be reused for 6G, new frequency bands will be identified and harmonised. Industry and governments need to identify the opportunities related to spectrum that can be suitable for 6G and be made available with the potential to be harmonised at global level. 6G technology will also have the potential to make a further step towards a multi-purpose service platform replacing legacy radio services for dedicated applications. This could help the progress in defragmenting the radio spectrum and drastically enhance spectrum efficiency that will in turn free up new bands for 6G or other purposes.

Such outcomes in global standardisation and spectrum harmonisation need to be prepared by proactive and effective international cooperation at government and industry-level. This includes regular dialogues with leading regions and possible focused joint initiatives in R&I, standardisation or regulation.

I am looking forward to the creativity and ambition of the global research and innovation community to shape the new generation of communication technology throughout this decade.

Let's kick this off!

Peter Stuckmann
Head of Unit, Future Connectivity Systems, European Commission

Akihiro Nakao, The University of Tokyo, Japan

Mobile network systems have evolved from communication infrastructures to critical and indispensable social infrastructures over the generations. The 5th generation mobile network system (5G) has been getting deployed commercially since 2019 and is bringing new innovations, both in terms of technology and business models. New models of 5G private network deployments are indeed emerging, and the connectivity landscape appears to be more and more split between various players and domains. Beyond 5G networks are expected to be deployed around 2025 onward, and studies on standardization of 6G have already begun.

6G networks and services are expected to play a central role as the backbone of our future societies by tightly integrating virtual and physical spaces. Japanese governmental agencies have forged the term Society 5.0 to designate this future society that Japan should aspire to be. Following the hunting society (Society 1.0), agricultural society (Society 2.0), industrial society (Society 3.0), and information society (Society 4.0), Society 5.0 should achieve a high degree of convergence between cyberspace (virtual space) and physical space (real space). In this future Society 5.0, huge amounts of information from sensors in physical space are accumulated in cyberspace and analyzed by artificial intelligence (AI) to provide intuitive and near-real-time feedback to humans in physical space. This vision first drawn by science fiction authors in the early 1980s is about to become a reality. “Cyberspace. . . Data abstracted from the banks of every computer in the human system. Unthinkable complexity.” wrote William Gibson (who coined the term of cyberspace) in his 1984 novel *Neuromancer*.

The recent COVID-19 misfortune might appear as a new step toward this Society 5.0, as we have re-recognized the need for enhancing and upgrading information communication infrastructure to ensure the continuity of our social activities, as well as the growing blurring between virtual and real relationships. On this road, it is essential not only to promote research and development of technology but also to consider the global environmental impacts (such as carbon neutral and green recovery), the social inclusiveness so that no one will be left behind, and the ethics and social acceptability of these forthcoming technologies.

This wish for a future better and enhanced society shall be and remain the underlying foundation for designing future 6G networks. It should bond all the stakeholders engaged in research and development of next-generation cyber infrastructure, 6G mobile network systems, to globally unite forces to define new requirements, use cases, and fundamental theories and technologies that must be realized for the next decade. These researches are also a way to progress for accomplishing the 2030 Agenda for Sustainable Development adopted by the United Nations in 2015, where one of the sustainable development goals is about building resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.

Although it is just the very beginning of our journey for developing 6G mobile networking, we can assume that the next-generation cyber infrastructure will bring us communications features very close to human capability, such as ultralow latency, ultra-high capacity, ultra-large number of connected devices, ultralow power communication, stringent security and privacy, autonomy enabled by machine learning and AI, and ultra-coverage and extensibility including non-terrestrial networks, underwater communication, etc.

This journey will not only be driven by the telecom industry. Many countries have allocated frequency white space to private 5G usage and made open to non-telecommunication companies so that they can operate their own customized 5G networks. We believe that this "democratization" (i.e. making something accessible to anyone) of 5G networks will open a door to new innovations coming from the civil society as well as from industrial players. 6G will thus be the opportunity to conciliate various types of innovations: grassroots innovations coming from local players with new use cases and ad hoc solutions, radio and core layer innovations coming from Telco players, and also real-time software innovations coming from Internet player. Besides the regular migration path from 5G to 6G promoted by telecommunication operators and vendors, there is another evolution avenue possible, from private 5G to private 6G and then to public 6G because a lot more stakeholders may participate in the game of developing custom solutions tailored for their real use cases that may be eventually distilled and adopted as viable 6G technologies to be standardized.

Along with the editors, I hope that this book serves as a navigating compass in our endeavor for developing 6G infrastructure for the next decade, by providing the insights from internationally known distinguished experts.

Akihiro Nakao
The University of Tokyo, Japan

r

s