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## Introduction and Motivation

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### 1.1 5<sup>th</sup> Generation Mobile and Wireless Communications

The 5<sup>th</sup> 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<sup>1</sup>, 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

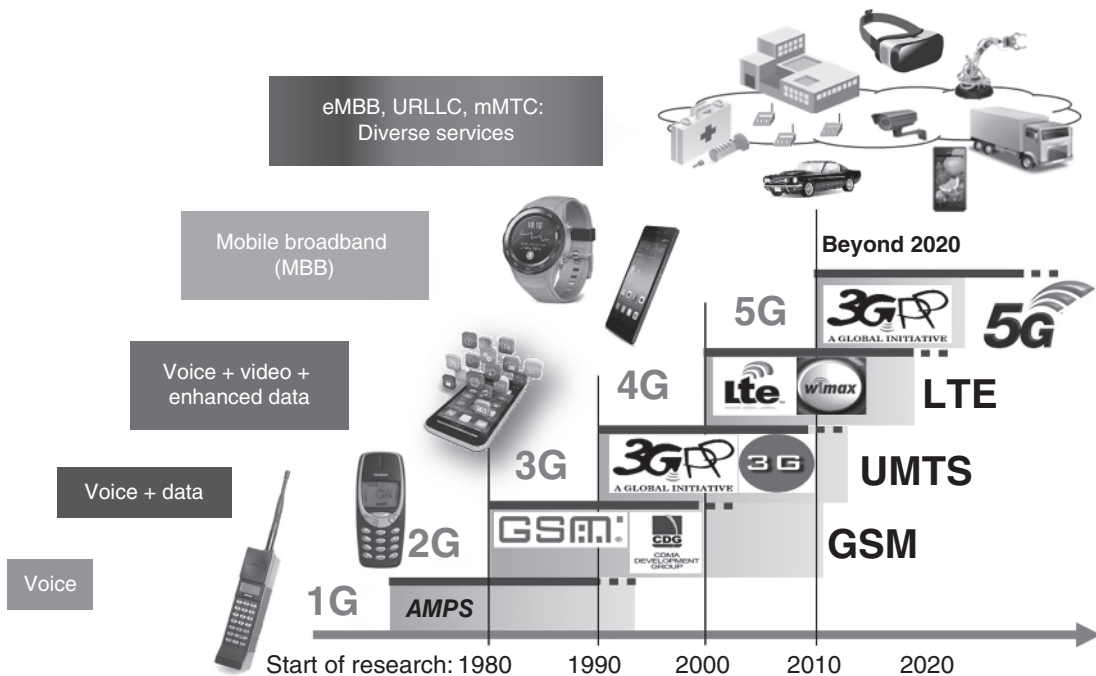


Figure 1-1. Main drivers behind past cellular communications generations and 5G.

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 show-stopper 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;

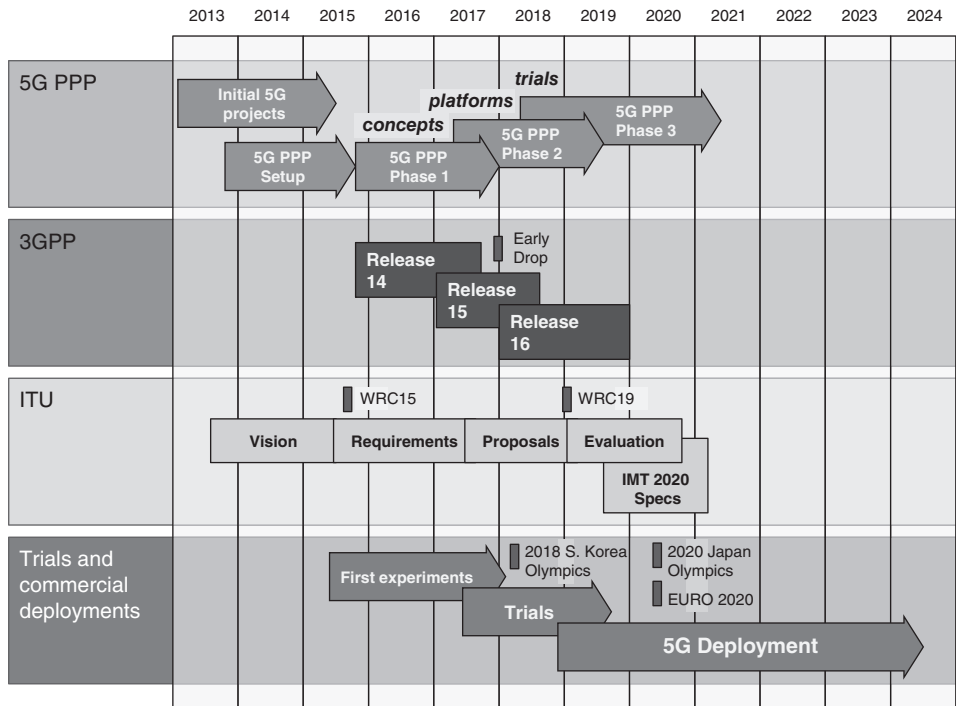


Figure 1-2. Combined overall 5G timeline of the mentioned different bodies.

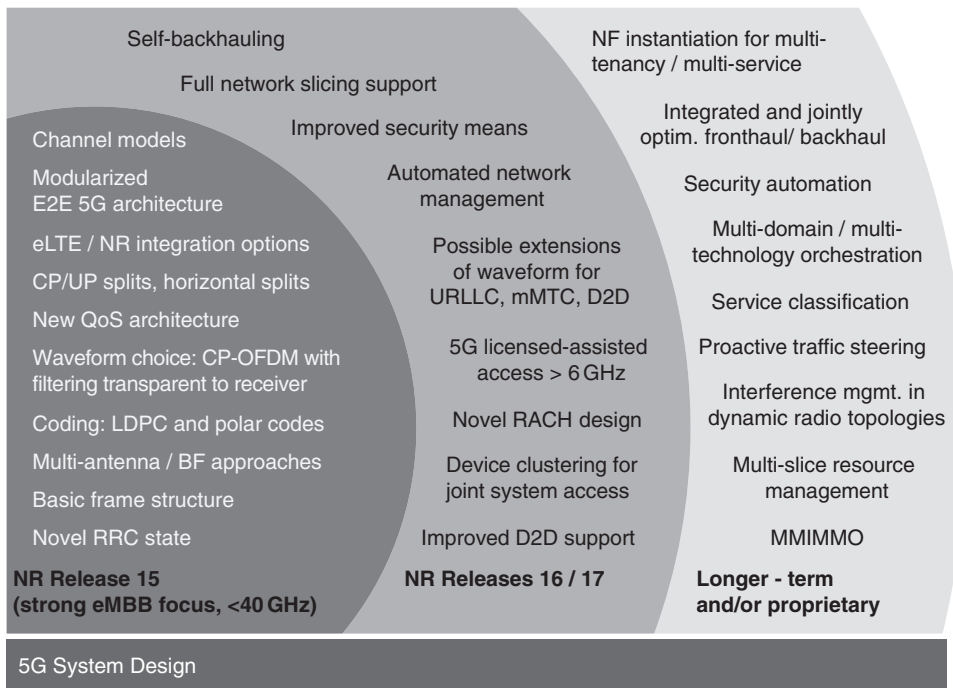
- **5G-Xhaul**, which has developed a converged optical and wireless network solution able to flexibly connect small cells to the core network;
- **COHERENT**, which has developed a unified programmable control framework for coordination and flexible spectrum management in 5G heterogeneous access networks;
- **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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