5G SYSTEM DESIGN

ARCHITECTURAL AND FUNCTIONAL CONSIDERATIONS AND LONG TERM RESEARCH

EDITED BY

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To my wife Ines and our kids Philipp and Daniel for their continuous love and support, and to the great team in Nokia Wrocław that I was privileged to work with in the past years.

Patrick Marsch

To my family for their continuous support and encouragement over the years and my big brother Mesut Bulakçı, MD for guiding me to the right career path at my early age.

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For Eskil, Ellen and Ester.

Olav Queseth

To the memory of my father Ivano.

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Foreword 1

Digital technologies have a profound transformative impact on our societies and economies. The digital revolution opens the door to novel activities, applications and business cases that could not be envisaged before. As part of the Digital Single Market initiative launched as one of the ten priorities of the Juncker Commission, the European Commission proposed in 2016 an ambitious package of measures to foster the advent of a digital society and economy in Europe.

5G is an important pillar of this strategy. The European 5G vision co-created with a multiplicity of actors is fully aligned with our wider digitization strategy, as 5G is designed to support smart connectivity in domains as diverse as the automotive, healthcare, factories, energy or media sectors.

The stakes are high. 5G has the potential to open new B2B businesses, whilst operators are currently facing a stagnation of their revenues in Europe. Market estimates point at a potential of € 550 billion extra revenues in 2025 from vertical industries, adding to the classical broadband consumer markets. The "connectivity package" released in September 2016 by the European Commission has thus proposed an ambitious strategy for 5G in Europe. It includes a new connectivity strategy moving Europe in the Gigabit/s connectivity era, a reform of the telecom regulatory framework with specific spectrum and investment friendly measures, and a 5G Action Plan with a package of actions to put in place the right framework conditions for the launch of 5G in Europe in 2020.

European efforts are indeed key to keep abreast of a fierce global competition. The USA and South Korea have already announced the deployment of early versions of 5G technology in 2018. Japan plans 5G introductions in 2020, and China pursues a bold technological development plan. These pre-commercial initiatives are putting high pressure on the quick release of the required standards. In that context, it is imperative that the European 5G strategy targeting vertical markets gets quickly validated, both from a technology and business perspective. The 5G Action Plan consequently calls for early cross-industry and large-scale trials in Europe. These will be supported by the next phase of

the 5G Public Private Partnership (5G PPP), a € 700 million Research and Innovation initiative launched in 2013 by the European Commission to materialize our bold ambitions in this domain.

The European 5G vision requires a versatile network platform that can adapt to demanding requirements of a multiplicity of business models, whilst current networks are more designed as "one size fits all" platforms. Moving towards 5G, deployment will largely piggyback on the results of previous phases of the 5G PPP, which have invested tremendous 5G research efforts in a multiplicity of domains, covering issues as diverse as new radio access technologies, network architectures with co-operation of a multiplicity of fixed or mobile access networks including satellites, operation of new spectrum in the millimeter wave ranges, network virtualization, redesign of the core network, applications of software techniques to network management, as typical examples.

This book presents the results of the research carried out in these multiple domains during the first phase (2014-16) of the 5G PPP. It shows an impressive set of technological achievements, unlocking many of the roadblocks on the road towards achieving the most demanding KPIs of 5G, such as data rates beyond 10 Gbit/s, latencies in the milliseconds range, or service creation and deployment within a few minutes. This work has also been instrumental in supporting the European industry to make informed choices for what concerns 5G standards and spectrum requirements and allocation.

I am grateful to all the colleagues who have shown undivided commitment to make 5G a reality in Europe, and I am sure that the readers will enjoy reading this book as a testimony to these efforts.

Khalil Rouhana, Deputy Director-General in DG CONNECT,
European Commission

Foreword 2

As chairman of the 5G Infrastructure Association board, it is with great pleasure that I see this book come to fruition, and I welcome the chance to add a personal message of support. I believe this is a timely and important work, which in hindsight will be seen as one of the key results from the 5G pre-standardization period.

Although not limited to only European research work, the major input to this book represents the key results from the 5G Public Private Partnership (5G-PPP) research programme. Within the 5G PPP programme, the 5G Infrastructure Association (5G IA) is the organization which represents European industry. The 5G IA is committed to the advancement of 5G in Europe and to building global consensus on 5G. To this aim, the Association brings together a global industry community of telecoms & digital actors, such as operators, manufacturers, research institutes, universities, verticals and SMEs. I believe this book may play a useful role for this 5G IA goal of advancement of 5G, by providing a definitive source for the current state of 5G research.

This book is timely because we are at a water shed in both the 5G PPP and in terms of 5G in general. Within the 5G PPP, we are at a time where most of the phase 1 projects have completed or are about to complete. This means that a lot of the fundamental 5G research has been completed and the focus of the programme in phase 2 will move more towards demonstration of trial systems and integration of vertical domains such as automotive, e-health and Industry 4.0. As such, it is a perfect time to document and disseminate the key results of those phase 1 5G PPP projects.

In terms of the broader view, 5G is also moving from the pre-standardization to post-standardization phase. At the time of writing this book, 3GPP has almost concluded on the so-called first drop of 5G technology, focusing on non-stand-alone operation of 5G in conjunction with (e)LTE. This first drop will of course not include the complete functionality, and it is important to point out that standardization will need many years to completely specify 5G. Nonetheless, some aspects of 5G will be finalized in the near future, and the influence of the 5G PPP projects on many of the design choices made both through direct research and creation of pre-standardization consensus should not be underestimated.

As well as giving an important snapshot of where we are in terms of 5G today and some clear guidance of where we think it should go in the future, I believe the depth and quality shown in this book is a clear validation for the vision and goals of the 5G PPP in general. There is still much work to do to make 5G a reality that lives up to the promised goals, and I believe this book is an important step on that journey.

Dr. Colin Willcock, Chairman of the Board,
5G Infrastructure Association

Acknowledgments

In the mid of 2015, the first phase of 5th Generation Public Private Partnership (5G PPP) projects kicked off, and the time until now has been hectic, but also very rewarding. During this period, 5G has moved from vision and concepts to technologies that are almost ready to be deployed, and we are glad and proud to have been part of this work.

This book is based on the outcome of 12 projects within the 5G PPP framework, as detailed in Section 1.2, and complemented by contributions from various additional 5G experts across the globe. We would like to thank all the contributors for the substantial effort and engagement invested into this book, despite the fact that the writing of the book collided with that of the final deliverables of most of the involved projects. In particular, we would like to express a big thank you to the main chapter editors for consolidating the often diverse viewpoints and terminologies used by different projects or entities into a coherent story. Knowing that many contributors have also spent their free time to finalize the book, and given that the work behind the development of new technologies like 5G is typically as demanding and time-consuming as it is rewarding and inspiring, we would also like to thank the families of the contributors for their continuous patience and support.

Naturally, we would like to thank the European Commission for funding the projects that have led to this book, and in particular Bernard Barani for his personal support of the book.

Beyond the researchers who have been directly involved in the projects, there are of course much more persons involved in our home organizations. We would hence like to thank all our colleagues in the mobile communications industry, research institutes and universities for inspiring discussions, the contribution of ideas, and the help on various tasks.

Dr. Bulakçı would also like to thank Wu Jianjun and Dr. Egon Schulz from Huawei for the support in preparation of this book.

Last but not least, we would like to thank Sandra Grayson, Louis Manoharan and Adalfin Jayasingh from Wiley for the pleasant collaboration and continuous support throughout the writing and production process of this book.

Patrick Marsch, Ömer Bulakçı, Olav Queseth and Mauro Boldi
On behalf of the book contributors

List of Abbreviations

Term	Meaning
3D	Three-Dimensional
3G	3rd Generation (*cellular communications*)
3GPP	3rd Generation Partnership Project
4G	4th Generation (*cellular communications*)
5G	5th Generation (*cellular communications*)
5G AP	5G Action Plan
5G IA	5G Infrastructure Association
5G PPP	5th Generation Public Private Partnership
5GAA	5G Automotive Association
5GC	5G Core Network
5GMF	Fifth Generation Mobile Communication Promotion Forum
5GPoAs	5G Points of Attachment
5GTTI	5G Trial & Testing Initiative
AAS	Active Antenna System
ABG	Alpha Beta Gamma
ABS	Almost Blank Subframes
ABNO	Applications-Based Network Operations
ACDM	Algebraic Channel Decomposition Multiplexing
ACK	Acknowledged
A-CPI	Application-Controller Plane Interface
ADB	Aggregated Data Bundle
ADC	Analog-to-Digital Converter
AE	Action Enforcer
AF	Application Function
AF-x	Adaptation Function–*number* x
AI	Air Interface
AIV	Air Interface Variant
AL	Aggregation level
AM	Acknowledged Mode
AMC	Adaptive Modulation and Coding
AMF	Access and Mobility Management Function

AN	Access Network
ANDSF	Access Network Discovery and Selection Function
AN-I	Access Network-Inner (*layer*)
ANN	Artificial Neural Networks
AN-O	Access Network-Outer (*layer*)
ANQP	Access Network Query Protocol
AP	Access Point
API	Application Programming Interface
APT	Average Power Tracking
AR	Augmented Reality
ARIB	Association of Radio Industries and Businesses
ARP	Allocation and Retention Priority
ARPU	Average Revenue Per User
ARQ	Automatic Repeat reQuest
AS	Access Stratum
ASIC	Application Specific Integrated Circuit
AS-PCE	Active Stateful Path Computation Element
ATIS	Alliance for Telecommunications Industry Solutions
AUSF	Authentication Server Functions
BB	BaseBand
BBU	BaseBand Unit
BCH	Reed Muller or Bose, Ray-Chaudhuri and Hocquenghem codes
BCJR	Bahl, Cocke, Jelinek and Raviv algorithm
BF	BeamForming
BF-OFDM	Block-Filtered OFDM
BH	BackHaul
BLER	Block Error Rate
BMS	Broadcast/Multi-cast Services
BPSK	Binary Phase Shift Keying
BRP	Beam Resource Pool
BS	Base Station
BSM	Basic Safety Message
BSR	Buffer State Reporting
BSS	Business Support System
B-TAG	Backbone VLAN Tag
BV	Bandwidth-Variable
BVT	Bandwidth-Variable Transponders
C/I	Carrier-to-Interference (*ratio*)
CA	Carrier Aggregation
CAGR	Compound Annual Growth Rate
CAM	Cooperative Awareness Messages
CAPEX	Capital Expenditures
CCDF	Complementary Cumulative Distribution Function
CCE	Control Channel Entity
CCH	Control Channel

CCNF	Common Control Network Functions
CCSA	China Communications Standards Association
CD	Code Division
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CDN	Content Delivery Network
CH	Cluster Head
CI	Close-In
CIoT	Cellular Internet of Things
C-ITS	Cooperative-ITS
CLI	Cross-Link Interference
CMO	Control, Management and Orchestration
CMOS	Complementary Metal-Oxide Semiconductor
CN	Core Network
CoMP	Coordinated/Cooperative Multi-Point
COST	European Cooperation in Science and Technology
COTS	Commercial Off-The-Shelf
CP	Control Plane
CPE	Common Phase Error
CPM-19	Conference Preparatory Meeting in 2019
CP-OFDM	Cyclic Prefix OFDM
CPRI	Common Public Radio Interface
CPU	Central Processing Unit
CQI	Channel Quality Indicator
C-RAN or CRAN	Centralized/Cloud Radio Access Network
CRC	Cyclic Redundancy Check
C-RNTI	Cell Radio Network Temporary Identifier
CRS	Cell-specific Reference Symbols
CSI	Channel State Information
CSIT	Channel State Information (*transmitter side*)
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSP	Communication Service Provider
CTC	Convolutional Turbo Codes
CTO	Chief Technology Officer
CU	Central Unit
D2D	Device-to-Device
D2N	Device-to-Network
DAC	Digital-to-Analog Converter
DAS	Distributed Antenna System
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
DC	Dual Connectivity
DCC	Decentralized Congestion Control
DCI	Downlink Control Information
DCN	Dedicated Core Network
D-CPI	Data-Controller Plane Interface

DD-OFDM	Direct Detection OFDM
DDoS	Distributed Denial of Service
DECOR	Dedicated Core
DEI	Drop Eligible Indicator
DEN	Decentralized Environmental Notification
DFT	Digital Fourier Transform
DFT-s-OFDM	DFT-spread OFDM
DL	Downlink
DM	Decision-Maker
DMC	Dense Multipath Component
DMRS	DeModulation Reference Signal
DNS	Domain Name System
DoS	Denial of Service
DPD	Digital Pre-Distortion
DPDK	Data Plane Development Kit
DR	D2D Receiver
D-RAN	Distributed Radio Access Network
DRB	Data Radio Bearer
DRX	Discontinuous Reception
DSC	Decentralized Congestion Control Sensitivity Control
DSP	Digital Signal Processor
DSRC	Dedicated Short Range Communications
DT	Decision Tree
DTT	Digital Terrestrial Television
DTX	Discontinuous Transmission
DU	Distributed Unit
DVB	Digital Video Broadcasting
DWDM	Dense Wavelength Division Multiplexing
E2E	End-to-End
EATA	European Automotive-Telecom Alliance
EC	European Commission
ECDSA	Elliptic Curve Digital Signature Algorithm
EDCA	Enhanced Distributed Channel Access
eDECOR	evolved DECOR
eICIC	Enhanced Inter-Cell Interference Coordination
eIMTA	Enhanced Interference Mitigation and Traffic Adaptation
EIRP	Effective Isotropic Radiated Power
eLTE	enhanced Long-Term Evolution
EM	Element Management
eMBB	enhanced Mobile BroadBand
eMBMS	enhanced Mobile Broadband Multimedia Services
EMF	Electro-Magnetic Field
eNB	enhanced Node-B
EPC	Enhanced Packet Core
ePDCCH	enhanced PDCCH

EPS	Evolved Packet System
ET	Envelope Tracking
ETH	Ethernet
ETN	Edge Transport Nodes
ETSI	European Telecommunications Standards Institute
EU	European Union
E-UTRA	Evolved-UTRA
EVM	Error Vector Magnitude
F1	*Horizontal interface in the RAN*
F1-C	*Horizontal interface in the RAN (control plane)*
F1-U	*Horizontal interface in the RAN (user plane)*
FBMC	Filter Bank Multi-Carrier
FBR	Front-to-Back Ratio
FCAPS	Fault Configuration, Accounting, Performance, Security
FCC	Federal Communications Commission
FC-OFDM	Flexibly Configured – OFDM
FD	Full Duplex
FDD	Frequency Division Duplexing
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FDV	Frame-Delay Variation
FEC	Forward Error Correction
FeICIC	Further enhanced Inter-Cell Interference Coordination
FFT	Fast Fourier Transform
FH	Fronthaul
FI	Float Intercept
FIR	Finite Impulse Response
FN	False Negatives
FP	False Positives
FPGA	Field Programmable Gate Array
FQAM	Frequency Quadrature Amplitude Modulation
FS	Feature Selection
Fs-C	*Intra-RAN control plane interface*
FSPL	Free-Space Path Loss
Fs-U	*Intra-RAN user plane interface*
FTP	File Transfer Protocol
FTTA	Fiber-to-the-Antenna
GA	Genetic Algorithm
GAA	General Authorized Access
GaN	Gallium Nitride
GAN	Generic Access Network
GDB/GLDB	GeoLocation DataBase
GEPON	Gigabit Ethernet PON
GFDM	Generalized Frequency Division Multiplexing
GLOSA	Green Light Optimal Speed Advice

GMPLS	Generalized Multi-Protocol Label Switching
gNB	Gigabit (enhanced) Node-B
GOPS	Giga Operations
GPON	Gigabit PON
GPP	General Purpose Processing
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSCM	Geometry-based Stochastic Channel Model
GSM	Global System for Mobile Communications
GTP	GPRS Tunnelling Protocol
GUI	Graphical User Interface
HARQ	Hybrid Automatic Repeat reQuest
HD	High Definition
HO	HandOver
HPA	High Power Amplifier
HSIC	Hybrid Self Interference Cancellation
HSPA	High-Speed Packet Access
HSS	Home Subscriber System
HSTD	Horizontal Security and Trust Domains
HTHP	High Tower High Power
HW	Hardware
I2I	Indoor-to-Indoor
IaaS	Infrastructure-as-a-Service
IAD	Interference-Aware Detection
IAN	Interference-as-Noise
IASD	Interference-Aware Successive Decoding
IAT	Inter-Arrival Time
IATN	Inter Area Transport Node
IBFD	In-Band Full-Duplex
ICI	Inter Carrier Interference
ICIC	Inter-Cell Interference Coordination
I-CPI	Intermediate-Controller Plane Interface
ICT	Information and Communications Technology
ID	Identifier
IDFT	Inverse DFT
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
iFFT	inverse Fast Fourier Transform
IFOM	IP Flow Mobility
IIC	Industrial Internet Consortium
IIR	Infinite Impulse Response
IMS	IP Multimedia Subsystem
IMT	International Mobile Telecommunications
IMT2020 or IMT-2020	IMT for year 2020 and beyond

IMT-A	IMT-Advanced
INR	Interference-to-Noise Ratio
IoT	Internet of Things
IP	Internet Protocol
IPr	Intellectual Property
IPsec	Internet Protocol Security
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
IQ	Inphase and Quadrature Phase
IR	Incremental Redundancy
IR-HARQ	incremental redundancy HARQ
ISD	Inter-Site Distance
ISG	Industry Standard Group (in ETSI)
ISI	Inter Symbol Interference
ISM	Industrial, Scientific and Medical
ISO	International Organization for Standardization
IT	Information Technology
I-TAG	Backbone Service Instance Tag
ITS	Intelligent Transport Systems
ITU	International Telecommunication Union
ITU-R	ITU - Radiocommunication sector
JT	Joint transmission
KED	Knife Edge Diffraction
KPI	Key Performance Indicator
KSP	Known Symbol Padding
KTX	Korea Train eXpress
LAA	License(d)-Assisted Access
LBT	Listen-Before-Talk
LCP	Logical Channel Prioritization
LD	Linear Discriminant
LDM	Local Dynamic Map
LDPC	Low Density Parity Check
LIME	Linda in a Mobile Environment
LIPA	Local IP Access
LLC	Logical link control
LNA	Low Noise Amplifier
LO	Local Oscillator
LoRa	Long Range, low power technology
LOS	Line-of-Sight
LPWA	Low Power Wide Area
LSA	Licensed Shared Access
LSE	Least Squares Estimation
LSO	Lifecycle Service Orchestration
LTE(-A)	Long-Term Evolution (Advanced)
LWA	LTE-WLAN Aggregation

LWAAP	LTE-WLAN Aggregation Adaptation protocol
LWIP	LTE/Wi-Fi Radio Level Integration Using IPsec Tunnel
M2M	Mobile-to-Mobile
MAC	Medium Access Control
MANO	Management & Orchestration
MAP	Maximum a Posteriori
MAPCON	Multi-Access PDN Connectivity
MBB	Mobile BroadBand
MBHM	Map-Based Hybrid Modeling
MBMS	Multimedia Broadcast Multicast Services
MBSFN	Multicast-Broadcast Single Frequency Network
MC	Multi-Carrier
MCC	Mission Critical Communications
MCP	Measurement Configuration Profile
MCS	Modulation and Coding Scheme
MdO	Multi-domain Orchestrator
MD-PCE	Multi-Domain Path Computation Element
MEC	Mobile Edge Computing *or* Multi-Access Edge Computing
ME	Multi-Edge
ME-LDPC	Multi-Edge LDPC
MeNB	Master (enhanced) Node-B
METIS (-II)	Mobile and wireless communications Enablers for the Twenty-twenty Information Society (-II)
MIB	Master Information Block
MIC	Ministry of Internal Affairs and Communications, Japan
MIIT	Ministry of Industry and Information Technology
MIMO	Multiple-Input Multiple-Output
MIPS	Million Instructions Per Second
MISO	Multiple Input Single Output
ML	Machine Learning
MLD	Maximum Likelihood Decoding
MM	Mobility Management
MMC	Massive Machine Communications
MME	Mobility Management Entity
MMIMMO	Massive Multiple-Input Massive Multiple-Output
MMSE-IRC	Minimum Mean Squared Error – Interference Rejection Combining
mMTC	Massive Machine-Type Communications
mmW, mmWave	millimeter-Wave
MNO	Mobile Network Operator
MOCN	Multi-Operator Core Network
MOP	Multi-Objective Optimization
MORAN	Mobile Operator Radio Access Network
MP	Memory Polynomial
MP	Message Passing
MPLS	Multi Protocol Label Switching

MPLS-TP	MPLS Transport Profile
MP-TCP	Multi-Path Transmission Control Protocol
M-RRC	Master Radio Resource Control
MS	Min-Sum
MSE	Mean-Square-Error
MSIP	Ministry of Science, Information and Future Planning, South Korea
MT	Mobile Terminated
MTA	Multi-Tenancy Application
MTC	Machine-Type Communications
MTU	Maximum Transmission Unit
MU-MIMO	Multi User MIMO
MVNO	Mobile Virtual Network Operator
MWC	Mobile World Congress
N2	*Control plane interface betw. RAN and core network in 5G → NG-C*
N3	*User plane interface betw. RAN and core network in 5G → NG-U*
NACK	Negative Acknowledged
NAICS	Network Assisted Interference Cancellation and Suppression
NAS	Non Access Stratum
NB	NarrowBand
NBAP	Node-B Application Part
NBI	North Bound Interface
NBIFOM	Network-Based Internet Protocol Flow Mobility
NB-IoT	NarrowBand Internet of Things
NCO	Numerically Controlled Oscillator
NEF	Network Exposure Function
NF	Network Function
nFAPI	Network functional Application Programming Interface
NFV	Network Function Virtualization
NFVI	Network Function Virtualization Infrastructure
NFVO	NFV Orchestrator
NG	Next Generation
NG-C	*Control plane interface betw. RAN and core network in 5G → N2*
NGCO	New Generation Central Office
NGFI	Next Generation Fronthaul Interface
NGMN	Next Generation Mobile Networks
NGPoP	Next Generation Point of Presence
NG-RAN	Next Generation Radio Access Network
NG-U	*User plane interface betw. RAN and core network in 5G → N3*
NG-Uu	*Interface between network and device in 5G*
NHTSA	National Highway Traffic Safety Administration
NIC	Network Interface Controller
NLoS	Non-Line-of-Sight
NMSE	Normalized Mean Square Error
NN	Nomadic Node
NNSF	Network Node Selection Function

NOI	Notice of Inquiry
NPRM	Notice of Proposed Rulemaking
NPV	Net Present Value
NR	New Radio
NRA	National Regulatory Authority
NRF	Network Repository Function
NS	Network Service
NSA	Non-StandAlone
NSD	Network Service Descriptors
NS-FAID	Non-Surjective Finite Alphabet Iterative Decoder
NSI	Network Slice Instance
NSMF	Network Slice Management Function
NSSF	Network Slice Selection Function
NST	Network Slice Template
NYU	New York University
O2I	Outdoor-to-Indoor
O2O	Outdoor-to-Outdoor
OAI	Open Air Interface
OAM	Operations, Administration and Management/Maintenance
OBSAI	Open Base Station Architecture Initiative
OBU	On-Board Unit
OF	OpenFlow
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
OFNC	Open-Flow Network Controller
OLT	Optical Line Terminal
ONF	Open Networking Foundation
ONU	Optical Network Unit
OOB	Out Of Band
OPEX	Operational Expenditures
OPI	Offload Preference Indicator
OPS	Operations
OQAM	Offset Quadrature Amplitude Modulation
OS	Operating System
OSI	Open System Interconnection
OSM	Open Source Management and Orchestration
OSS	Operations Support System
OTN	Optical Transport Network
OTT	Over The Top
OvS	Open vSwitch
OVSDB	Open vSwitch Database Management Protocol
PA	Power Amplifier
PaaS	Platform-as-a-Service
PAE	Power Added Efficiency
PAL	Primary Access Licenses

PAM	Pulse-Amplitude Modulation
PAPR	Peak-to-Average Power Ratio
PBB	Provider Backbone Bridging
PBCH	Physical Broadcast CHannel
PC	Polar Codes
PCA	Principal Component Analysis
PCell	Primary Cell
PCF	Policy Control Function
PCHA	Personal Connected Health Alliance
PCI	Physical Cell ID
PCM	Parity Check Matrices
PCP	Priority Code Points
PCR	Pilot Contamination Regime
PCRF	Policy and Charging Rules Function
PDCA	Plan, Do, Check, Adjust
PDCCH	Physical Downlink Control CHannel
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
PDP	Power Delay Profile
PDSCH	Physical Downlink Shared Channel
PDU	Protocol Data Unit
PDV	Packet Delay Variation
PER	Packet Error Rate
PGIA	Pre-emptive Geometrical Interference Analysis
PGW	Packet Data Network Gateway
PHY	Physical layer
PLL	Phase-Locked Loop
PLMN	Public Land Mobile Network
PLOS	Probability Loss
PLS	Physical Layer Security
PMI	Precoding Matrix Indicator
PMIP	Proxy Mobile IP
PMSE	Programme Making and Special Events
PN	Polyphase Network
PNF	Physical Network Function
P-OFDM	Pulse Shaped OFDM
PON	Passive Optical Network
PoP	Point of Presence
PPC	PolyPhase Components
PPDR	Public Protection and Disaster Relief
PPI	Power Preference Indicator
PPN	PolyPhase Network
PPP	Public Private Partnership
PRACH	Physical Random Access CHannel
PRB	Physical Resource Block

PRG	Precoding Resource Block Group
PS	Packet Switched
PSS	Primary Synchronization Signal
PTM	Point-To-Multi-point
PUCCH	Physical Upling Control CHannel
PUSCH	Physical Uplink Shared CHannel
PVM	Probe Vehicle Message
PVNO	Private Virtual Network Operator
PWS	Public Warning System
QAM	Quadrature Amplitude Modulation
QC	Quasi-Cyclic
QCI	QoS Class Identifier
QFI	QoS Flow Identity
QoE	Quality of Experience
QoS	Quality of Service
QPP	Quadratic Permutation Polynomial
RA	Random Access
RACH	Random Access Channel
RAM	Random Access Memory
RAN	Radio Access Network
RAT	Radio Access Technology
RAU	Radio Aggregation Unit
RB	Resource Block
RCC	Radio Cloud Center
RCLWI	RAN Controlled LTE WLAN Interworking
RE	Resource Element
REG	Resource Element Groups
REM	Radio Environment Map
RF	Radio Frequency
RFSIC	Radio Frequency Self Interference Cancelation
RIT	Radio Interface Technology
RITA	Research and Innovative Technologies Administration
RLC	Radio Link Control
RM	Resource Management
RMS	Root Mean Square
RNC	Radio Network Controller
RoE	Radio over Ethernet
RoHC	Robust Header Compression
ROI	Return on Investment
RRC	Radio Resource Control
RRH	Remote Radio Head
RRM	Radio Resource Management
RRU	Remote Radio Unit
RS	Reference Symbol
RSA	Roadside Alert

RSC	Resources Sharing Cluster
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RTA	RAN Tracking Area
RTT	Round Trip Time
RU	Remote Unit
Rx	Receiver
SaaS	Software-as-a-Service
SAE	Society of Automotive Engineers
SAS	Spectrum Access System
SBI	Service-Based Interface
sBH	Self-BackHauling
S-BVT	Sliceable-Bandwidth Variable Transponders
SC	Single Carrier
SCell	Secondary Cell
SCF	Small Cell Forum
SC-FDMA	Single Carrier Frequency Division Multiple Access
SCM	Spatial Channel Model
SCME	Spatial Channel Model Extension
SCNF	Slice-specific Control Network Function
SD	Slice Differentiator
SDAP	Service Data Adaptation Protocol
SDMA	Space Division Multiple Access
SDM-C	Software-Defined Mobile Network Controller
SDM-X	Software-Defined Mobile Network Coordinator
SDN	Software-Defined Networking
SDR	Software-Defined Radio
SD-RAN	Software-Defined Radio Access Network
SDT	Small Data Transmission
SDU	Service Data Unit
SeNB	Secondary enhanced Node-B
SFBC	Spatial-Frequency Block Codes
SFN	Single Frequency Network
SGW	Serving Gateway
SHF	Super High Frequency
SI	Self Interference
SIB	System Information Block
SiC	Silicon Carbide
SIC	Self Interference Cancelation
SIM	Subscriber Identity Module
SIMO	Single Input Multiple Output
SINR	Signal to Interference plus Noise Ratio
SIPTO	Selected IP Traffic Offloading
SIW	Substrate Integrated Waveguide
SLA	Service Level Agreement

SMA	Service Monitoring & Analytics
SMF	Session Management Function
SMS	Spectrum Management System
SN	Sequence Number
SNR	Signal-to-Noise Ratio
S-NSSAI	Single Network Slice Selection Assistance Information
SOI	Silicon-On-Insulator
SON	Self-Organizing Network
SP	Strict Priority
SPAT	Signal Phase and Timing
SPM	Security Policy Manager
SPS	Semi-Persistent Scheduling
SPTP	Small Packet Transmit Procedure
SR	Scheduling Request
SRIT	Set of RITs
SRM	Slice Resource Manager
S-RRC	Secondary Radio Resource Control
SRS	Sounding Reference Signal
SSB	Synchronization Signal Block
SSS	Secondary Synchronization Signal
SST	Slice/Service Type
SU	Single User
SVD	Single Value Decomposition
SVM	Support Vector Machine
SW	Software
SWA	Software Architectures
SWCM	Sliding-Window Coded Modulation
SYNC	Synchronization
TA	Timing Advance
TAC	Transmit Access Control
TAU	Tracking Area Update
TBCC	Tail-Biting Convolutional Codes
TBS	Transport Block Size
TC	Turbo Code
TCP	Transmission Control Protocol
TD	Time Division
TDC	Transmit Datarate Control
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TE	Traffic Engineering
TG	Task Group
THR	Throughput
TM	Transverse Magnetic
TMC	Traffic Management Center
TMS	Transmission Mode Selection

TN	Transport Node
TNeg	True Negatives
TO	Timing Offset
TOSCA	Topology and Orchestration Specification for Cloud Applications
TP	True Positives
TPC	Transmit Power Control
TR	Technical Report
TRC	Transmit Rate Control
TRP	Transmission Reception Point
TS	Technical Specification
TSDSI	Telecommunications Standards Development Society
TSN	Time-Sensitive Networking
TSON	Time Shared Optical Network
TTA	Telecommunications Technology Association
TTC	Telecommunication Technology Committee
TTI	Transmission Time Interval
TV	Television
Tx	Transmitter
UC	Use Case
UCA	Use Customer Address
UDM	Unified Data Management
UDN	Ultra-Dense Network
UDP	User Datagram Protocol
UE	User Equipment
UEFA	Union of European Football Associations
UF-OFDM	Universal Filtered OFDM
UHD	Ultra High Definition
UHF	Ultra High Frequency
UK	United Kingdom
UL	Uplink
UM	Unacknowledged Mode
UMA	Unlicensed Mobile Access
UP	User Plane
UPF	User Plane Function
URLLC	Ultra-Reliable Low-Latency Communications
US	United States (*of America*)
USRP	Universal Software Radio Peripheral
UTRA	Universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access
UW	Unique Word
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

VCO	Voltage-Controlled Oscillator
VGA	Variable Gain Amplifier
VI	Virtualized Infrastructure
VIM	Virtual Infrastructure Manager
VLAN	Virtual Local Area Network
VLIW	Very Long Instruction Word
VNF	Virtual Network Function
VNFM	VNF Manager
VNN	Vehicular Nomadic Node
VoD	Verify-on-Demand
VoLTE	Voice over LTE
VPN	Virtual Private Networks
VR	Virtual Reality
vRAN/VRAN	Virtual Radio Access Network
VSF	Virtual Security Function
VSTD	Vertical Security and Trust Domains
WAN	Wide Area Network
WAS	Wireless Access System
WAVE	Wireless Access in Vehicular Environments
WBI	West Bound Interface
WCDMA	Wideband Code Division Multiple Access
WDM	Wavelength Division Multiplexing
WFQ	Weighted Fair Queueing
WI	Work Item
Wi-Fi	*Technology for wireless local area networking based on IEEE 802.11 standards*
WIM	WAN Infrastructure Manager
WIMAX	Worldwide Interoperability for Microwave Access
WINNER-II	Wireless world INitiative NEw Radio phase II
WLAN	Wireless Local Area Network
W-OFDM	Windowed OFDM
WP5D	ITU-R Work Package 5D
WRC	World Radiocommunication Conference
WRC-15	WRC in 2015
WRC-19	WRC in 2019
WRR	Weighted Round Robin
WSLM	Weighted Selective Mapping Technique
WSMP	WAVE Short Message Protocol
WT	WLAN Termination
X2	*Interface between base stations in LTE*
XaaS	Everything-as-a-Service
XGPON	10-Gigabit-capable passive optical network
xMBB	extreme Mobile BroadBand
Xn	*Interface between base stations in 5G*
ZC	Zadoff-Chu
ZP	Zero Padding
ZP-OFDM	Zero Padding OFDM
ZT	Zero Tail

Part 1

Introduction and Basics

1

Introduction and Motivation

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1.1   5th Generation Mobile and Wireless Communications

The 5th generation (5G) of mobile and wireless communications is expected to have a large impact on society and industry that will go far beyond the information and communications technology (ICT) field. On one hand, it will enable significantly increased peak data rates compared to previous cellular generations, and allow for high experienced data rates almost anytime and anywhere, to support enhanced mobile broadband (eMBB) services. While there is already a wide penetration of mobile broadband services today, 5G is expected to enable the next level of human connectivity and human-to-human or human-to-environment interaction, for instance with a pervasive usage of virtual or augmented reality [1], free-viewpoint video [2], and tele-presence.

On the other hand, 5G is expected to enable ultra-reliable low-latency communications (URLLC) and massive machine-type communications (mMTC), providing the grounds for the all-connected world of humans and objects. This will serve as a catalyst for developments or even disruptions in various other technologies and business fields beyond ICT, from the ICT perspective typically referred to as *vertical industries*, that can benefit from omnipresent mobile and wireless connectivity [3]. To name a few examples[1], it is expected that 5G will

- foster the 4th industrial revolution, also referred to as Industry 4.0 [4] or the Industrial Internet, by enabling reliability- and latency-critical communication between machines, or among machines and humans, in industrial environments;
- play a key role for the automotive sector and transportation in general, for instance allowing for advanced forms of collaborative driving and the protection of vulnerable road users [5], or increased efficiency in railroad transportation [6];

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1 Note that more use case examples are described in Chapter 2 and in Section 17.3.

- enable the remote control of vehicles or machines in dangerous or inaccessible areas, as for instance in the fields of mining and construction [7];
- revolutionize health services, for instance through the possibility of wirelessly enabled smart pharmaceuticals or remote surgery with haptic feedback [8];
- accelerate and, in some cases, enable the adoption of solutions for so-called Smart Cities, improving the quality of life through better energy, environment and waste management, improved city transportation, etc. [9].

Ultimately, directly or indirectly through the stated impacts on vertical industries, 5G is likely to have a huge impact on the way of life and the societies in which we live [10].

The mentioned wide diversity of technology drivers and use cases is a unique characteristic of 5G in comparison to earlier generations of cellular communications, as illustrated in Figure 1-1. More precisely, previous generations have always been tailored towards one particular need and a particular business ecosystem, such as mobile broadband in the case of Long-Term Evolution (LTE), and have hence always been characterized by one monolithic system design. In contrast, 5G is from the very beginning associated with the need for multi-service and multi-tenancy support, as detailed in Section 5.2, and is commonly understood to comprise a variety of tightly integrated radio technologies, such as enhanced LTE (eLTE), Wi-Fi, and different variants of novel 5G radio interfaces that are tailored to different frequency bands, cell sizes or service needs.

Beyond the technology as such, 5G is also expected to imply an unprecedented change in the value chain of the mobile communications industry. Although a mobile-operator-centric ecosystem may
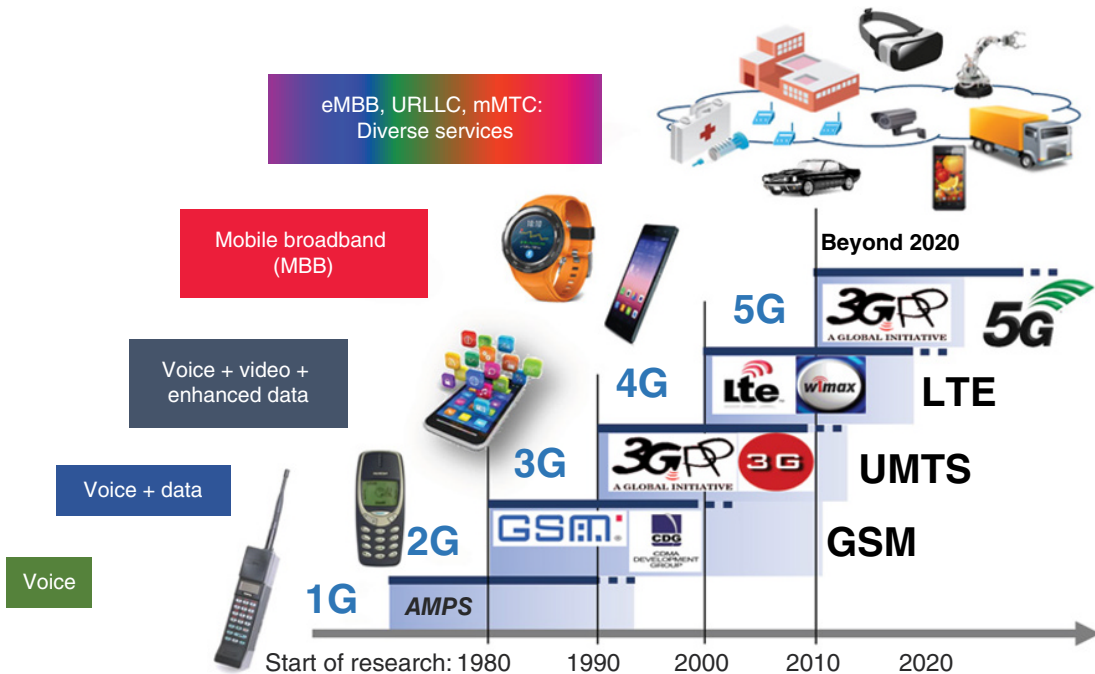
Figure 1-1. Main drivers behind past cellular communications generations and 5G.

prevail, a set of new players are deemed to enter the arena, such as enhanced connectivity providers, asset providers, data centre and relay providers, and partner service providers, as detailed in Section 2.6.

Clearly, the path to 5G is a well-beaten track by now. Early research on 5G started around 2010, and the first large-scale collaborations on 5G, such as METIS [11] and 5GNow [12] were launched in 2012. In the meanwhile, most geographical areas have launched initiatives and provided platforms for funded research or collaborative 5G trials, as detailed in Section 7.3. The International Telecommunications Union (ITU) has defined the requirements that 5G has to meet to be chosen as an official International Mobile Telecommunications 2020 (IMT-2020) technology [13], and published related evaluation guidelines [14]. On the way towards the fulfilment of the IMT-2020 framework, the standardization of an early phase of 5G by the 3rd Generation Partnership Project (3GPP) is in full swing [15], as summarized in the following section and detailed in Section 17.2.1. Further, 5G has now gained major public visibility through pre-commercial deployments alongside the Winter Olympics in South Korea, and will soon be showcased at further large-scale events such as the Summer Olympics in Tokyo in 2020 and the UEFA EURO 2020 soccer championship.

Nevertheless, even though 5G is moving full pace ahead towards first commercial deployments, there are still various design questions to be answered, and many topics are still open for longer-term research. This is in part due to the continuous acceleration of the 5G standardization timeline, requiring to set priorities and postpone parts of the original 5G vision to later, as detailed in the following section.

At this vital point in the 5G development timeline, this book aims not only to summarize the consensus that has already been reached in 3GPP and in research consortia, but also to elaborate on various design options and choices that are still to be made towards the complete 5G system, which is ultimately envisioned to respond to all the use cases and societal needs as listed before, and address or exceed the IMT-2020 requirements.

As a starting point to the book, Section 1.2 elaborates in more detail on the timing of the book w.r.t. the 5G developments in 3GPP and global initiatives. Section 1.3 stresses the exact scope of the 5G system design as covered in this book, and in particular puts this into perspective to what is currently covered in 3GPP Release 15 and likely covered in subsequent releases. Finally, Section 1.4 explains the approach pursued in writing this book, and introduces the structure and the following chapters of this book.

1.2 Timing of this Book and Global 5G Developments

At the time of the publication of this book, the Winter Olympic Games in South Korea are taking place, constituting the first large-scale pre-commercial 5G deployment connected to a major international event, and hence marking a major milestone in the 5G development.

Further, by the time the book appears, **3GPP** has likely just concluded the specification of the so-called *early drop* of New Radio (NR) [16], reflecting a subset of 5G functionalities that are just sufficient for very first commercial 5G deployments in so-called *non-stand-alone* (NSA) operation, i.e. where 5G radio is only used in conjunction with existing LTE technology, as detailed in Section 5.5.2. The full completion of 3GPP Release 15, often referred to as the Phase 1 of 5G, is expected for the second half of 2018, and will also include *stand-alone* (SA) operation [16]. More details on the 3GPP timeline can be found in Section 17.2.1.

Naturally, as the 5G standardization in 3GPP has been heavily accelerated to allow for very early commercial deployments, some prioritization had to be made w.r.t. the scope of the 5G system that is captured in Release 15. For instance, the discussion in 3GPP so far tends towards eMBB use cases, as most specific 5G deployment plans and related investments that have already been announced are related to eMBB, as visible in Section 17.3. In consequence, some design choices in 3GPP have so far been made with eMBB services in mind, leaving further modifications and optimizations for other service types for future study in upcoming releases. One example for such decisions is the choice of cyclic prefix based orthogonal frequency division multiplex (CP-OFDM) as the waveform for NR Release 15 [17][18], possibly enhanced with filtering that is transparent to the receiver. This approach is seen as suitable for eMBB as well as for several URLLC services, but it may not fully address the needs of some other specific URLLC and mMTC services or device-to-device (D2D) communications, as detailed in Sections 11.3 and 14.3. Another example is the choice of Low Density Parity Check (LDPC) codes and Polar codes for data and control channels in NR Release 15 [19], respectively, which has been accepted as a combination for eMBB, but which may not be the final choice for all service types envisioned for 5G, as detailed in Section 11.4. Again for the reason of speed, 3GPP is currently also putting most attention towards carrier frequencies below 40 GHz, i.e., not yet covering the full spectrum range up to 100 GHz envisioned in the longer term, see Section 3.4, which will be tackled in later releases.

However, one has to stress that 3GPP in general pursues the approach that whatever is introduced in early 5G releases has to be future-proof, or *forward-compatible*, i.e., it must not constitute a showstopper for further developments in future releases. An example for this approach is the way how 3GPP handles self-backhauling, i.e., the usage of the same radio technology and spectrum for both backhaul and access links, as detailed in Section 7.4. While 3GPP will not be able to fully standardize this in Release 15, it ensures that the basic operation and essential features of NR that will also be needed for self-backhauling, such as flexible time division duplex (TDD), a minimization of always-on signals, asynchronous Hybrid Automated Repeat reQuest (HARQ), flexible scheduling time units, etc., are already covered well in Release 15. Based on this, the further standardization of self-backhauling, particularly covering higher-layer aspects in 3GPP RAN2 and RAN3, can then be taken up in Release 16.

Ultimately, 3GPP standardization is expected to take place in Releases 15 and 16 until 2020 [15], with the aim to submit a 5G system design to ITU, where NR, and NR in combination with enhanced LTE (eLTE), i.e. Release 15 and onwards, meet the IMT-2020 requirements [20][21]. The IMT process is covered in detail from a performance evaluation perspective in Section 15.2.1, and from an overall 5G deployment perspective in Section 17.2.2. Beyond the ITU submission, 5G standardization is naturally expected to continue further in Release 17 and beyond.

This book has been written at a point in time when most of the so-called Phase 1 of the **5G Public Private Partnership** (5G PPP) research projects have been concluded, and the Phase 2 has just started [22]. While Phase 1 has focused on 5G *concepts*, Phase 2 is dedicated to *platforms*, and Phase 3 to *trials*, as depicted in Figure 1-2. In fact, a big portion of this book is based on the output of the 5G PPP Phase 1 projects, in particular on the output of (in alphabetical order) [23]:

- **5G-Crosshaul**, which has developed a 5G integrated backhaul and fronthaul transport network enabling a flexible and software-defined reconfiguration of all networking elements in a multi-tenant and service-oriented unified management environment;
- **5GEx**, which has aimed at enabling the cross-domain orchestration of services over multiple administrations or over multi-domain single administrations;
- **5G-NORMA**, which has developed a novel, adaptive and future-proof 5G mobile network architecture, with an emphasis on multi-tenancy and multi-service support;
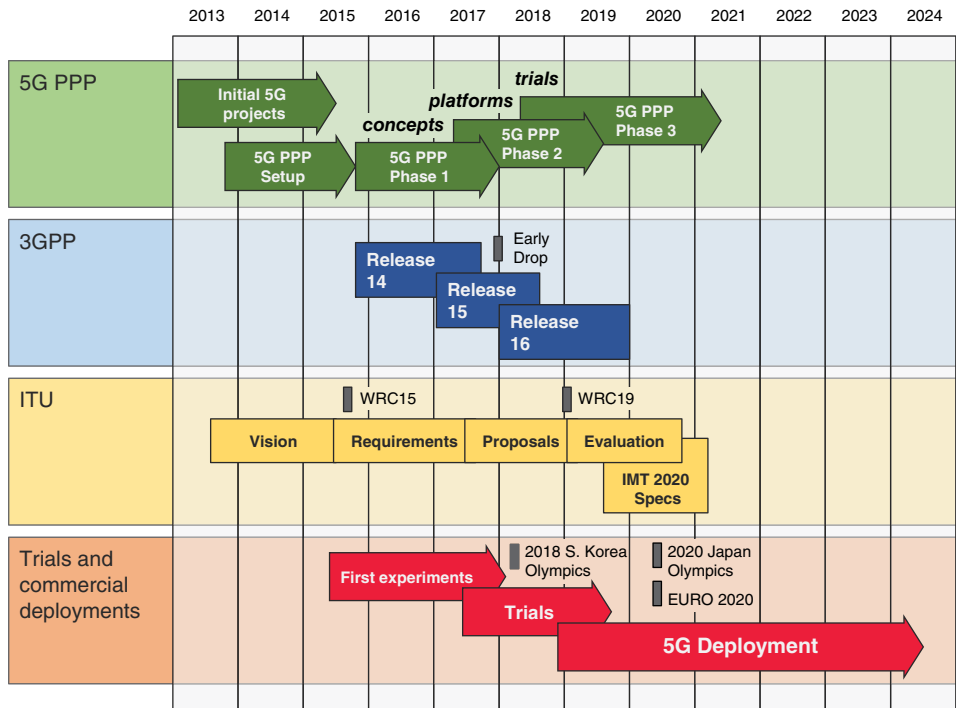
Figure 1-2. Combined overall 5G timeline of the mentioned different bodies.

- **5G-Xhaul**, which has developed a converged optical and wireless network solution able to flexibly connect small cells to the core network;
- **COHERENT**, which has developed a unified programmable control framework for coordination and flexible spectrum management in 5G heterogeneous access networks;
- **CHARISMA**, which has focused on an intelligent hierarchical routing and paravirtualized architecture uniting a devolved offload with an end-to-end security service chain via virtualized open access physical layer security;
- **FANTASTIC-5G**, which has developed a 5G flexible air interface for scalable service delivery, with a comprehensive PHY, MAC and RRM design;
- **Flex5GWare**, which has developed highly reconfigurable hardware and software platforms targeting both network elements and devices, and taking into account increased capacity, reduced energy footprint, as well as scalability and modularity for a smooth transition to 5G;
- **METIS-II**, which has developed an overall 5G RAN design, focusing on the efficient integration of evolved legacy and novel air interface variants (AIVs), and the support of network slicing;
- **mmMAGIC**, which has developed new RAN architecture concepts for millimeter-wave (mmWave) radio access technology, including its integration with lower frequency bands;
- **Selfnet**, which has developed an autonomic network management framework to achieve self-organizing capabilities in managing network infrastructures by automatically detecting and mitigating a range of common network problems; and finally
- **SPEED-5G**, which has investigated resource management techniques across technology 'silos', and medium access technologies to address densification in mostly unplanned environments.

The combined overall 5G timeline regarding the planned trials, 3GPP standardization, the IMT-2020 process of ITU, and 5G PPP is depicted in Figure 1-2, and detailed further in Chapter 17.

In a nutshell, while the finalization of the first features of 5G are ongoing these days, this book offers a clear overview of what the complete 5G system design could be at the end of the standardization phase, and even beyond, with an exploration of innovative features that may only be fully exploited far beyond 2020. The book is thus useful not only to have a clear understanding of what the current 3GPP specification defines, but also to have inspirations on future trends in research to further develop the 5G system and improve its performance.

1.3 Scope of the 5G System Described in this Book

The system design described in this book aims to capture the *complete* 5G system that is expected to exist after several 3GPP releases, which will meet or exceed the IMT-2020 requirements, and which will address the whole range of envisioned eMBB, URLLC and mMTC services as introduced at the beginning of this chapter and detailed in Section 2.2. Also, the book does not only describe 5G design aspects that are subject to standardization, but also concepts that may be proprietarily implemented, such as resource management (RM) strategies, orchestration frameworks, or general enablers of the 5G system that are independent of a particular standards release. Consequently, the book clearly goes beyond the scope of 3GPP NR Release 15, and covers aspects that are expected to be relevant in the Release 16 and 17 time frame, or further beyond, as illustrated in Figure 1-3.

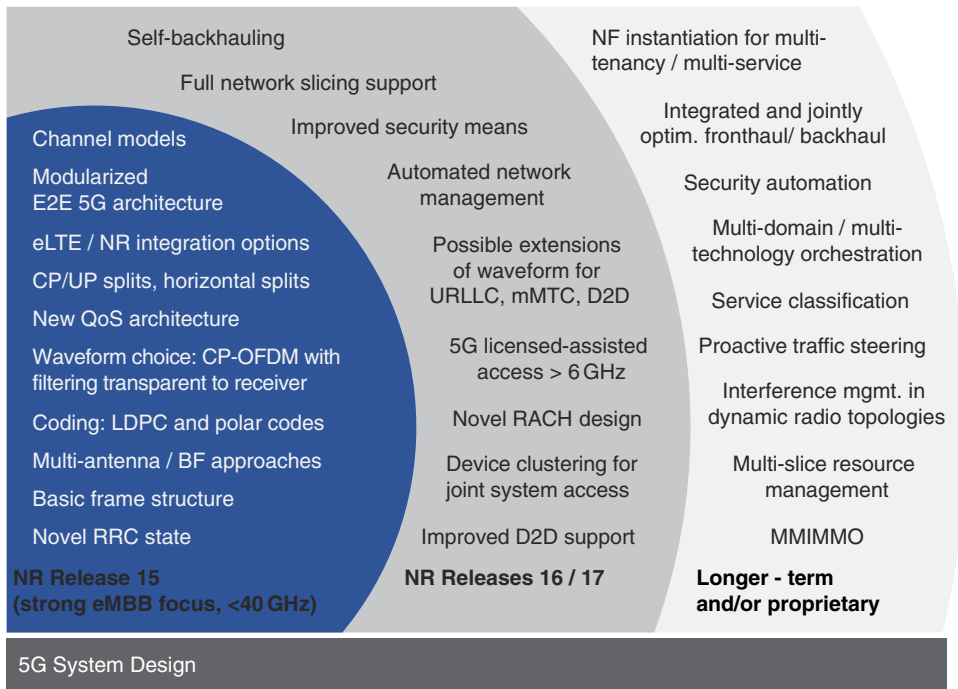**Figure 1-3.** Illustration of the scope of the 5G system design covered in this book, in the form of few selected examples of the many topics covered in the book.

Just to provide some examples, for **NR Release 15** (including the "early drop"), the book covers all the early conclusions that have been drawn in 3GPP, for instance on:

- The extended channel models to be used for 5G (see Chapter 4);
- The overall modularized E2E 5G architecture that 3GPP has defined (Section 5.4.1), the various options for eLTE/NR integration (Section 5.5), and the forms of control/user plane (CP/UP) and horizontal RAN function splits that are envisioned (Section 6.6);
- The new QoS architecture that enables a dynamic mapping of so-called *QoS flows* to data radio bearers on RAN level (Sections 5.3.3 and 12.2.1);
- The waveform choice (Section 11.3), coding approaches (Section 11.4), multi-antenna and beam-forming support (Section 11.5) and basic frame structure (Section 11.6);
- The introduction of a new RRC state (Section 11.3) and related signalling optimizations.

As possible candidates for standardization in **NR Releases 16 or 17**, the book, for instance, covers:

- Self-backhauling, i.e., the usage of the same radio interface and spectrum for backhaul and access links (see Section 7.4);
- The extension of NR towards full network slicing support (Chapter 8);
- Improved security means and related architecture for 5G (Section 9.4);
- Automated network management and orchestration for 5G (Section 10.7);
- Possible extensions of waveforms for specific URLLC and mMTC services (Section 11.3) or better D2D support (Section 14.3);
- 5G licensed-assisted access (LAA) to enable NR operation in unlicensed bands, also above 6 GHz (Section 12.5.1);
- Novel Random Access CHannel (RACH) design for service prioritization already at initial access (Section 13.2);
- Device clustering for joint system access (Sections 13.2.6 and 13.4.2);
- Improved D2D support, e.g., through sidelink mobility management (Section 14.5).

Finally, the book also covers various concepts that are of further **longer-term nature**, and/or which could be **implemented proprietarily**, for instance:

- Network function instantiation for multi-tenancy and multi-service support (see Section 6.4.4);
- Integrated and jointly optimized fronthaul and backhaul (Section 7.6);
- Security automation (Section 9.4.6);
- Orchestration in multi-domain and multi-technology scenarios (Section 10.4);
- Machine-learning based service classification (Section 12.2);
- Proactive traffic steering that provides an early assessment of mmWave links to reduce link failures (Section 12.4.2);
- Interference management in dynamic radio topologies, for instance involving moving access nodes and related novel interference challenges (Section 12.5.1);
- Multi-slice resource management, based on real-time SLA monitoring and ensuring SLA fulfilment via slice-specific QoS enforcement (Section 12.6);
- Massive multiple-input massive multiple output (MMIMMO) involving a large number of antenna elements at both transmitter and receiver side (Section 11.5.4);
- Detailed hardware and software implementation considerations, based on flexible HW/SW partitioning (Chapter 16).

1.4 Approach and Structure of this Book

Several books on 5G have already been published. For instance, [24] and [10] have focused on identifying the main use cases for 5G and their requirements, as well as key technology components needed to address these. The authors of [25] have focused in particular on signal processing challenges related to 5G, for instance in the context of novel waveforms or massive multiple-input multiple-output (MIMO), while [26] takes a bit more critical stand on 5G, pointing out that continuous connectivity may be more relevant in the 5G era than ultra-high peak data rates in hotspots, and that many of the often claimed 5G capabilities are economically questionable. [27] views 5G from a R&D technical design perspective, with a particular focus on the physical layer, while [28] focuses on key protocols, network architectures and techniques considered for 5G The authors in [29] focus on mmWave and massive MIMO communications as specific technology components in 5G, while the authors in [30] delve into simulation and evaluation methodology for 5G, and [31] focuses on the specific usage of 5G for the Internet of Things.

This book differs from all mentioned publications in that it does not describe single 5G technology components, but rather captures the complete 5G system in its likely overall system design, i.e., covering all technology layers that are required to operate a complete 5G system. For this reason, the book does not contain chapters on typical 5G keywords such as massive MIMO, mmWave communications, or URLLC support, but instead describes the system from an overall architecture perspective and then layer-by-layer, inherently always covering all relevant components on each layer, and covering the support of all three main 5G service types stated before.

Further, this book is unique in that it is based on consolidated contributions from 158 authors from 54 companies, institutes or regional bodies, hence capturing the consensus on 5G that has already been obtained by key stakeholders, while also stressing the diversity of further system design concepts that have been raised, but not yet agreed, and which could hence appear in future 3GPP releases.

While this book is to a large extent based on the results of European Commission funded 5G PPP projects, as mentioned in Section 1.2, the fact that there are also many non-European partners involved in these projects ensures that the book does not only represent a purely European view. Further, various authors from outside Europe and outside the 5G PPP ecosystem have been invited to contribute to this book, for instance to Chapter 17 on the global deployment plans for 5G, to ensure that the book can legitimately claim to capture a global view on 5G.

This book is written such that it should be decently easily digestible for persons who are not yet familiar with cellular communications in general or with 5G, through detailed introductions and explanations of all covered topics, while also providing significant technical details for experts in the field. Naturally, a key challenge inherent to writing a book on a technology that is yet in the process of standardization, in particular a technology that is being as pushed and accelerated as 5G, is that certain technical details of the book may quickly become outdated. For instance, it is almost inevitable that there are aspects described in this book which are marked as "under discussion", which may have already been agreed upon or dropped by 3GPP by the time the book is published. For this reason, the book does not aim to meticulously capture the latest agreements in 3GPP, but rather explain general 5G design decisions from a more didactic perspective, also elaborating on the advantages and disadvantages of concepts that may have already been discarded in 3GPP, or which may be far further down the 5G horizon than what is currently covered in 3GPP. This way, the book is expected to also serve as a good *reference book* on cellular communication system design in general, irrespective of the specific road taken by 3GPP.

This book is structured into 4 parts, which are shortly introduced in the following:

Part 1 – Introduction and Basics

This part of the book sets the scene for the following parts, and in particular covers various basic aspects related to the expected 5G ecosystem and the spectrum usage in 5G, which are central to many 5G system design aspects discussed in the subsequent parts of the book. Beyond this introduction chapter, **Chapter 2**, for instance, covers the main service types and use cases typically considered for 5G, and elaborates on the related requirements and the expected transformation of the mobile network ecosystem in the context of 5G. **Chapter 3** ventures into spectrum usage in the 5G era, in particular stressing the need for different spectrum sharing forms, and the usage of diverse frequency bands from the sub-6 GHz regime up to 100 GHz, in order to address the diverse and stringent 5G requirements. **Chapter 4** then builds upon this and introduces the reader to the particular propagation challenges inherent in the usage of higher frequency bands in 5G, and the additional channel models that had to be introduced to be able to design and evaluate a 5G system appropriately.

Part 2 – 5G System Architecture and E2E Enablers

This largest part of the book then focuses on the architecture of the 5G system, and various required E2E enablers. Here, **Chapter 5** initially provides the big picture on the 5G E2E architecture, covering everything from the core network to transport network and radio access network (RAN), and introducing various general design principles, such as modularization, softwarization, network slicing and multi-tenancy. **Chapter 6** then focuses on the 5G RAN architecture, for instance discussing changes in the protocol stack w.r.t. 4G and the notion of service-specific protocol stack optimization and instantiation. It further covers RAN-based multi-connectivity among (e)LTE and 5G or within 5G, horizontal and vertical function splits in the RAN, and subsequent deployments. **Chapter 7** then delves into the same level of detail on the transport network architecture, explaining a possible holistic user plane and control plane design for the transport network as well as available transport technologies and specific overall concepts, such as self-backhauling. Based on the previous chapters, **Chapter 8** then takes an E2E perspective again and covers in detail the establishment and management of network slices, constituting E2E logical networks that are each operated to serve a particular business need. **Chapter 9** addresses a topic that is essential especially in the context of the many new use cases and business forms envisioned in the 5G era, namely that of security, by elaborating on the main attack vectors to be considered, security requirements, and possible security architecture to address these. Finally, **Chapter 10** elaborates on how an overall 5G system incorporating the aspects introduced in the previous chapters, and in particular based on software-defined networking (SDN) and network function virtualization (NFV), can be efficiently managed and orchestrated.

Part 3 – 5G Functional Design

This part of the book then delves into the details of the functional design of the system. More precisely, **Chapter 11** describes the lower part of the RAN protocol stack, namely the physical layer and Medium Access Control (MAC) layer, covering topics such as waveform design, coding, Hybrid Automatic Repeat reQuest (HARQ), frame design and massive MIMO. **Chapter 12** deals with traffic

steering and resource management, which play a critical role to fulfil the stringent service and slice requirements envisioned for 5G in the context of highly heterogeneous networks. In particular, the chapter covers the classification of traffic, the fast steering of traffic to different radio interfaces, dynamic multi-service or multi-slice scheduling, interference management and RAN moderation. **Chapter 13** handles the control plane procedures for the access of user equipments (UEs) to the network, state handling and mobility, in particular covering novelties in 5G such as an extended Radio Resource Control (RRC) state machine and further means to reduce control plane latency in 5G and support a larger number of devices and diverse service requirements. Finally, **Chapter 14** delves into specific functionalities related to D2D and vehicular-to-anything (V2X) communications, also providing an in-depth background and implementation details on the usage of cellular technologies for Intelligent Transport Systems (ITS).

Part 4 – Performance Evaluation and Implementation

This part of the book finally focuses on vary practical aspects related to the development, implementation and roll-out of 5G technology. **Chapter 15**, for instance, focuses on evaluation methodology for 5G that allows to quantify the performance of key 5G design concepts long before any type of hardware and field implementation is available. Further, the chapter introduces the methodology and results related to the evaluation of 5G deployments from an energy efficiency and techno-economic perspective. Next, **Chapter 16** is dedicated to the implementation of 5G concepts and components from a hardware and software perspective, considering for instance the need for increased hardware versatility and the ability to operate with increasingly higher bandwidths and related data rates, especially at mmWave bands. The chapter explicitly also covers the notion of flexible hardware/software partitioning and contains a detailed study on practical virtualized RAN deployments for 5G. Finally, the book is concluded with **Chapter 17**, which presents the roadmap of the expected standardization and regulation activities towards a full 5G system deployment and covers trials and early commercialization plans in the three regions Europe, Americas and Asia.

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