Towards Sustainable and Trustworthy 6G

Challenges, Enablers, and Architectural Design

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Dedications

To my parents, siblings, niblings, my wife Anna, and our kids Yunus and Ela for their continuous love and support, and to the victims of Türkiye-Syria earthquakes.

Ömer Bulakçı

To my lovely daughter Lina, my family, and friends for their love and support, and to my team from the 6G networks group, who provided great contributions to this book, and to all the people who are striving their effort and dedications in research to make our dreams into reality.

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Mikko Uusitalo

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Patrik Rugeland

To my family, and to the memory of all those killed and involved in wars.

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Since the start of the 5th generation public–private partnership (5G PPP) projects in mid-2015, there have been three major phases contributing to the design and further development of the 5G system. In the same period, 5G has moved from vision to actual deployments, and the further evolution of 5G, known as 5G Advanced, is already being specified. As 5G has become a commercial reality, attention in research and development has been shifting towards the 6th generation (6G).

This book is based on the outcome of Phase 3 projects within the 5G PPP framework primarily coming from the Architecture Working Group and the flagship Hexa-X project, and complemented by contributions from various additional experts. We would like to thank all the contributors for the substantial effort and engagement invested into this book. In particular, we would like to thank the main chapter editors for consolidating the diverse contents originated from different projects into a coherent structure and story, namely, Mårten Ericson and Dr. Bahare Masood Khorsandi for Chapter 2, Dr. Mir Ghoraishi for Chapter 3, Dr. John Cosmas for Chapter 4, Dr. Marco Gramaglia, Dr. Xi Li, and Dr. Gines Garcia-Aviles for Chapter 5, Dr. Agapi Mesodiakaki and Dr. Md Arifur Rahman for Chapter 6, Dr. Dimitris Tsolkas for Chapter 7, Dr. Alexandros Kostopoulos for Chapter 8, and Mauro Boldi, Dr. Mikko Uusitalo, and Dr. Patrik Rugeland for Chapter 9. Considering that many contributors have also used their free time to finalize the book in parallel to technology development and project work, we would also like to thank the families of the contributors for their continuous patience and support.

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Ömer Bulakçı, Xi Li, Marco Gramaglia, Anastasius Gavras,
Mikko Uusitalo, Patrik Rugeland, and Mauro Boldi
On behalf of the book contributors

Foreword by 6G Infrastructure Association

This book represents an important step towards future 6th generation (6G) networks. Created by the 5th generation public–private partnership (5G PPP) Architecture Working Group (WG) together with the European 6G flagship project Hexa-X, it contains the latest results from the European Research Community, compiling the outcomes from many projects into a coherent book that provides the reader with essential information about the main trends for the development of the new generation of 6G networks.

Modern telecommunication networks play a critical role in all aspects of everyday life. During the 2010s, the world witnessed a dramatic improvement in telecommunication services with the arrival of 4th generation (4G) networks. Since the early 2010s, scientists and organizations worldwide have laboured to design and deploy 5G networks. In addition to enhanced mobile broadband, the target was to provide an advanced set of new services that would lay the foundations for the digital transformation of various vertical markets (e.g., smart industry, energy, automotive, transportation and logistics, health, media, gaming, etc.). The 5G story is still near its beginning, and it will remain the key mobile network technology for many years to come. However, due to the complexity and long lead time, research on 6G has already started.

The book you hold (or digitally explore) contains the latest results from the European Research Community on 6G networks. This work includes the research outcomes for beyond 5G and 6G architectural design from a significant number of research projects in the context of European Union (EU) activities. The first group of projects has been working for the long-term vision of 6G networks and the realization of pervasive mobile virtual services. The second group has been building the foundation of beyond 5G/6G networks. Among this group of projects,

the Hexa-X project has acted as the European flagship, leading the European 6G research activities.

The editorial team has successfully compiled the outcome from all these projects into a coherent book that provides the reader with essential information about 6G networks. The editors and authors have carefully selected all the technical areas where 6G networks will be different compared to previous generations and presented them in a comprehensive way. More specifically, the book analyses the key strategic goals and requirements to develop 6G networks and discusses what effect these will have on the overall architecture. Notably, the role of sustainability in 6G networks is elevated in a dedicated chapter. Key topics like the further evolution of the access network, the expected importance of accurate positioning solutions, the native support of Artificial Intelligence/Machine Learning (AI/ML) in the network, and the expansion of programmability in telecommunication functions are presented in detail. Moreover, as security and privacy are expected to play a fundamental role in 6G networks, the book authors explain how this can be achieved while also focusing on important aspects like the trustworthiness of these solutions.

Each chapter provides information on current solutions and future research trends. Overall, I expect that this book, written by several top professionals of the European information and communications technology (ICT) sector, will be a reference point for the future research activities on 6G networks and thus extremely useful for professionals and academics.

Dr. Colin Willcock, Chairman of the Board,
6G Infrastructure Association

Foreword by European Commission

Recent years have shown us the importance of resilient and high-speed communications infrastructure. Trust and acceptance in connectivity infrastructure have grown, as global societies have discovered their benefits. Indeed, it offers possibilities not only for remote working but also for citizens' daily lives. Also, businesses have understood the critical importance of high-speed networks and technologies in maintaining operations and processes.

These developments illustrate both the potential that 5th Generation (5G) networks have to provide in terms of 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 – 6th Generation (6G) – in the long term.

5G technology and standards will evolve in several phases over the next few years as deployment advances. Operators worldwide have launched commercial 5G networks with a focus on cities. This early deployment builds on 4th Generation (4G) networks and primarily aims to enhance mobile broadband services for consumers and businesses. Huge investments need to be unlocked for a more comprehensive deployment covering all urban areas and major transport paths by 2025.

5G networks have already started employing "standalone" 5G core networks, enabling gigabit speeds and 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 (McKinsey Global Institute, 2/2020). For such critical services, we need to ensure that 5G networks will be sufficiently secure.

Research & Innovation (R&I) initiatives focusing on 6G technologies have been kicked off in leading regions worldwide. The first products and infrastructure are

expected at the end of this decade. 6G systems will offer a new step change in performance, moving us from gigabit towards terabit capacities and sub-millisecond response times. This will enable new critical applications, such as real-time automation or extended reality ("Internet of Senses"), by 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 drastically enhance the energy efficiency of connectivity platforms despite major traffic growth, and keep electromagnetic fields under safe limits. They will form the technology base for a human-centric next-generation internet, and they will address sustainable development goals, 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, for more open and interoperable interfaces in radio access networks (RAN). This is part of the convergence with new technologies in the areas of cloud and edge computing, Artificial Intelligence (AI), and components and devices beyond smartphones.

Success in 6G will first depend on the extent to which regions succeed in building a solid 5G infrastructure, on which 6G technology experiments and, later, 6G deployments can be built. In this context, building 5G ecosystems will be of key importance. Furthermore, we must bear in mind that industry R&I investments tend to relocate to where markets are more advanced.

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

One important success factor in creating and seizing such opportunities is that Europe is a standard-setter in 6G and 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. This will ensure the delivery of advanced service features while meeting energy-efficiency requirements, for example, through the effective use of software technologies and open interfaces.

Spectrum resources are another key factor that will determine success in 6G. Bands currently allocated for mobile communications will be reused for 6G; new frequency bands will be identified and harmonized. 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 harmonized at a global level.

6G technology has the potential to take a further step towards a multi-purpose service platform replacing legacy radio services for dedicated applications. This

could help 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 standardization and spectrum harmonization need to be prepared by proactive and effective international cooperation at government and industry levels. This includes regular dialogues with leading regions and possible focused joint initiatives in R&I, standardization, or regulation.

The issues at stake call for a strategic R&I roadmap to be set out and followed by a critical mass of European actors. So, we have created the Smart Networks and Services Joint Undertaking (SNS JU) to implement research activities on 6G technology under Horizon Europe. Commission funding of €900 million is to be matched by the same amount through co-funding by the industry.

Other world regions are moving; there is no time to waste. In Europe, a first set of 6G projects[1] was launched in 2021, and we recently scaled up the 6G research portfolio[2] to activities worth around €300 million in total.

The Hexa-X project is part of this portfolio and a good illustration of its potential. The flagship is developing the first 6G system concept, imagining the technology of the future with near-instant and unrestricted wireless connectivity to enable embedding ourselves in entirely virtual or digital worlds. One possible vision is an x-enabler fabric of empowered connected intelligence, networks of networks, and sustainability aspects to address the major challenges of our society, with trustworthiness ingrained as a fundamental design principle.

Furthermore, the 5G public–private partnership (5G PPP) Initiative has established working groups (WGs) that provide collaboration platforms for the European projects to attain a joint view on the key technology areas. In this regard, the overall goal of the Architecture WG is to consolidate the main technology enablers and leading-edge design trends in the context of the architecture. As a result, it provides a consolidated view of the architectural efforts developed in the European projects and other research efforts, including standardization. This effort serves not only to review the current state of the art, but also to identify promising trends towards the next generation of mobile and wireless communication networks, namely, 6G. For instance, since October 2020, 45 Phase III 5G PPP projects have contributed to the evolving architecture discussions over the various editions of the white paper[3] prepared by the WG.

1. https://smart-networks.europa.eu/5g-innovations-and-beyond-5g-calls/
2. https://smart-networks.europa.eu/europe-scales-up-6g-research-investments-and-selects-35-new-projects-worth-e250-million/
3. https://5g-ppp.eu/white-papers/

This current book, as a joint effort between the Hexa-X project and the Architecture WG, is the culmination of the European architecture work as a whole. It highlights the latest requirements on the future architecture along with the architectural design principles to respond to technical, economical, and societal needs. Moreover, it elevates the perspective from the long-term evolution of the 5G technologies towards the introduction of the 6G system. It thus provides a reference point for future 6G architecture work to continue in the SNS JU.

We count on the Hexa-X flagship as well as collaborative facilities under the 5G PPP and SNS JU, such as the Architecture WG, to continue creating the critical mass in Europe towards this vision.

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.

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

Glossary

Symbols

3G - *3rd generation mobile network*. 42

3GPP - *3rd Generation Partnership Project*. 2, 4, 7, 29, 40, 41, 51, 58, 64, 67, 79, 80, 83, 84, 121, 123, 160, 170–172, 180, 224, 273, 277, 278, 280, 287, 291, 299, 301–304, 306, 307, 363, 364

4D - *4 dimensional*. 27

4G - *4th Generation mobile network*. 2, 24, 42, 283, 288

5G - *5th Generation mobile network*. 2–7, 11, 13–15, 17–20, 24, 33, 40–43, 45, 51, 64, 65, 78–83, 92, 110, 121, 123, 125–127, 129, 131, 147, 148, 163, 167, 171, 189, 192, 200, 204, 218, 219, 224, 239, 242, 276–278, 280–283, 286–289, 291–294, 303, 307, 308, 315, 316, 318–320, 325, 328, 335, 362–366

5G PPP - *5th Generation Public Private Partnership*. 4, 5, 7

5G-NR - *5G-New Radio*. 254

6D - *6 dimensional*. 21

6G - *6th Generation mobile network*. 3–9, 11–13, 15, 16, 18–25, 27, 29–36, 40–44, 46, 51, 55, 64, 69, 79, 80, 86, 100, 106, 109, 110, 121–124, 140, 142, 143, 147, 148, 155, 160–162, 169–171, 177, 178, 186–192, 194–198, 200, 214, 215, 218, 219, 224, 228, 235–240, 242, 254, 261, 264, 267, 274–278, 286–289, 292–294, 299, 320, 325–327, 332, 333, 335, 338, 341, 347–351, 353, 360–366, 368

6G IA - *6G Industry Association*. 368

6gNB - *6th Generation NodeB*. 124–126

A

ACLR - *Adjacent Channel Leakage Ratio*. 206

ACT - *Actuator*. 178

ACT-S - *Actuating Functions Sublayer*. 181

ADC - *Analogue to Digital Converter*. 51, 91, 93, 94, 96, 100, 101

AE - *Analytics Engines*. 178, 191, 216–218, 224, 225, 227

AE-S - *Analytic Engines Sublayer*. 181

AF - *Application Functions*. 163

AGC - *Automatic Gain Control*. 91, 93, 96

AGV - *Automated guided vehicle*. 122, 123, 151, 264, 265, 337

AI - *Artificial Intelligence*. 5, 9, 15–18, 20, 22, 25, 27, 33, 35, 41, 123, 125, 126, 161–165, 169, 170, 173, 177, 178, 187, 189, 191, 199, 201, 202, 204, 207, 208, 215–217, 219, 224, 228, 248, 267, 275, 315, 318, 326, 338, 351–353, 364

AIaaS - *AI as a Service*. 35, 164

AMF - *Access and Mobility Function*. 283

ANN - *Artificial Neural Networks*. 201

AoA - *Angle of Arrival*. 103, 121–125, 136–138, 140, 141, 149, 211

AP - *Access Point*. 40, 41, 43–53, 57–60, 63, 64, 66, 67, 74, 75, 124, 125, 137, 213

APD - *Avalanche photodiode*. 130

API - *Application Programming Interface*. 9, 23, 32, 122, 130, 164, 174–176, 180, 273–276, 279, 280, 286, 287, 289, 299–308, 310, 318–320, 341

APU - *Antenna Processing Unit*. 47, 48, 55

AR - *Augmented Reality*. 17, 18, 122, 123

AR/VR - *Augmented Reality/Virtual Reality*. 86, 219

ARP - *Adress Resolution Protocol*. 85

ASLT - *Asynchronous Sampling Localisation Technique*. 141

AT3S - *ATSSS*. 79, 80, 84

ATSSS - *Access Traffic Steering Switching and Splitting*. 79

AWGN - *Additive White Gaussian Noise*. 88, 101

B

B5G - *Beyond 5G*. 170, 177, 186–188, 239, 292, 325, 341

BER - *Bit Error Rate / Bit Error Ratio*. 88, 95, 132, 133, 206, 207

BIOS - *Basic Input/Output System*. 342

BLER - *Block Error Rate*. 201

BRF - *Bayesian Recursive Filtering*. 136, 139

BS - *Base Station*. 42, 43, 45, 48, 61–64, 66, 67, 70, 72, 74–76, 78, 83, 87, 93, 125, 133, 146, 147, 149–152, 202, 210, 211, 219–222, 256, 257

BSS - *Business Support System*. 180, 184, 224, 315

BW - *Bandwidth*. 106

C

C&C - *Command and Control*. 331

CAD - *Computer Aided Design*. 125, 144

CAPEX - *Capital Expenditure*. 237, 254

CDF - *Complementary Distribution Function*. 58, 106

CDN - *Content Delivery Network*. 332

CED - *Cumulative Energy Demand*. 243

CF - *Cell Free*. 43, 51–53, 196

ChE - *Channel Estimation*. 207

CI/CD - *Continuous Integration and continuous Delivery/Continuous Deployment*. 32, 33, 186, 309

CIR - *Channel Impulse Response*. 125, 136–138, 145

CKM - *Channel Knowledge Map*. 146, 147

CMOS - *Complementary Metal-Oxide-Semiconductor*. 97

cMTC - *critical Machine Type Communication*. 17

CN - *Core Network*. 2, 4, 5, 14, 15, 23, 25, 35, 63, 64, 78, 81, 110, 277

CNF - *Cloud-native Network Function*. 35, 180, 182, 241, 242, 279

CNN - *Convolutional Neural Network*. 205, 206, 225, 226

CoCoCoCo - *Connect-Compute-Control Co-design*. 261

CoT - *Chain of Trust*. 345

CP - *Control Plane*. 29

CPE - *Customer Premises Equipment*. 81

CPM - *Constant Phase Modulation*. 101

CPU - *Central Processing Unit*. 43–45, 47, 48, 50–52, 56, 180, 192, 194, 216, 217, 256–260, 296, 344, 346

CQI - *Channel Quality Indicator*. 199, 216

CSI - *Channel State Information*. 40, 46, 51, 71, 132, 147, 212, 244, 245, 348

CSMF - *Consumer Service Management Function*. 35, 180

CSP - *Cloud Service Provider*. 244, 274, 288, 346, 361

CU - *Centralised Unit*. 45, 51, 63, 64, 216, 217

CZF - *Centralized Zero-Forcing*. 57, 58

D

D-DRL - *Decentralized Deep Reinforcement Learning*. 191

D-MIMO - *Distributed Multiple-Input Multiple-Output*. 7, 24, 41–43, 45–53, 55, 56, 63, 67, 69, 109

D2D - *Device-to-device*. 70, 86

DA - *Decision Agents*. 218, 220, 221

DAC - *Digital to Analogue Converter*. 51, 61, 62, 91, 93, 96, 200

DDoS - *Distributed Denial of Service*. 185, 330

DDQN - *Double Deep Q-Learning*. 222

DE - *Decision Engines*. 178, 191, 218, 224, 227

DE-S - *Decision Engines Sublayer*. 181

DePF - *DNN-assisted Particle Filter*. 137

DFP - *Dynamic Function Placement*. 164–166, 168

DLIRL - *Deep Learning Integrated Reinforcement Learning*. 126

DMO - *Domain Management Orchestrator*. 180, 181

DMRS - *Demodulation Reference Signal*. 40, 204

DNN - *Deep Neural Network*. 125, 126, 137, 138, 172, 196, 212–214, 222, 226, 227, 288

DNS - *Domain Name System*. 242, 331

DoA - *Direction of Arrival*. 125

DoD - *Direction of Departure*. 125

DPD - *Digital Pre-Distortion*. 200, 202

DRAM - *Dynamic Random Access Memory*. 345

DRL - *Deep Reinforcement Learning*. 191, 199, 218, 221, 222

DRL-NN - *Deep Reinforcement Learning-Neural Network*. 125

DRX - *Discontinuous Reception*. 247

DS-OMP - *Double-structured Orthogonal Matching Pursuit*. 210

DSF - *Domain Shared Functions*. 180, 181

DSP - *Digital Signal Processing*. 47, 94, 100

DT - *Digital Twin*. 16, 17

DTX - *Discontinuous Transmission*. 247

DU - *Distributed Unit*. 45, 51, 55, 63, 64, 173, 216

DZF - *Distributed Zero Forcing*. 57

E

E2E - *End-to-End*. 7, 11, 17, 20–22, 27, 32, 33, 35, 147, 161, 170, 180, 181, 186–189, 191, 205, 206, 216–218, 224, 238, 240, 245, 246, 253, 254, 256–261, 285, 286, 292, 293, 349, 368

EC - *European Commission*. 4, 310

ECDF - *Empirical Cumulative Density Function*. 217

EDR - *Endpoint Detection and Response*. 330

EIRP - *Equivalent Isotropic Radiation Power*. 49, 90

ELPC - *Extremely Low-Power Communications*. 18, 251, 252

EM - *Electromagnetic*. 70

eMBB - *Enhanced Mobile Broadband*. 17, 81, 131, 172, 294

EMC - *Electromagnetic Compatibility*. 361

EMF - *Electric and Magnetic Field*. 14, 246, 247, 258–261, 365

eMMC - *Embedded MultiMediaCard*. 341

ENI - *Enhanced Network Management Interface*. 178, 215

ESPRIT - *Estimation of Signal Parameters via Rational Invariance Techniques*. 138

ETSI - *European Telecommunications Standards Institute*. 170, 171, 175, 176, 178, 219, 224, 237, 239–242, 279, 280, 286, 289, 291, 318, 352, 363

EU - *European Union*. 360, 361, 365, 366

eURLLC - *extremely Ultra-Reliable and Low-Latency Communications*. 18, 251, 252

EVM - *Error Vector Magnitude*. 99, 202

F

F-DRL - *Federated Deep Reinforcement Learning*. 191

FaaS - *Function-as-a-Service*. 188

FDD - *Frequency Division Duplex*. 43

FeMBB - *Further enhanced Mobile BroadBand*. 18, 251, 252

FER - *Frame Error Rate*. 95

FHPPP - *Finite Homogeneous Poisson Point Process*. 65

FL - *Federated Learning*. 162, 215–218, 220–222

FlexRIC - *Flexible RAN Intelligent Controller*. 293

FMCW - *Frequency Modulated Continuous Wave*. 122

FoM - *Figure Of Merit*. 94

FW - *Firmware*. 30

G

GA - *Genetic Algorithm*. 68

GaAS - *Gallium-Arsenide*. 97

GCN - *Graph Convolutional Networks*. 226

GDF - *Gaussian density functions*. 138, 139

GDP - *Gross Domestic Product*. 13

GDPR - *General Data Protection Regulation*. 332

GeSI - *Global Enabling Sustainability Initiative*. 236

GHG - *Green House Gases*. 237

GHz - *Gigahertz*. 108

gNB - *gNodeB (5G base station)*. 45, 83, 124–126, 254, 258, 274

GPS - *Global Positioning System*. 148, 152, 154, 155

gRPC - *Google Remote Procedure Call*. 185

GTP - *Geometrical Theory of Propagation*. 125

H

HERO - *Heuristic for Energy-efficient VNF placement, traffic Routing and user assOciation*. 254–257

HetNet - *Heterogeneous Network*. 24, 42, 79

HPBW - *Half Power Bandwidth*. 106, 145

HW - *Hardware*. 30

I

I/O - *Input/Output*. 341, 344

IAB - *Integrated Access and Backhaul*. 7, 41, 42, 62–69, 109

IADZF - *Interference Aware Distributed Zero-Forcing*. 57, 58

IBN - *Intent-Based Network*. 275, 312, 313, 315, 316

ICNIRP - *International Commission on Non-Ionizing Radiation Protection*. 14, 365

ICT - *Information and Communications Technology*. 4, 13, 236, 237, 243, 362, 363, 366

ICT 20 - *Information and Communication Technologies 20*. 4

ID - *Identifier*. 141

IDM - *Infrastructure Domain Manager*. 181

IDMO - *Inter-Domain Manager and Orchestrator*. 180, 181

IDSM - *Inter-Domain Slice Manager*. 180

IEC - *International Electrotechnical Commission*. 352, 361

IF - *Intermediate Frequency*. 98

IFFT - *Inverse Fast Fourier Transform*. 205

IL - *Insertion Loss*. 93

IMT - *International Mobile Telecommunications*. 67, 362

InP - *Indium-Phosphide*. 97, 332

IOMF - *Infrastructure Orchestrated Management Functions*. 181

IoT - *Internet of things*. 15, 70, 110, 123, 192, 219, 242, 243, 307, 326, 335, 336, 338, 349

IP - *Internet Protocol*. 80, 176, 281

IQ - *In phase / Quadrature*. 91, 95

IR - *Infrared*. 129

ISAC - *Integrated Sensing And Communication*. 24

ISG - *Industry Specification Group*. 291, 292, 363

ISM - *In-Slice Management*. 181

ISO - *International Organization for Standardization*. 352, 361

ITU - *International Telecommunication Union*. 108, 109, 236, 237, 243, 362–364

ITU-R - *International Telecommunication Union Radiocommunication Sector*. 18, 362

J

JCAS - *Joint Communication and Sensing*. 24, 124, 147, 148, 154, 155

JT-CoMP - *Joint Transmission Coordinated Multi-Point*. 43

JU - *Joint Undertaking*. 7, 365, 366

K

kHz - *Kilohertz*. 152

KPI - *Key Performance Indicator*. 20, 21, 41, 101, 166, 168, 171, 172, 176, 180, 185, 194, 196–198, 211, 224–227, 237, 246, 260, 267, 315, 346

KVI - *Key Value Indicator*. 21, 235, 236, 246, 260

KVM - *Kernel-based Virtual Machine*. 341

L

L-BRF - *Linearized BRF*. 136, 137

LADN - *Local Area Data Network*. 239

LCA - *Life Cycle Assessment*. 243

LCM - *Life Cycle Management*. 177–181

LD - *Location Database*. 140

LDHMC - *Long-Distance and High-Mobility Communications*. 18, 251, 252

LDPC - *Low-Density Parity-Check*. 201

LED - *Light Emitting Diode*. 129, 130

LIDAR - *Laser/Light Imaging, Detection and Ranging*. 29, 122, 124, 140, 141, 151

LL - *Low-Layer*. 80

LLR - *Log Likelihood Ratio*. 201

LMMSE - *Linear Minimum Mean Square Error*. 206

LNA - *Low Noise Amplifier*. 91–93, 97, 98

LNaaS - *logical network-as-a-service*. 280, 288

LO - *Local Oscillator*. 93, 95, 98

LoS - *Line of Sight*. 46, 68, 72, 76, 89, 102, 103, 124, 137, 138, 154, 155

LP - *Low Passs*. 91

LS - *Location Server*. 141

LSCPA - *Large Scale Cooperative Predictor Antenna*. 147

LTE - *Long Term Evolution*. 43

LTI - *Linear-Time-Invariant*. 262

LTV - *Linear-Time-Variant*. 262

M

M&O - *Management and Orchestration*. 7, 12, 27, 30, 32, 33, 35, 36

MA-DRL - *Multi-Agent Deep Reinforcement Learning*. 191, 194, 196–198

MA-RL - *Multi-Agent RL*. 195

MaaS - *Management as a Service*. 181

MAC - *Medium Access Control*. 45, 85, 180

MAE - *Mean Absolute Error*. 189

MANO - *Management and Orchestration*. 160, 162, 171, 176–182, 189–191, 215, 224, 242, 279, 348

MANO-MS - *MANO Monitoring System*. 181, 182

MAP - *Multi Antenna Processing*. 53

MAPE - *Monitor-Analyse-Plan-Execute*. 178, 181

MAPE-K - *Monitor-Analyze-Plan-Execute over a shared Knowledge*. 173, 174

MARL - *Multi-Agent Reinforcement Learning*. 248

MBS - *Macro Base Station*. 63, 68

MCS - *Modulation and Coding Scheme*. 87, 88, 90, 201

MDP - *Markov Decision Process*. 195, 196

ME - *Mobile Edge*. 239

MEAO - *Mobile Edge Application Orchestrator*. 240, 242

MEC - *Multi-access Edge Computing*. 70, 123, 140, 188, 239–242, 245, 246, 253, 258, 287

MEO - *MEC Orchestrator*. 239, 242

MEPM - *MEC Platform Manager*. 242

MHz - *Megahertz*. 58

MILP - *Mixed-Integer Linear Programming*. 172

MIMO - *Multiple Input Multiple Output*. 40–43, 63, 69, 87, 95, 100, 132, 147, 199, 203, 212, 248

MISO - *Multiple Input Single Output*. 244

MJLS - *Markov Jump Linear System*. 262

ML - *Machine Learning*. 6, 9, 16, 22, 27, 33, 35, 51, 55, 65, 68, 161–163, 169, 177, 183–186, 194, 202, 204, 206, 207, 212–214, 219, 315, 316, 318, 326–328, 330, 338, 347, 351–353

mMIMO - *Massive MIMO*. 40, 42, 43, 52, 53, 69, 155

MMSE - *Minimum Mean Squared*. 207, 208

mMTC - *Massive Machine-Type Communications*. 17, 131, 294

mmWave - *millimeter Wave*. 24, 41, 50, 63, 64, 86, 92, 110, 121, 123, 125, 129, 140, 141, 143, 144, 146, 151, 210, 254

MNO - *Mobile Network Operator*. 3, 32, 33, 332, 348, 350

MPC - *Multipath Component*. 136, 149

MPTCP - *Multi-Path Transmission Control Protocol*. 79–85

MRF - *Media Resource Function*. 35

MS - *Monitoring System*. 178, 181, 216, 217, 221, 224, 225

MS-S - *Monitoring System Sublayer*. 181

MSE - *Mean Square Error*. 189

MSLE - *Mean Aquared Logarithmic Error*. 189

MT - *Mobile Termination*. 64

MTTF - *Mean Time to Failure*. 263, 264

MU - *Mobile Unit*. 136, 137

MUSIC - *Multiple Signal Classification*. 137, 138

MVNO - *Mobile Virtual Network Operator*. 332, 333, 348, 350

N

N-MAPE-K - *Network MAPE-K*. 174

N3IWF - *Non-3GPP Interworking Function*. 81, 277

NAS - *Non-Access Stratum*. 283, 286

NBI - *Northbound API*. 180

NCC - *Network Centric Clustering*. 53

Near-RT RIC - *Near-Real Time RAN Intelligent Controller*. 53, 55

NEF - *Network Exposure Function*. 176, 287, 307, 308

NF - *Network Function*. 35, 161, 163–169, 274, 278, 279, 285, 287, 295–298

NFV - *Network Function Virtualization*. 35, 172, 176, 186, 219, 224, 239, 241, 242, 280, 318, 348, 363

NFV MANO - *Network Functions Virtualization Management and Orchestration*. 175

NFVI - *Network Functions Virtualization Infrastructure*. 180, 181, 239

NFVO - *Network Functions Virtualization Orchestrator*. 35, 180, 239, 251

NG - *Next Generation*. 283

NI - *Network Intelligence*. 6, 160, 161, 170–175, 181, 182, 184–186, 189, 190, 228

NIF - *Network Intelligence Function*. 161, 171–177, 186–188

NIF-C - *NIF Component*. 174–176

NIO - *Network Intelligence Orchestrator*. 171, 175

NIP - *Network Intelligence Plane*. 171, 189

NIS - *Network Intelligence Service*. 171–173, 175–177

NIST - *National Institute of Standards and Technology*. 352

NLoS - *Non Line of Sight*. 50, 68, 102, 103, 137, 138, 155, 210

NMSE - *Normalized Mean Square Error*. 208, 211

NN - *Neural Network*. 175, 201, 203, 207, 208, 210, 211, 222, 226, 227

NNRT - *Non-Near Real-Time*. 168

NP - *Non-deterministic Polinomial*. 192

NPN - *Non-Public Network*. 15, 276, 277

NR - *New Radio*. 2, 64, 81, 302

NRF - *Network Registry Function*. 176

NRT - *Near-Real-Time*. 168, 220

NS - *Network Service*. 23, 25, 27, 33, 319

NSA - *Non-Standalone*. 2, 239

NSaaS - *Network Slice as a Service*. 239

NSB - *Network Slicing Broker*. 334

NSD - *Network Service Descriptor*. 180

NSI - *Network Slice Instance*. 224, 318

NSM - *Network Service Mesh*. 165

NSMF - *Network Slice Management Function*. 180, 224

NSSMF - *Network Sub-Slice Management Function*. 180

NST - *Network Slice Template*. 180

NTN - *Non-Terrestrial Network*. 24, 87

NWDAF - *Network Data Analytics Function*. 171, 176

O

O-DU - *Open Distributed Unit*. 51–53, 55, 109, 127

O-RAN - *Open RAN*. 9, 170–172, 176, 220, 320, 363, 364

O-RU - *Open Radio Unit*. 51–53, 55, 109, 127

OAM - *Operation Administration and Maintenance*. 165

OCI - *Open Container Initiative*. 340

OFDM - *Orthogonal Frequency-Division Multiplexing*. 101, 122, 124, 127, 133, 151, 154, 205, 206, 247

OPEX - *Operational Expenditure*. 173, 237, 254

OS - *Operating System*. 339

OSM - *Open-Source Management and Orchestration*. 309, 315, 316, 318, 319

OSS - *Operations Support System*. 180, 184, 224, 315

OTFS - *Orthogonal Time Frequency Space*. 122, 124, 132, 133

OTT - *Over-The-Top*. 239, 318

OVS - *Open vSwitch*. 293, 294

OWC - *Optical Wireless Communications*. 121, 123, 129, 140, 143, 144

P

PA - *Power Amplifier*. 96

PA - *Predictor Antenna*. 49, 58, 90–98, 147, 200–202, 204–206

PAPR - *Peak to Average Power Ratio*. 100, 101

PCR - *Platform Configuration Register*. 344

PE - *Positioning Error*. 131

PEF - *Protected Execution Facility*. 345

PF - *Particle Filter*. 137

PGM - *Particle Gaussian Mixture*. 137–139

PHY - *Physical Layer*. 45, 103

PL - *Path Loss*. 244

PN - *Pseudo Random Noise*. 127

PNF - *Physical Network Function*. 35, 180

PPDP - *Privacy Preserving Data Publishing*. 327

PPP - *Public Private Partnership*. 33, 65

PRB - *Physical Resource Block*. 216, 217, 220, 221, 252

ps - *Pico seconds*. 127

PSO - *Particle Swarm Optimization*. 348

Q

QAM - *Quadrature amplitude modulation*. 88, 206

QoE - *Quality of Experience*. 32, 315, 316, 325, 332

QoS - *Quality of Service*. 15, 29, 32, 43, 57, 70, 165, 180, 188, 198, 248, 254, 261, 278, 287, 295, 307, 315, 316, 325

R

RA - *Receive Antenna*. 147

RAM - *Random Access Memory*. 344

RAN - *Radio Access Network*. 4, 5, 14, 15, 23, 25, 40–42, 52, 53, 63, 70, 79, 109, 141, 150, 173, 176, 180, 195, 196, 198, 214–221, 224, 237, 238, 241, 245, 252, 267, 274, 277, 278, 284, 292, 293, 315, 316, 318, 363–365

RANO - *Radio Access Network Orchestrator*. 180

RE - *Resource Element*. 204

REM - *Radio-Environment Map*. 265, 266

RF - *Radio Frequency*. 42, 45, 50, 61, 62, 71, 78, 86–92, 94, 95, 98–101, 106, 110, 143–145, 199–201, 238, 244, 363

RFC - *Request For Comments*. 80

RFIC - *Radio-Frequency Integrated Circuit*. 94

RIC - *RAN Intelligent Controller*. 52, 79, 220, 252, 284

RIS - *Reconfigurable Intelligent Surface*. 6, 7, 41, 42, 69–78, 110, 147, 199, 208, 210, 211

RISA - *RIS Actuator*. 71

RISC - *RIS Controller*. 71

RISO - *RIS Orchestrator*. 71

RL - *Reinforcement Learning*. 125, 126, 194–198, 222, 249, 252, 319

RLC - *Radio Link Control*. 45

RMF - *Risk Management Framework*. 352

RNTI - *Radio Network Temporary Identifier*. 128

ROM - *Read Only Memory*. 344

RoT - *Root of Trust*. 344, 345

RRH - *Remote Radio Head*. 42

RRM - *Radio Resource Management*. 212, 348

RSS - *Received Signal Strength*. 121–124, 129, 140, 154

RSSI - *Received Signal Strength Indicator*. 130

RT - *Ray Tracing*. 125, 126, 143–146, 168, 170, 185, 196, 197, 219, 220

RTT - *Round Trip Time*. 83

RU - *Remote Unit*. 45, 51, 53, 55, 63, 87, 125, 126, 252

Rx - *Receiver*. 105

S

SA - *Standalone*. 2, 363

SaaS - *Sensing as a Service*. 24

SAI - *Securing Artificial Intelligence*. 352

SBA - *Service-Based Architecture*. 14, 239, 278, 287, 307

SBL - *Sparse Bayesian Learning*. 135

SBS - *Small Base Station*. 63, 65, 66, 68

SBTi - *Science Based Targets initiative*. 236

SC - *Small Cell*. 254

SC-FDE - *Single-Carrier Frequency Domain Equalization*. 101

SCP - *Service Communication Proxy*. 167, 280

SD - *Secure Digital card*. 341

SDG - *Sustainable Development Goal*. 13, 21, 235, 236, 366

SDK - *Software Development Kit*. 9, 293, 305, 320

SDN - *Software-Defined Networking*. 7, 25, 180, 182–186, 219, 286, 289, 291, 318, 339

SDO - *Standards Developing Organization*. 289, 361–364

SE - *Spectral Efficiency*. 58–60

SEV - *Secure Encrypted Virtualization*. 345

SFC - *Service Function Chain*. 253, 254, 256

SFL - *Slice Functional Layer*. 180, 181

SiGe - *Silicon-Germanium*. 97

SINR - *Signal to Interference plus Noise Ratio*. 55, 58, 59, 125, 256, 257

SISO - *Single-Input Single-Output*. 42

SLA - *Service-Level Agreement*. 189, 215, 217, 218, 220, 224, 312

SLAM - *Simultaneous Localisation and Mapping*. 16, 121, 123, 149

SmartNICs - *Smart Network Interface Cards*. 285

SME - *Small and Medium-sized Enterprises*. 6

SML - *Slice Management Layer*. 180, 181

SNR - *Signal to Noise Ratio*. 57, 64, 87–90, 93–95, 99–101, 126, 149, 201, 206

SNS - *Smart Networks and Services*. 7, 365, 366

SNS JU - *Smart Networks and Services Joint Undertaking*. 360, 366

SoC - *System-on-Chip*. 47

SOD - *Slice Orchestration Domain*. 180

SRTT - *Smooth Round Trip Time*. 80

stdev - *Standard deviation*. 127

StFL - *Statistical Federated Learning*. 217, 218

SW - *Software*. 30, 300, 301

SWO - *Software Ontology*. 187

T

TaaS - *Trust as a Service*. 326, 349, 350

TCG - *Trusted Computing Group*. 338

TCO - *Total Cost of Ownership*. 237

TCP - *Transmission Control Protocol*. 80, 81, 83

TDD - *Time Division Duplex*. 44, 49, 58, 63, 64, 92

TDoA - *Time Difference of Arrival*. 123, 124, 136, 140

TDX - *Trust Domain Extensions*. 345

TEE - *Trusted Execution Environment*. 338, 344–346

TFS - *TeraFlowSDN*. 183, 185, 289, 291

THz - *Terahertz*. 122, 123

TNSaaS - *Transport Network Slice as a Service*. 288, 289

ToA - *Time of Arrival*. 121, 122, 124, 126, 127, 133, 136, 149

ToF - *Time of Flight*. 124, 125

TPM - *Trusted Platform Module*. 338, 343, 344

TRP - *Transmission/Reception Point*. 216

TSN - *Time-Sensitive Networking*. 276, 278

Tx - *Transmitter*. 106

U

UAV - *Unmanned Aerial Vehicle*. 29, 70, 77, 78, 110, 133, 264–266

UCC - *User Centric Clustering*. 53

UDM - *Unified Data Management*. 350

UE - *User Equipment*. 29, 42–45, 50–53, 55, 57–59, 62–68, 73, 78–80, 84, 109, 110, 121, 122, 124–128, 132, 133, 136–141, 146–150, 162, 192, 199, 202, 239, 240, 254–258, 281–289, 299–302, 308, 363

UEFI - *Unified Extended Firmware Interface*. 342

UMi - *Urban Micro*. 206

umMTC - *Ultra-massive Machine-Type Communications*. 18, 251, 252

UN - *United Nations*. 13, 21, 235, 236

UP - *User Plane*. 29, 286

UPF - *User Plane Function*. 79, 80, 239–241, 286

URA - *Uniform Rectangular Array*. 133

URLLC - *Ultra-Reliable Low Latency Communications*. 17, 82, 172, 240, 241, 286

UWB - *Ultra-Wideband*. 148, 151

V

V2X - *Vehicle-to-Everything*. 27, 219, 303

VAE - *Vertical Application Enablers*. 274, 287, 303

VC - *Verifiable Credential*. 336, 337

VCO - *Voltage Controlled Oscillator*. 98

VIM - *Virtual Infrastructure Manager*. 239, 241

VLAN - *Virtual Local Area Networks*. 180

VLP - *Visible Light Positioning*. 129, 130, 140

VM - *Virtual Machine*. 80, 81, 180, 239, 242, 253, 301, 339–341

VMM - *Virtual Machine Monitor*. 341

VNA - *Vector Network Analyser*. 108, 134

VNF - *Virtual Network Function*. 35, 140, 173, 180, 191, 216, 239, 241, 242, 253–257, 279, 315, 318, 319

VR - *Virtual Reality*. 17, 18

vRAN - *virtualised Radio Access Network*. 173, 238, 239

W

W3C - *World Wide Web Consortium*. 336

WAT - *Wireless Access Technology*. 79, 81

WDM - *Wavelength-Division Multiplexing*. 55

WG - *Working Group*. 5, 363

WPT - *Wireless Power Transfer*. 238, 242, 244

WRR - *Weighted Round Robin*. 81

X

XR - *Extended Reality*. 17–19, 142

Z

ZSM - *Zero-touch network and Service Management*. 35, 177, 178, 215, 219, 363

ZXM - *Zero-Crossing Modulation*. 101