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.

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- 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

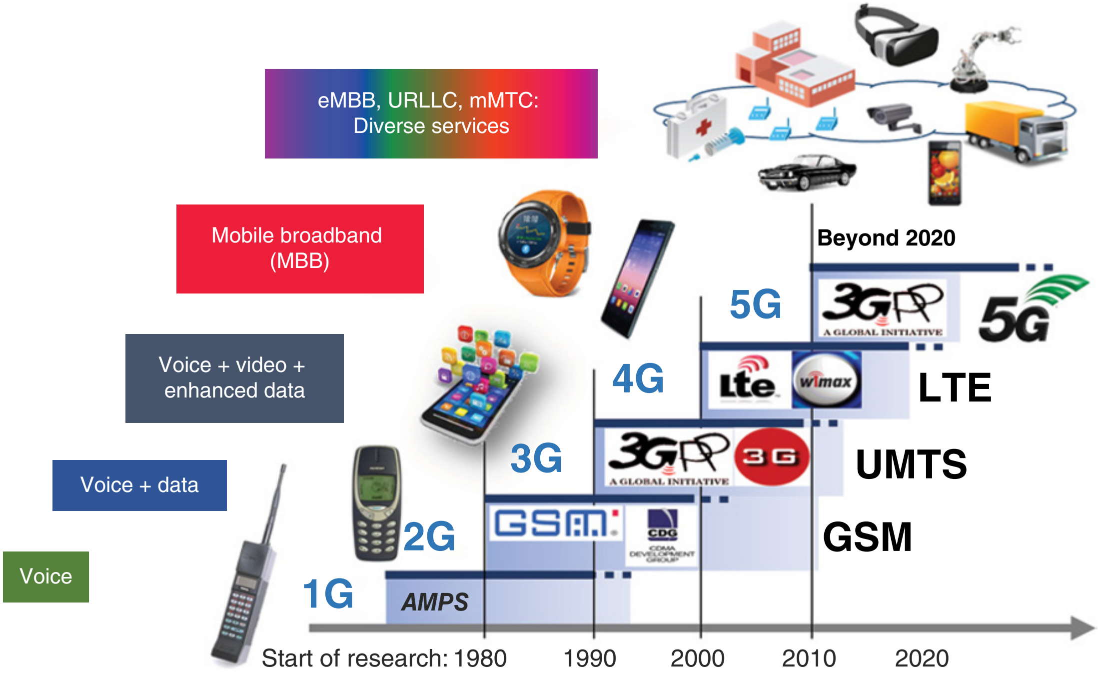

Figure 1-1. Main drivers behind past cellular communications generations and 5G.

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;

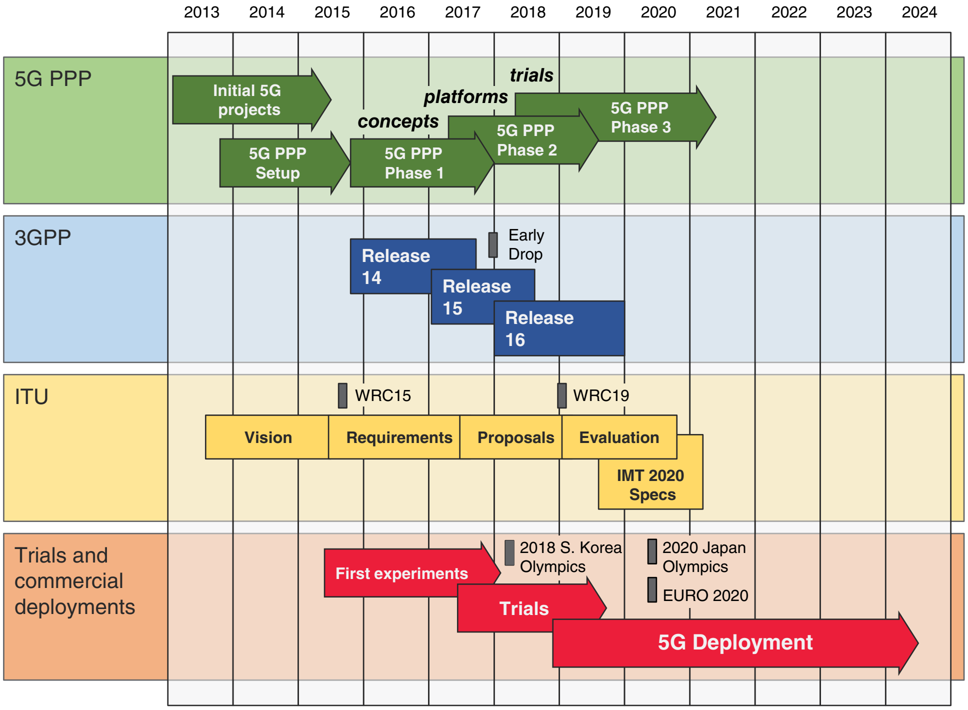

Figure 1-2. Combined overall 5G timeline of the mentioned different bodies.

- **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.

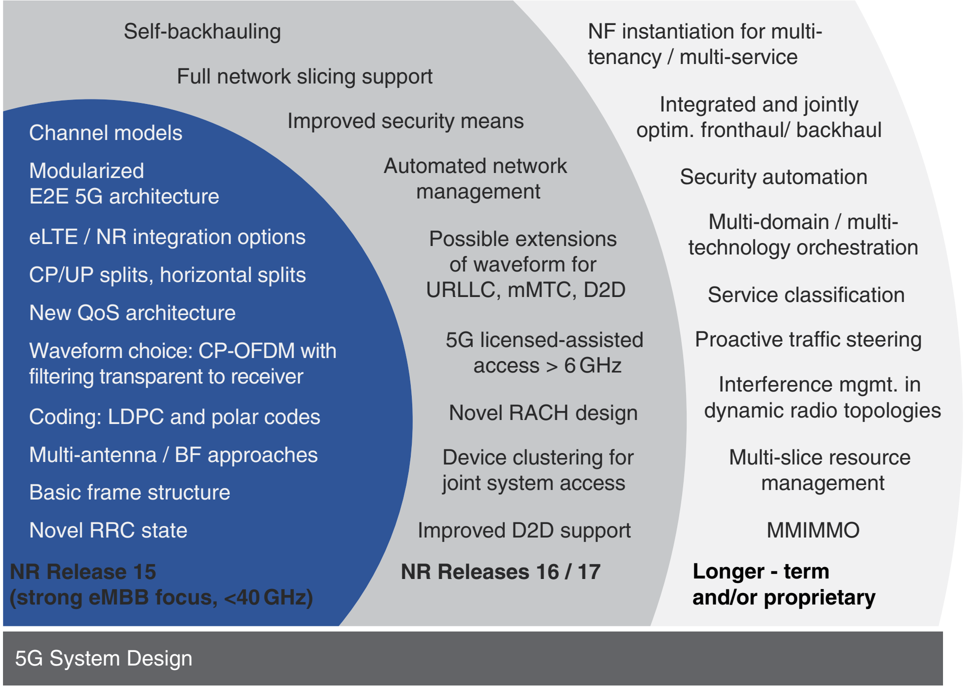

Figure 1-3. Illustration of the scope of the 5G system design covered in this book, in the form of few selected examples of the many topics covered in the book.

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 beamforming 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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2

Use Cases, Scenarios, and their Impact on the Mobile Network Ecosystem

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2.1 Introduction

This chapter delves in detail into the use cases (UCs) widely assumed to be addressed by the 5th generation (5G) wireless and mobile communications system, and the related requirements. In particular, this chapter takes into consideration and aggregates the requirements from different bodies like the International Telecommunication Union (ITU), Next Generation Mobile Networks (NGMN), and the 5G Public Private Partnership (5G PPP). The next part of the chapter is an analysis of the 5G ecosystem evolutions that are needed, and the novel value chains that can be expected for some UCs.

The chapter is structured as follows. The main service types considered for 5G are initially introduced in Section 2.2, before their detailed requirements are discussed in Section 2.3. Section 2.4 then presents key 5G UCs as considered by NGMN and different 5G PPP research projects, and Section 2.5 elaborates particularly in the UCs further discussed in specific parts of this book. Section 2.6 then delves into the likely ecosystem evolutions from a 5G mobile network perspective, with emerging value chains of mobile network operators (MNOs), before the chapter is summarized in Section 2.7.

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2.2 Main Service Types Considered for 5G

After several years of research and standardization on 5G wireless and mobile communications, there is broad consensus on the fact that 5G will not just be a simple evolution of 4G networks with new spectrum bands, higher spectral efficiencies and higher peak throughput, but also target new services and business models. In this respect, the main 5G service types typically considered are:

- **Enhanced mobile broadband (eMBB)**, related to human-centric and enhanced access to multimedia content, services and data with improved performance and increasingly seamless user experience. This service type, which can be seen as an evolution of the services nowadays provided by 4G networks, covers UCs with very different requirements, e.g. ranging from hotspot UCs characterized by a high user density, very high traffic capacity and low user mobility, to wide area coverage cases with medium to high user mobility, but the need for seamless radio coverage practically anywhere and anytime with visibly improved user data rates compared to today;
- **Ultra-reliable and low-latency communications (URLLC)**, related to UCs with stringent requirements for capabilities such as latency, reliability and availability. Examples include the wireless control of industrial manufacturing or production processes, remote medical surgery, distribution automation in a smart grid, transportation safety, etc. It is expected that URLLC services will provide a main part of the fundament for the 4th industrial revolution (often referred to as Industry 4.0) and have a substantial impact on industries far beyond the information and communication technology (ICT) industry;
- **Massive machine-type communications (mMTC)**, capturing services that are characterized by a very large number of connected devices typically transmitting a relatively low volume of non-delay-sensitive data. However, the key challenge is here that devices are usually required to be low-cost, and have a very long battery lifetime. Key examples for this service type would be logistics applications (e.g., involving the tracking of tagged objects), smart metering, or for instance agricultural applications where small, low-cost and low-power sensors are sprinkled over large areas to measure ground humidity, fertility, etc.

It is worth noting that these three service types have been considered quite early in the METIS project [1], under the names of extreme mobile broadband (xMBB, equivalent to eMBB), ultra-reliable machine-type communications (uMTC, equivalent to URLLC) and mMTC. They have also been adopted by ITU-R Working Party 5D (WP5D), who have recently issued the draft new recommendation “IMT Vision - Framework and overall objectives of the future development of IMT for 2020 and beyond” [2], where IMT stands for International Mobile Telecommunications.

It should further be stressed that many services envisioned in the 5G era cannot easily be mapped to one of the three main service types as listed above, as they combine the challenges and requirements related to multiple service types. As an example, augmented reality is expected to play a major role in the 5G era, where information is overlaid to the real environment for the purpose of education, safety, training or gaming, and which poses high requirements on both throughput and latency. Similarly, some Factory of the Future [3] related UCs foresee the wireless communication of items in a factory environment where both energy efficiency and latency play a strong role. Especially such compound use cases combining different types of requirements ultimately pose the strongest challenges towards the development of the 5G system.

It goes without saying that considering each service type, or even single UCs, separately and building a 5G network accordingly, one would likely end up with very different 5G system designs and architectures. However, only a common design that accommodates all three service types is seen as an economically and environmentally sustainable solution, as discussed in more detail in Sections 15.3 and 15.4 on energy efficiency and techno-economic assessment, respectively. In the following, we briefly present the groups of 5G UCs typically found in literature, which have been proposed as representative and specific embodiments of the three service types or mixtures thereof, with the main aim to understand the scenarios envisaged in the 2020-2030 time horizon and have a reference for the development of the 5G system. We first start, in the next section, by listing the detailed requirements of these main 5G UCs.

2.3 5G Service Requirements

Even if the qualitative requirements of the three main 5G service types can be roughly understood from their description, there is a need for defining them in quantitative terms. Towards this aim, the ITU-R has considered a set of parameters to be key capabilities of IMT-2020 [3]:

- **Peak data rate**, referring to the maximum achievable data rate under ideal conditions per user or device in bits per second. The minimum 5G requirements for peak data rate are 20 Gbps in the downlink (DL) and 10 Gbps in the uplink (UL);
- **Peak spectral efficiency**, defined as the maximum data rate under ideal conditions normalized by the channel bandwidth, in bps/Hz. The target set by ITU-R is 30 bps/Hz in the DL and 15 bps/Hz in the UL. The combination of this key performance indicator (KPI) and the aforementioned peak data rate requirement results in the need for 2-3 GHz of spectrum to meet the stated requirements;
- **User experienced data rate**, referring to the achievable data rate that is available ubiquitously across the coverage area to a mobile user or device in bits per second. This KPI corresponds to the 5% point of the cumulative distribution function (CDF) of the user throughput, and represents a kind of minimum user experience in the coverage area. This requirement is set by ITU-R to 100 Mbps in the DL and 50 Mbps in the UL;
- **5th percentile user spectral efficiency**, referring to the 5% point of the CDF of the user throughput normalized by the channel bandwidth in bps/Hz. The minimum requirements for this KPI depend on the test environments as follows:
  - Indoor Hotspot: 0.3 bps/Hz in the DL, 0.21 bps/Hz in the UL;
  - Dense Urban: 0.225 bps/Hz in the DL, 0.15 bps/Hz in the UL;
  - Rural: 0.12 bps/Hz in the DL, 0.045 bps/Hz in the UL.
- **Average spectral efficiency**, also known as spectrum efficiency and defined as the average data throughput per unit of spectrum resource and per cell in bps/Hz/cell. Again, the minimum requirements depend on the test environments as follows:
  - Indoor Hotspot: 9 bps/Hz/cell in the DL, 6.75 bps/Hz/cell in the UL;
  - Dense Urban: 7.8 bps/Hz/cell in the DL, 5.4 bps/Hz/cell in the UL;
  - Rural: 3.3 bps/Hz/cell in the DL, 1.6 bps/Hz/cell in the UL.
- **Area traffic capacity**, defined as the total traffic throughput served per geographic area in Mbps/m^2. ITU-R has defined this objective only for the indoor hotspot case, with a target of 10 Mbps/m^2 for the DL;
- **User plane latency**, given as the contribution of the radio network to the time from when the source sends a packet to when the destination receives it. The one-way end-to-end (E2E) latency requirement is set to 4 ms for eMBB services and 1 ms for URLLC;

- **Control plane latency**, reflecting the transition time from idle to active state. The objective is to make this transition in less than 20 ms;
- **Connection density**, corresponding to the total number of connected and/or accessible devices per unit area. ITU-R has specified a target of 1 000 000 devices per km^2 for mMTC services;
- **Energy efficiency**, on the network side referring to the quantity of information bits transmitted to or received from users, per unit of energy consumption of the RAN, and on the device side to the quantity of information bits per unit of energy consumption of the communication module, in both cases in bits/Joule. The specification given by ITU-R in this respect is that IMT-2020 air interfaces must have the capability to support a high sleep ratio and long sleep duration;
- **Reliability**, defined as the success probability of transmitting a data packet before a given deadline. The target is to transmit Medium Access Control (MAC) packets of 32 bytes in less than 1 ms in the cell edge of the dense urban test environment with 99.999% probability;
- **Mobility**, here defined as the maximum speed at which a defined quality of service (QoS) and seamless transfer between radio nodes which may belong to different layers and/or radio access technologies can be achieved. For the rural test environment, the normalized traffic channel link data rate at 500 km/h, reflecting the average user spectral efficiency, must be larger than 0.45 bps/Hz in the UL;
- **Mobility interruption time**, being the time during which the device cannot exchange data packets because of handover procedures. The minimum requirement for mobility interruption time is 0 ms, essentially meaning that a *make-before-break* paradigm has to be applied, i.e., the connection to the new cell has to be set up before the old one is dropped;
- **Bandwidth**, referring to the maximum aggregated system bandwidth. At least 100 MHz must be supported, but ITU-R encourages proponents to support bandwidths of more than 1 GHz.

The set of the eight most significant capabilities expected for IMT-2020 are shown in Figure 2-1 (a), in comparison with those of IMT-Advanced. Since the importance of the achieved capability values is not the same for all three service types, the comparison among the service types is additionally given in Figure 2-1 (b).

As of energy efficiency, it is considered as an overall design goal for the entire 5G system. For eMBB services, the energy consumption on the infrastructure side is very important, while device battery life is critical for mMTC services. The METIS-II project adopted the principle that the energy efficiency improvement in 5G should follow at least the capacity improvement [5], i.e., the overall energy consumption should be similar or ideally lower than that in existing networks [6] [7], despite the large traffic growth. Since the 5G system is expected to see several hundred times or even a thousand times the traffic of legacy systems, while having the same or less energy consumption, network energy efficiency consequently also has to increase by a factor of several hundred times or a thousand.

2.4 Use Cases Considered in NGMN and 5G PPP Projects

Several 5G PPP projects have proposed new scenarios for identifying the requirements of 5G. Similarly, other initiatives like NGMN, and standardization bodies like 3GPP and ITU-R, have captured the respective requirements so as to drive the research for handling the future demands. This process has resulted in a large number of UCs with diverse requirements. The METIS-II project has

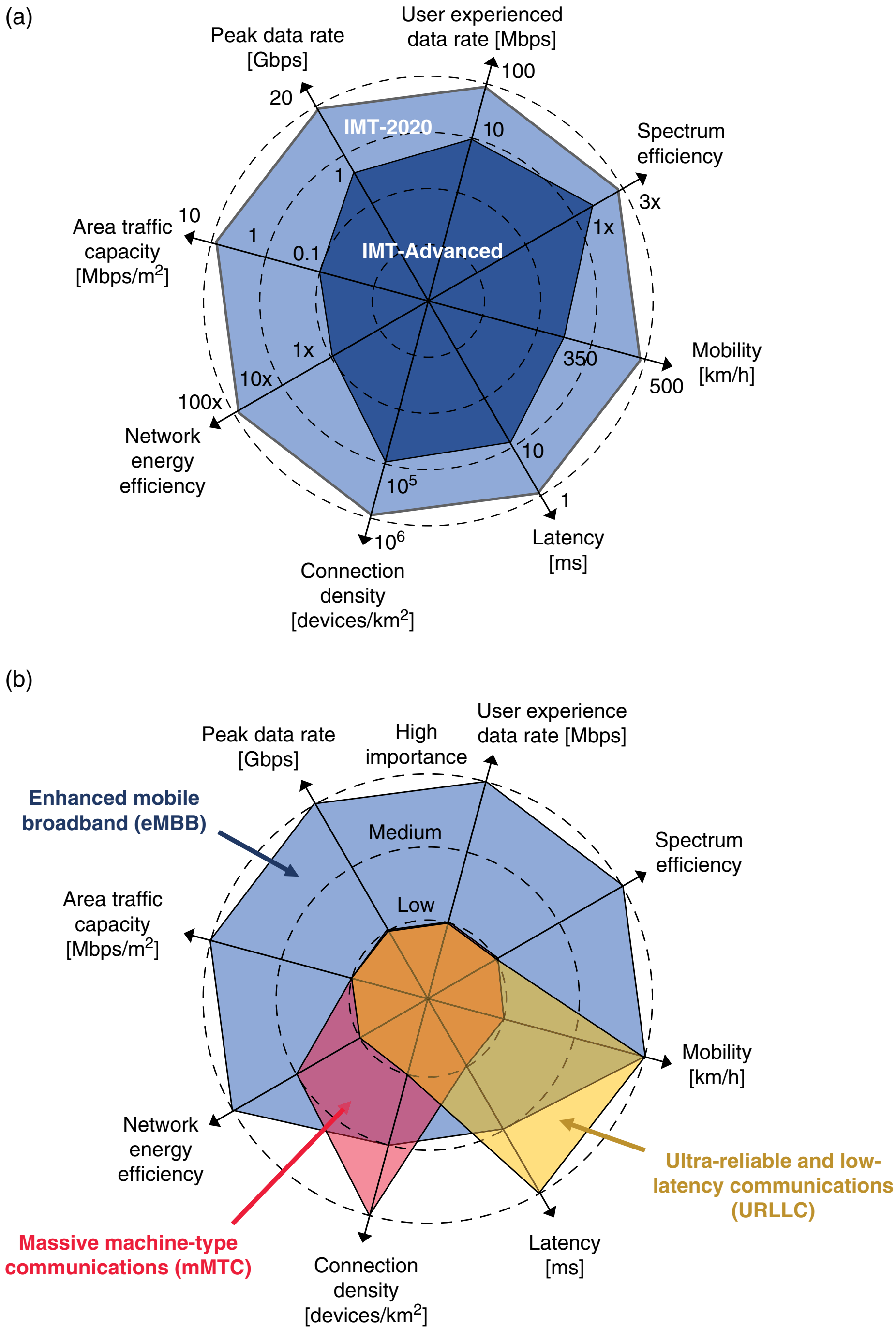

Figure 2-1. Key capabilities of IMT beyond 2020 [2]. a) Expected enhancements of IMT-2020 vs. IMT-Advanced. b) Importance of KPIs for different service types.

performed a detailed analysis of these in order to identify the similarities and the gaps between the already proposed UCs [4]. We present here a summary of this analysis of the challenging UCs originating from NGMN and from 5G PPP Phase 1 projects [7].

2.4.1 NGMN use Case Groups

According to NGMN [5], the business context beyond 2020 will be notably different from today, since it will have to handle the new UCs and business models driven by the customers' and operators' needs. According to the NGMN vision, 5G will have to support, apart from the evolution of mobile broadband, new UCs ranging from delay-sensitive video applications to ultra-low latency, from high speed entertainment applications in a vehicle to mobility for connected objects, and from best effort applications to reliable and ultra-reliable applications, for instance related to health and safety.

Thus, NGNM has performed a thorough analysis for capturing all the customers' and operators' needs. The analysis is based on 25 UCs for 5G grouped into eight UC families, as listed in Table 2-1 and illustrated in Figure 2-2. The UCs and UC families serve as an input for stipulating requirements and defining the building blocks of the 5G system design.

According to the NGMN 5G White Paper [5], the UC analysis is not exhaustive, though it provides a thorough and comprehensive analysis of the requirements of 5G. One can identify the key requirements and characteristics of each UC proposed by NGMN as listed in Table 2-1.

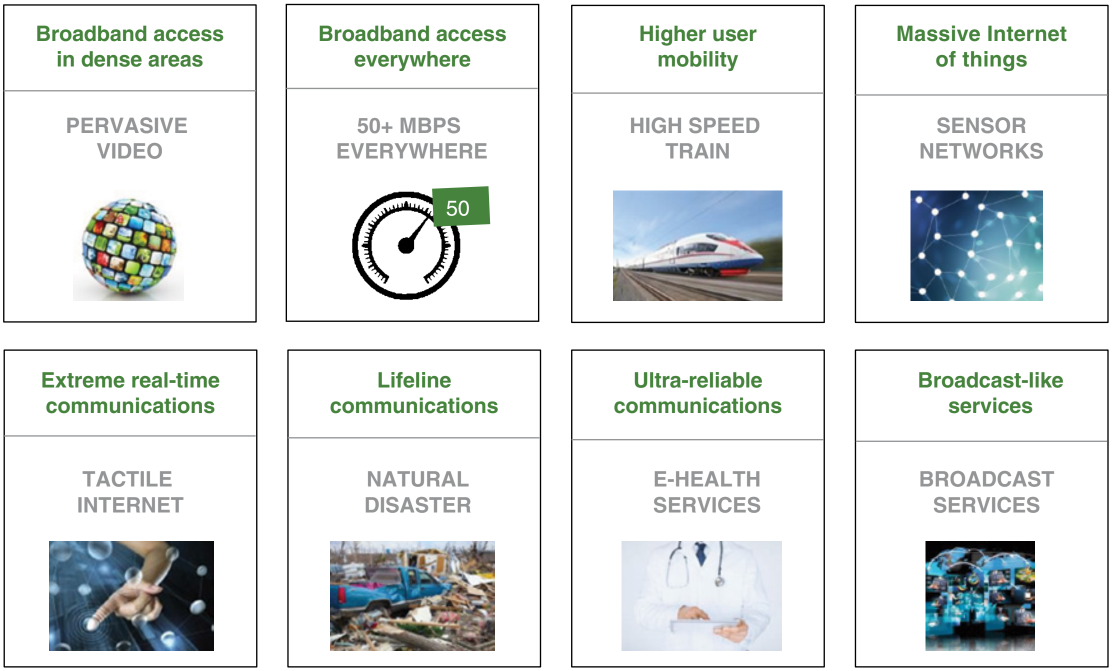

Figure 2-2. UC families considered by NGMN with representative UCs [6].

Table 2-1. NGMN use case analysis by their characteristics and the dominant 5G service type, with H = high, L = low, and M = medium denoting the stringency of requirements.

UC description		UC requirements						Service type		
UC	**UC name**	**Number of devices**	**Mobility**	**Traffic type**	**Latency**	**Reliability**	**Availability**	**eMBB**	**URLLC**	**mMTC**
1	Pervasive video	H	L	Continuous	L	-	L	X	-	-
2	Smart office	H	No	Continuous	L	-	L	X	-	-
3	Operator cloud services	H	Yes	Continuous	M	-	L	X	-	-
4	HD video/photo sharing in stadiums or open air gatherings	H	No	Continuous	M	-	H	X	-	-
5	50+ Mbps everywhere	L	H	Continuous	H	-	H	X	-	-
6	Ultra-low-cost networks	L	M	Continuous	M	-	L	X	-	-
7	High-speed train	M	H	All types	L	-	L	X	-	-
8	Remote computing	L	H	Continuous	L	-	L	X	-	-
9	Moving hotspots	L	H	Bursty	L	-	H	X	-	-
10	3D connectivity, e.g. for aircrafts	L	H	H	L	-	H	X	-	-
11	Smart wearables	H	H	Periodic	L	-	H	-	-	X
12	Sensor networks	H	L	Periodic	L	-	H	-	-	X
13	Mobile video surveillance	H	H	Continuous	L	-	H	X	-	X
14	Tactile Internet	H	H	Various types	L	H	H	-	X	-
15	Natural disaster	H	L	Short messages	H	H	H	-	X	X
16	Automated traffic control and driving	L	H	All types	L	H	H	-	X	-
17	Collaborative robots: A control network for robots	L	No	Continuous	L	H	H	-	X	-
18	eHealth: extreme life critical	H	No/L	Short messages	L	H	H	-	X	-

(Continued)

Table 2-1. (Continued)

UC description		UC requirements						Service type		
UC	**UC name**	**Number of devices**	**Mobility**	**Traffic type**	**Latency**	**Reliability**	**Availability**	**eMBB**	**URLLC**	**mMTC**
19	Remote object manipulation, e.g. for remote surgery	L	L	Continuous	L	H	H	-	X	-
20	3D connectivity, e.g. for drones	L	H	Continuous	L	H	H	-	X	-
21	Public safety	L	L	Continuous	L	H	H	-	X	-
22	News and information	H	H	All types	H	-	-	X	-	-
23	Local broadcast-like services	H	L	All types	H	-	-	X	-	-
24	Regional broadcast-like services	H	H	All types	H	-	-	X	-	-
25	National broadcast-like services	H	H	All types	H	-	-	X	-	-

2.4.2 Use Case Groups from 5G PPP Phase 1 Projects

Taking into consideration the rich literature of 5G UCs and scenarios including those of NGMN described before, 5G PPP Phase 1 projects have defined a set of UCs with the aim of evaluating the technological and architectural innovations developed in the projects. Without entering into the details of each project UC, we present here a grouping of these UCs and a mapping between these and the business cases identified in vertical industries.

Even if different 5G PPP projects have defined their own UCs, an in-depth analysis of these reveals strong similarities. This is because all 5G PPP projects agree on the three 5G service types listed in Section 2.2, and start in their UC definitions from the results of the METIS project, NGMN, ITU and other fora.

The UCs of 5G PPP Phase 1 projects can, ultimately, be classified into six families, as described in the 5G PPP White Paper on UCs and performance models [8] and detailed in Table 2-2.

This classification into UC families allows having a general idea on the individual UCs and their requirements, e.g., a UC belonging to the family "Future smart offices" is necessarily characterized by an indoor environment and very high user rates. However, this general classification does not reveal the detailed requirements of the UC, which may differ depending on the targeted application. Some UC families may feature enhanced diversity in terms of mixed requirements as well as mixed application environments, an example being the "Dense urban" UC family, where early 5G users could experience services demanding extreme data rates, such as virtual reality and ultra-high definition video in both indoor and outdoor environments, both requiring very high data rates but having heterogeneous latency requirements.

2.4.3 Mapping of the 5G-PPP Use Case Families to the Vertical Use Cases

While the 5G PPP projects have been intentionally mixing services with different requirements for the purpose of challenging the 5G RAN design, the 5G Infrastructure Association (5G IA), i.e. the private side of the 5G PPP including industry manufacturers, telecommunications operators, service providers and SMEs, has adopted a vertical industry driven approach in its business case definition,

Table 2-2. 5G PPP Phase 1 use case families.

Group	Description
Dense urban	Indoor and outdoor UCs, all in a dense urban environment
Broadband (50+ Mbps) everywhere	UCs that focus on suburban, rural environments and high speed trains
Connected vehicles	UCs containing URLLC and/or eMBB services related to vehicles, i.e. vehicle-to-vehicle (V2V) and/or vehicle-to-anything (V2X) applications
Future smart offices	UCs with very high data rates and low latency, indoor
Low-bandwidth Internet of Things (IoT)	UCs with a very large number of connected objects
Tactile Internet and automation	UCs with ultra-reliable communication and eMBB flavor

where each business case describes a specific vertical need and its requirements, as described in the 5G PPP White Paper on vertical requirements [8]. Table 2-3 illustrates the ambition of 5G PPP for a 5G network federating the needs of vertical industries.

Having a closer look at the business cases of Table 2-3, we can see that the 5G PPP UC families cover the requirements of most of them. Consequently, Table 2-4 highlights the relationship between the 8 NGMN UC families, the 6 5G PPP UC families and the main 5G service types.

Table 2-3. Vertical industry business cases.

Vertical Industry	Associated business cases	Corresponding 5G PPP use case families
Automotive	A1-Automated driving A2-Road safety and traffic efficiency services A3-Digitalization of transport and logistics A4-Intelligent navigation A5-Information society on the road A6-Nomadic nodes	Connected vehicles
eHealth	H1-Assets and interventions management in hospitals H2-Robotics (remote surgery, cloud service robotics for assisted living) H3-Remote monitoring of health or wellness data H4-Smarter medication	Dense urban (H3, H4) Broadband everywhere (H3, H4) IoT (H3) Tactile Internet (H2, H3)
Energy	E1-Grid access E2-Grid backhaul E3-Grid backbone	Dense urban (E1) Broadband everywhere (E3) IoT (E1) Tactile Internet (E2, E3)
Media & Entertainment	ME1-Ultra high fidelity media ME2-On-site live event experience ME3-User generated content & machine generated content ME4-Immersive and integrated media ME5-Cooperative media production ME6-Collaborative gaming	Dense urban (ME2, ME6) Broadband everywhere (ME1, ME3, ME4) Future smart offices (ME5)
Factories of the future	F1-Time-critical process optimization inside factory to support zero-defect manufacturing F2-Non time-critical optimizations inside factory to realize increased flexibility and eco-sustainability, and to increase operational efficiency F3-Remote maintenance and control optimizing the cost of operation while increasing uptime F4-Seamless intra-/inter-enterprise communication, allowing the monitoring of assets distributed in larger areas, the efficient coordination of cross value chain activities and the optimization of logistic flows F5-Connected goods, to facilitate the creation of new value added services	Dense urban (F2, F3, F4, F5) Broadband everywhere (F2, F4) IoT (F5) Tactile Internet (F1, F3)

Table 2-4. Relationship between the NGMN use case families, 5G PPP use case families and the three main 5G service types.

NGMN UC families	5G PPP UC families	5G service types
Broadband access in dense areas	Dense urban, Future smart offices	eMBB
Broadband access everywhere	Broadband (50+ Mbps) everywhere	
Broadcast-like services		
Higher user mobility		
Massive Internet of Things	Low-bandwidth IoT	mMTC
Extreme real-time communications Lifeline communications	Tactile Internet and automation	URLLC
Ultra-reliable communications	Connected vehicles	

2.5 Typical Use Cases Considered in this Book

Although the different chapters of this book focus on different aspects of the system design and do not necessarily investigate specific UCs, there are several UCs that are mostly represented in the book, in particular when it comes to performance evaluation, as covered in detail in Chapter 15. This section gives additional context and explanations for setting certain 5G KPI requirements in these representative UCs.

2.5.1 Dense Urban Information Society

Dense urban information society is a UC referring to the connectivity requirements of humans living in dense urban areas. This environment can host each of the 5G generic service types as defined in Section 2.2: high data rates of eMBB for both indoor and outdoor users, a massive number of mMTC transmissions (despite the limited area, the 3D distribution of mMTC devices pushes the overall number of communicating machines to the extreme), and the presence of URLLC, e.g., for vehicles. Such combination of services makes this environment critical when considering potential 5G solutions.

Evaluation results for dense urban information society presented in this book, e.g. in Section 15.2, focus on challenges of eMBB communication for human-generated and human-consumed traffic. eMBB users are located both indoors (following a 3D distribution) and outdoors. 5G should be able to provide public cloud services with expected user throughputs of up to 300 and 50 Mbps in DL and UL, respectively. In case of transmissions used by device-centric services, as for instance the communication between user equipments (UEs) or sensors, the required user throughput is in the range of 10 Mbps. Altogether, the 5G network is required to maintain those data rates for 95% of locations and time, for the users that on average generate a traffic volume of 500 GBytes per month. These assumptions lead to the overall traffic volume density of 750 and 125 Gbps/km^2 in the busy hour for DL and UL, respectively. Finally, the network should achieve this performance while taking into account cost and energy consumption. These expenses should be at the similar level as today's expenses for both infrastructure and broadband UE devices.

To efficiently cope with the uneven distribution of the traffic in dense urban environments, radio access sites are deployed in a heterogeneous network (HetNet) configuration. On one hand, an urban macro layer provides wide network coverage and caters for the edge users' experience and for the users on the move. To enable high data rates and relatively wide coverage, macro stations operate at a carrier frequency of, e.g., 3.5 GHz and are deployed every, e.g., 200 m, with antennas above the rooftop level. On the other hand, a small cell base station (BS) layer boosts available capacity over specific areas. To avoid heavy interference, small cell BSs are deployed with the minimum distance of 20 m between each other. They operate at millimetre-wave (mmWave) frequencies around 30 GHz and utilize a total system bandwidth of about 800 MHz. In contrary to macro BSs, antennas of small cells are located below the roof-top level, e.g., on the lamp post. Both cell types are expected to exploit massive antenna arrays.

2.5.2 Smart City

The main idea behind the Smart City concept is to exploit wireless communication of mMTC and IoT devices, to improve the overall quality of urban life, as also discussed in the context of early 5G trials in Section 17.3.1. This improvement can manifest in various ways, e.g., through a more efficient usage of utilities, better health and social care, or even faster public transport. To achieve this effect, low-cost and low energy consumption devices interact with each other or with city dwellers through applications running, e.g., directly in their own smartphones or in the cloud. As the legacy cellular systems were initially developed for broadband applications and the notion of Smart Cities only arose when the standard was already mature, 5G has the chance to provide a native support for this UC to fully address its expectations in a cost-efficient manner.

Although there are numerous applications related to Smart City concepts, out of which some are already implemented while new ones are constantly developed, there are certain challenges related to wireless communication that are common to the majority of appliances, and which 5G should address. Coverage, often characterized by the maximum coupling loss of the radio link, is one of such challenges. It is commonly associated with rural deployments, but the extensive penetration losses related to the attenuation or radio signal while propagating through building walls for indoor devices may be a crucial factor (e.g., for the case of a gas meter located in a basement). Coverage is also directly linked with the availability of a given service in an urban area, which is expected to be at the level of at least 99.9%. Another crucial metric is the energy efficient operation of Smart City units, as these are often located in isolated locations where battery exchange or recharge is difficult. To keep the costs at a low level, at least 10 years of energy efficient radio operations on a single 5 Wh battery should be possible, assuming sporadic data exchange. Low cost is also the driver for reduced complexity, as the Smart City devices are expected to be deployed in large volumes, which is also challenging for the radio network. The latter may in extreme cases for instance need to handle up to 1 million devices per km^2. Especially initial access solutions, as detailed in Section 13.2, are critical to meet aforementioned requirements.

2.5.3 Connected Cars

The connected cars UC facilitates safe and time-efficient journey by enabling URLLC services between the cars and their surrounding, as covered in detail in Chapter 14. The most critical KPIs that quantify the performance of such communication are ultra-high reliability and very low latency for the low payload messages exchanged for safety and efficiency reasons. Additionally, when driving in a car, bus or train, passengers are expecting the availability of remote services, despite the high mobility conditions. Such eMBB service may be used to provide entertainment or connectivity for humans on the move.

The performance assessment of the connected cars UC that is given in this book in Section 15.2 is based on an evaluation of URLLC only. As the safety of the passengers is at stake, an unpreceded level of reliability of transmissions is expected, with a specific target of 99.999%. This reliability is expected for low payload messages (up to 1600 Byte packets) that are exchanged periodically every 100 ms between connected cars.

Different environments are foreseen for testing the performance of the connected cars UC, and each one brings slightly different challenges. In a highway scenario, cars are moving at the speed of 140 km/h, using 3 lines in each direction. Network coverage is provided by rural macro BSs distributed with a distance of 1732 m between each other, and operating at a carrier frequency around 800 MHz with antennas located on high masts. The challenging factor here is the high velocity and related physical phenomena that deteriorate the error rate of the radio transmission. In an urban scenario, cars are moving at the maximum velocity of 60 km/h. However, the density of vehicles in proximity is much higher than in a freeway case. Network coverage is provided by urban macro BSs deployed with an inter-site-distance of 500 m, and with 10 MHz reserved for URLLC services at a carrier frequency around 2 GHz. In both highway and urban scenarios, a carrier frequency of 5.9 GHz is used for the sidelink communication between the vehicles, related to the dedicated Intelligent Transport Systems (ITS) bands that are defined in detail in Section 14.2.3.

2.5.4 Industry Automation

The industry automation UC is URLLC-related and refers to the Factories of the Future, as defined in more detail in Table 2-3. It involves direct device-to-device (D2D) communications between machines as well as access point to machine communications. The focus in this book is on URLLC services within the factory, whose requirements depend on the specific UC and range in terms of latency from 1 to 10 ms, in all cases requiring very high reliability. The traffic pattern also depends on the specific industrial UC, and is typically a mix of periodic and event-triggered traffic. The performance of specific concepts for network slicing is best done against requirements and assumptions of this UC, and hence an industry automation UC is also used as a detailed example for network slicing in Section 8.2.5.

2.5.5 Broadcast/Multicast Communications

In addition to the legacy broadcast services deployed today, e.g. TV, the fully mobile and connected society will need an efficient distribution of information from one source to many destinations [11], see also the video broadcasting scenario in Section 15.2. These services may distribute contents as done today, i.e. typically only using DL, but also provide an UL feedback channel for interactive services or acknowledgement information. Both real-time and non-real-time services are possible. Furthermore, such services are well suited to accommodate the needs of vertical industries. These services are characterized by having a wide distribution, in terms of either geographical distribution and/or a large address space, i.e., many end-users.

2.6 Envisioned Mobile Network Ecosystem Evolution

2.6.1 Current Mobile Network Ecosystem

The value chain of mobile networks is currently specialized into segments that include content-related services and applications, network infrastructure, integration services, access devices, and a multitude of sub-segments and niche applications. Figure 2-3 presents the current value chain of the mobile telecommunications industry. This value chain starts with the hardware providers that manufacture network equipment (i.e., BSs, network controllers, gateways, etc.) and user devices (i.e., mobile phones, smartphones, tablets, dongles). Software providers developing software enablers (middleware and applications), occupy the second position as they allow operating infrastructure and devices. Then come the facility and equipment managers (i.e., tower companies and urban furniture managers) that own assets which are useful for network coverage and capacity extensions. Note that MNOs are also subcontracting some of the network operation and management tasks to equipment vendors or specialized companies. MNOs are then in the middle of this value chain, intermediating between infrastructure players and content and service-related players. Among this latter group, we can cite content providers, over-the-top (OTT) players, especially those that provide telecommunication services (e.g., voice and video conferencing) and service providers that offer wireless services to end clients. Their services include voice calls (e.g., local, regional, national, and international), voice services like voice mail, caller ID, call waiting, call forwarding, and data services like SMS messaging, text alerts, Web browsing, e-mailing, streaming, etc., and mobile TV services. End users occupy the last position in this value chain. Note that this denomination covers a wide spectrum of customers as will be detailed in Section 2.6.3.

2.6.2 Identification of New Players and their Roles in 5G

In its 5G White Paper [5], NGMN describes new business models expected with 5G. New business roles described in this document make reference to asset providers, connectivity providers and partner service providers. In this section, we use the previous section on the identification of the current players and NGMN's input as a basis to identify new players and roles in the 5G field, as developed in [5]. Note that 5G IA produced a White Paper for Mobile World Congress 2017 [12] which also identified new business roles with 5G, and the related analysis converges to a large extent to that of [5].

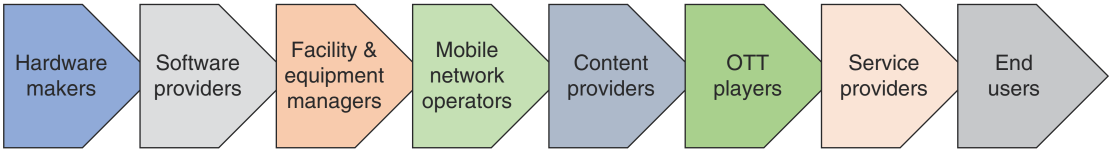

Figure 2-3. Current value chain of the mobile telecommunications industry.

2.6.2.1 Connectivity Providers

The business models associated to connectivity providers can be differentiated between “basic” and “enriched” models and are the following:

- **Basic connectivity providers**: In this model, only best effort IP connectivity is provided. This is the “dumb pipe” model for mobile operators, and we can include Wi-Fi access providers in the same model. In the years to come, we might see new players such as satellite service providers, low-power wide-area (LPWA) players, loons’ players, etc. Wi-Fi first players, which use Wi-Fi as the primary connection option and switch to a mobile network only as a “backup solution”, could play a bigger role in bundling other access networks as well (e.g., satellite, LPWA, loons). In the energy sector, an example of a basic connectivity provider is an evolution of the mobile virtual network operator (MVNO) concept called a private virtual network operator (PVNO). The long-term needs of energy grids are not fulfilled by existing mobile networks, leading the players of this sector to become MVNOs and to take full or partial control of a wireless network. The PVNO could control elements of the core network such as customer database and SIM cards. In countries like the Netherlands and France, utility companies have deployed cellular networks and were awarded spectrum for their own needs, as for instance in the 450 MHz band in the Netherlands;
- **Enhanced connectivity providers** could increase operator differentiation through network quality and configurability. Public safety players, new MVNOs providing machine-to-machine (M2M) enriched services (for vertical sectors, security purposes, etc.) could appear in this field. The broadcasting sector could also propose a new model called “tower overlay over 5G” (TOo5G), in which the broadcast operator would use its high-tower high-power (HTHP) infrastructure; the latter being already in place and serving for digital terrestrial television (DTT) services. This dedicated broadcasting infrastructure would provide broadcast and multicast services (such as video streaming) with lower transmission costs than in unicast mode, but the viability of this solution will depend on the 5G design choices, for instance related to the integration of digital video broadcasting (DVB) like air interfaces in 5G, and on the development of evolved multimedia broadcast multicast services (MBMS) solutions.

2.6.2.2 Asset Providers

The asset provider role covers both network sharing models and Anything-as-a-Service or Everything-as-a-Service (XaaS) models. With XaaS, everything can be accessed on demand via the cloud. XaaS gives a first sight at what would be the future of cloud services. Users have access to services remotely, whatever the device.

In addition to the Small-Cells-as-a-Service (SCaaS), XaaS asset provider models identified in the NGMN White Paper are Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS) and Network-as-a-Service (NaaS). They should bring completely new business models in the 5G field.

In the IaaS model, hardware (e.g., servers, routers, etc.) and software elements, maintenance and backup means are managed by a third-party provider. These providers are able to provide dynamic scaling and policy-based services. They charge their customers on a subscription basis and can also take into account the amount of virtual machine space used. In the IaaS model, it is expected that Internet or traditional information technology (IT) companies such as IBM, HP, Google, etc., could become important players with 5G.

As of SCaaS, other parties can also provide it, and vendors are already entering this market. Municipalities or real estate owners can also jump into the business and monetize access to small cells. For example, small cells located in street furniture can be deployed almost anywhere and very close to the user.

In the PaaS model, applications are delivered over the Internet. Hardware and software tools are hosted by the infrastructure provider which provides applications to its customers. Internet and IT companies (e.g., Salesforce, Google, Microsoft, etc.) and telecom players will play a role here.

In the NaaS business model, network services are virtually delivered over the Internet thanks to the virtualization of network functions, as detailed in Section 10.2.2. This can be done on a monthly subscription or on a pay-per-use basis.

Network sharing represents another dimension for asset providers with real-time network sharing. One could for instance envision dynamic network sharing between commercial mobile networks and public safety networks. Capacity would be made available to commercial operators in absence of emergencies. Spectrum brokers could also play a role in the future and manage spectrum resources on behalf of mobile network operators in order to allow for real-time management of the spectrum.

2.6.2.3 New Players in Relation with RAN Evolution

With the expected development of cloud RAN architectures, new players such as content delivery network (CDN) providers or data center players could play a significant role, as listed in the following:

- Data center players could also operate baseband units (BBUs) in a centralized infrastructure, i.e. data centers, in the form of a large concentration of servers and databases. A limit to their possible investment in this field is the limited number of data centers, which are today only present in large cities;
- CDN players could provide services to mobile operators in supporting content hosting closer to the edge of the network. Today, Akamai dominates the market, followed by LimeLight and Jetstream;
- New players could offer both BBU hosting and management and CDN capabilities, and play a role in RAN sharing agreements;
- Relay owners could propose relays to extend coverage of a wireless network or to increase the area spectral efficiency, by means of shortening the radio path distance among end users and access nodes. The actor running and maintaining the relay could be an MNO, an end user that wants to provide enhanced performance in its specific area, or a third party like a restaurant owner interested in providing coverage enhancement based on a specific agreement with an MNO and the usage of the radio resources of the same.

2.6.2.4 Partner Service Providers

Disintermediation of the value chain provides opportunities to create innovative services. With its network, the MNO provides bandwidth to customers and evolves from the former pricing model (i.e., per minute, per volume, per data rate, etc.) to a value pricing model (i.e., involving various QoS metrics, availability, prioritization, latency, etc.).

In the partner service provider model, the MNO offer can be enriched by partners or, the other way round, the partner offer could be enriched by MNOs' capabilities and services.

- **MNO capabilities and offers enriched by partners**: In this model, the mobile operator still provides the service to the end user. As an example, collaboration with OTTs enables MNOs to differentiate their offers. In the coming years, payment solutions, content or integrated streaming solutions could be added by partners. In vertical industries (e.g., related to Factories of the Future), new players could provide data analysis on top of sensing & communications provided by the 5G operator;

- **Partner offers enriched by MNOs' capabilities and services**: In the second model, third party or OTTs are using an MNO's network and have a direct relationship with customers. Products such as smart body analyzer devices or smart wearables could use health monitoring features and connectivity provided by the MNO.

2.6.3 Evolution of the MNO-Centric Value Net

Having identified, in the previous section, the main actors and the interactions between these, the focus of this section is now on the MNOs, as they are expected to play a central role in 5G, as in previous generations. We construct the value net of these MNOs and its evolution with 5G, the aim being to identify their coopetition relations with the other actors.

The value net model has been elaborated by [13]. This model is a complementary approach to the value chain framework, but the analysis is more comprehensive, as the main players have to be integrated in four categories, namely customers, suppliers, competitors and complementors, following a vertical and horizontal dimension. Figure 2-4 gives the current value net of MNOs.

We first begin by defining customers, as this will give us a clear view about the positioning of the MNO. Two kinds of customers are identified: End users, either in the mass market (i.e., individuals), or other business customers (i.e., private companies or public administrations) are contracting with

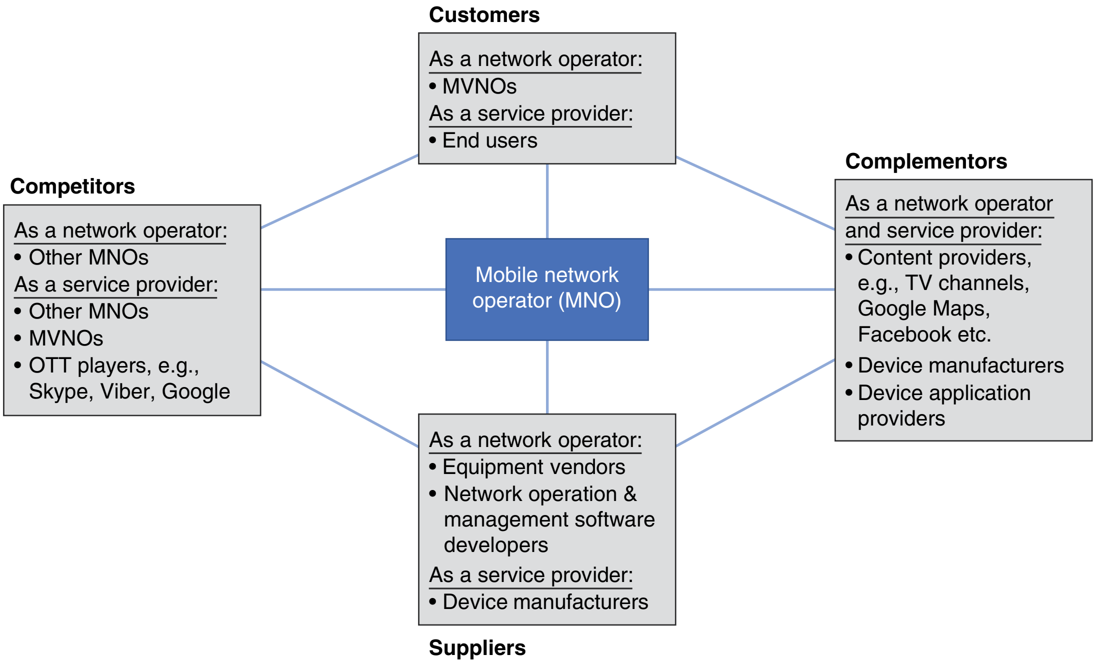

Figure 2-4. Current value net of MNOs [14].

the MNO as a service provider. MVNOs, however, are customers of the MNO, as they buy the right to use its network in order to serve their customers. When the MNO sells network access rights to MVNOs, it is behaving as a network operator. Based on this analysis, we can see that customer groups can be classified into two groups: customers of the MNO as a service provider, and customers of the MNO as a network operator. We will keep this classification for the rest of our analysis of the value net.

Next, we stay in the vertical dimension and identify suppliers. As a network operator, the MNO has as suppliers infrastructure vendors and network operation & management software makers, as identified in Figure 2-4. On the other hand, as a service provider, the MNO has as suppliers device manufacturers, as service providers usually buy devices from manufacturers and sell them at lower prices to end users.

Let us now move to the horizontal dimension and identify competitors. As a service provider, each MNO has as obvious competitors all other service providers, them being MNOs or MVNOs. OTT players, like Skype and Viber, are also seen as competitors of the MNO as a service provider, as they propose substitution services (e.g., voice, video conferences, etc.). As a network operator, the considered MNO has as competitors the other MNOs, as they offer the same services for MVNOs.

The most difficult task is to identify complementors whose presence incites customers to buy more services from the MNO. Obviously, content providers (e.g., online game developers, Google maps, TV channels, etc.) act as complementors, as people are more willing to buy mobile data access in order to benefit from their favorite contents everywhere. Device manufacturers are also complementors, as end users consider smartphones and tablets as valuable devices by themselves, and a smartphone or a tablet will be more useful with a wireless Internet connection. The device application developing industry is also a complementor, as the multitude of smartphone applications incites users to buy a smartphone and to subscribe to a mobile data connection. Note that we do not make a distinction between complementors of the MNO as service provider or as network operator, as they are generally the same in the way that they stimulate the need for network access.

Figure 2-5 shows the evolution of the value net of MNOs with 5G, based on the 5G player identification in the previous sections. We start with the evolution of the group of customers where PVNOs join MVNOs as customers of the MNO as a network operator, and where verticals, by directly buying connectivity to their customers, become customers of the MNO as a service provider. The same verticals become complementors as, by moving towards more connectivity, they provide needs for people (i.e., individuals and professionals) for 5G services.

As for the suppliers of the MNO, the increased heterogeneity and the virtualization of networks are expected to diversify their list. The lists of equipment vendors and of network operation and management software suppliers are joined by classical IT companies like IBM, HP, etc., which provide processing servers and virtual network software, for instance based on software-defined networking (SDN) and network function virtualization (NFV), as detailed in Section 10.2. Data center players may play a role in managing hostels of BBUs in this context, especially for cloud RAN architectures. Asset providers like facility managers, urban furniture managers and tower companies are expected to have a larger role in the deployment and the management of parts of the access network, reinforcing their position as suppliers of the MNO as a network operator. With the evolution of spectrum regulation and the allocation of new bands under innovative authorization schemes such as licensed shared access (LSA) and licensed-assisted access (LAA), detailed in Section 3.2, spectrum brokers could play a role in the future and manage spectrum resources on behalf of mobile network operators in order to allow real-time management of the spectrum. Finally, as a service

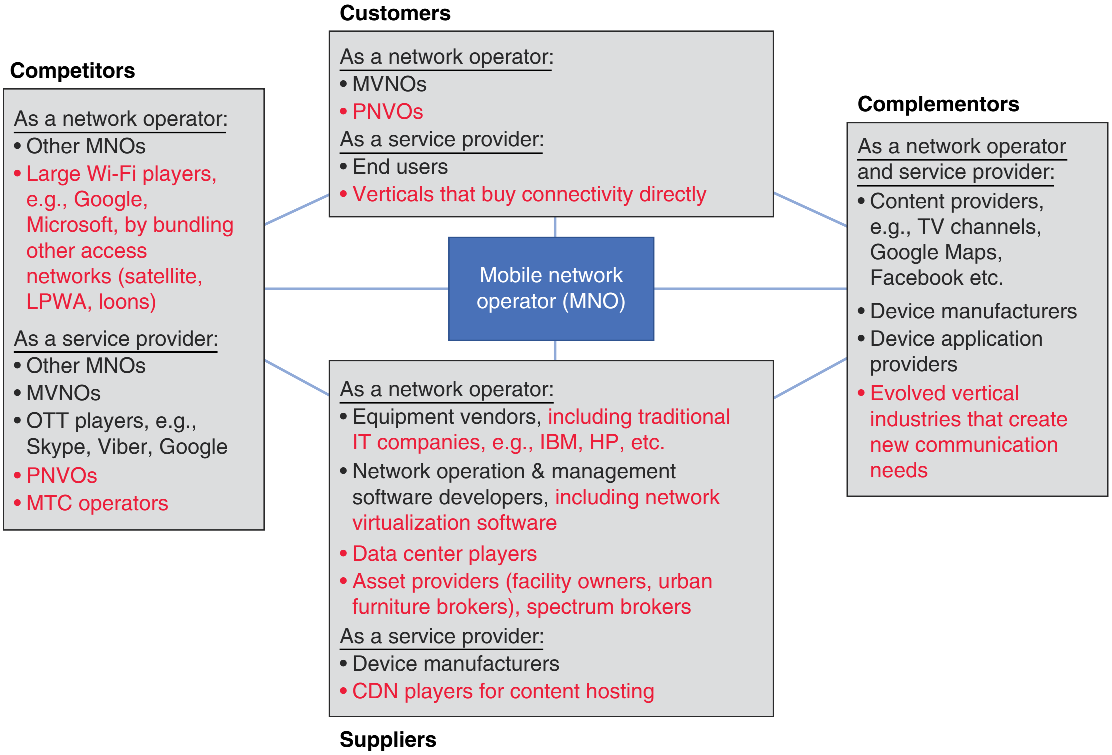

Figure 2-5. Evolution of the value net of MNOs with 5G [14].

provider, the MNO can make deals with CDN players for content hosting near end users at the network edge, making them suppliers with regards to its role as a service provider.

Finally, the advent of new LPWA networks and various access networks based on satellites and loons in addition to the increased integration of Wi-Fi evolutions within the 5G network introduce a variety of new competitors to the MNO in the RAN. A possible scenario, as discussed previously, is the emergence of large Wi-Fi players in the bundling of these various access networks. Regarding the service provider role of the MNO, PVNOs and MTC operators join MVNOs as competitors for offering services to end users.

2.7 Summary and Outlook

In this chapter, an overview of the envisioned main 5G service types eMBB, mMTC and URLLC and related requirements was presented, after which the 5G UCs from two main sources, namely NGMN and 5G PPP Phase 1 projects, were detailed. The synergies and commonalities between these UCs show a large consensus in the community on this topic. It was also shown how these UCs map to vertical needs, allowing 5G to reach a wide range of verticals, especially with mMTC and URLLC services.

The chapter then focused on highlighting the impact of the UCs on the evolution of the mobile network ecosystem, and showed how the mobile network operators' value net is expected to transform, with the introduction of new actors and the evolution of the position of existing actors.

It is clear that in order to fulfil the requirements of the identified 5G services and use cases, and to enable the discussed value net transformations, the 5G architecture has to substantially evolve from that of legacy systems, as detailed in Chapters 5-10.

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3

Spectrum Usage and Management

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3.1 Introduction

5th generation (5G) networks need to handle mobile data rates in the range from a few kbps up to several Gbps. The requirements w.r.t. the availability of wireless access and link reliability will also increase. Beside mobile broadband services, other utilizations like, e.g., automotive applications, smart grid or smart meter communications, manufacturing systems, and health care by electronic means are going to be incorporated into the 5G design for economies of scale, as pointed out in Chapter 2.

The total amount of spectrum below 6 GHz currently allocated for the mobile service and identified for International Mobile Telecommunications (IMT) in the International Telecommunication Union (ITU) Radio Regulations [1] is 1886 MHz (see Table 3-2). However, in individual countries, only parts of this spectrum are available or planned for mobile communications.

In principle, the capacity of mobile networks can be increased in three ways: a) through additional spectrum bands, b) through cell densification with the deployment of more access points, and c) by using advanced radio technologies obtaining higher spectral efficiency. Since cell densification and higher spectral efficiency alone are not sufficient to cope with the predicted extreme high mobile traffic for specific 5G usage scenarios, a significant amount of additional spectrum for mobile communications needs to be made available, preferably on a globally harmonized basis. For this reason, according to Resolution 238 in [1], a number of frequency bands between 24 GHz and 86 GHz (see Table 3-2) are under study for identification for 5G/IMT2020 at the World Radiocommunication Conference in 2019 (WRC-19).

Depending on the envisaged 5G use cases, spectrum is required in different frequency ranges: below 1 GHz, between 1 GHz and 6 GHz, and above 6 GHz. Consequently, 5G systems will need to be

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able to utilize various operational bandwidths in different deployment scenarios, in any frequency band ranging from below 1 GHz up to 100 GHz. Thus, a main challenge of spectrum management in future 5G networks is the integration of numerous frequency bands within a wide range of spectrum, and with differing spectrum access like, e.g., individual (licensed) or general (shared) authorization.

5G specifications need to support co-existence with legacy mobile technologies and flexible spectrum management to facilitate a smooth transition to 5G. Moreover, the principle of technology neutrality when authorizing spectrum usage provides operators with the flexibility to re-farm their spectrum holdings in order to allow for the evolution from existing to new technologies. For initial 5G deployments, the availability of new spectrum bands is required. This has been initiated in several regions and countries, for example in Europe with the adoption of a 5G Action Plan [2] and the nomination of 5G pioneer bands [3].

Exclusively licensed spectrum on a technology-neutral basis is essential to ensure a high quality of service, a good system performance, and the investment in network infrastructure needed for 5G. Shared spectrum and license-exempt spectrum can play a complementary role to increase capacity and user experience, while simultaneously allowing operators to guarantee a certain Quality of Service (QoS) in licensed spectrum [4].

In the following sections, a number of aspects related to spectrum utilization are considered in more detail. In Section 3.2, spectrum authorization schemes and usage scenarios relevant for 5G are introduced, as well as the spectrum usage requirements for these schemes and scenarios. Spectrum bandwidth demand for 5G is discussed in Section 3.3, by evaluating analysis tools, and elaborating on the impacts of 5G services and deployment scenarios on the spectrum demand estimation. Furthermore, a technology-agnostic approach for spectrum demand estimation is presented. Section 3.4 deals with frequency bands for 5G, depicting bands identified or under study for IMT, but also further potential candidate bands, as well as spectrum roadmaps for the 5G launch. In Section 3.5, spectrum usage aspects at high frequencies are analyzed, including propagation, coverage, deployment and co-existence. Evolutionary paths of dynamic spectrum management are discussed in Section 3.6, concluded by the introduction of a possible functional architecture. Finally, Section 3.7 gives a summary of this chapter and refers to studies above 86 GHz.

3.2 Spectrum Authorization and Usage Scenarios

In this section, spectrum authorization schemes and usage options for 5G are described, based on the findings of the work on spectrum aspects in the 5G Public Private Partnership (5G PPP) project METIS-II [5]. Furthermore, spectrum requirements for different 5G usage scenarios are considered.

3.2.1 Spectrum Authorization and Usage Options for 5G

Generally, the use of radio frequency spectrum can be authorized in two ways, first by “individual authorization” in the form of awarding licenses, and secondly by “general authorization”, also referred to as license-exempt or unlicensed. In [6], four different user modes for the operation of 5G radio access systems have been defined, namely the “service dedicated user mode”, the “exclusive user mode”, the “Licensed Shared Access (LSA) user mode”, and the “unlicensed user mode”. The relationship between these user modes and the two authorization schemes is illustrated in the upper part of Figure 3-1 named “regulatory framework domain”.

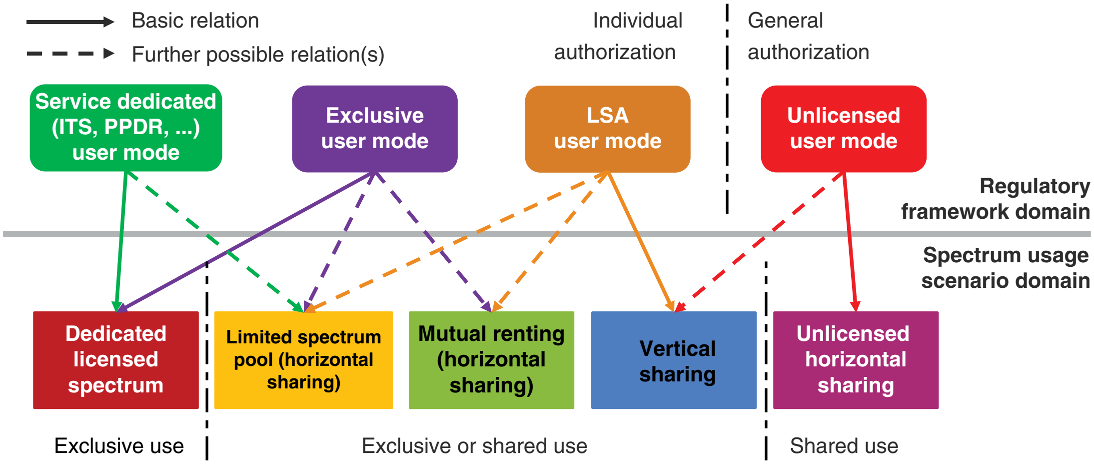

Figure 3-1. Concept for spectrum management and spectrum sharing [6].

Spectrum usage rights awarded by "individual authorization" are exclusive for the license holder at a given location and/or time. The "service dedicated user mode" refers to spectrum designated to services other than public mobile communications, which are indented to be integrated into the 5G ecosystem, for example Intelligent Transport Systems (ITS) or Public Protection and Disaster Relief (PPDR) applications. This spectrum is to be used only for dedicated services and applications. Spectrum designated to public mobile communications falls into the "exclusive user mode". In the "LSA user mode", a non-mobile communications license holder (incumbent) would share spectrum access rights with one (or more) LSA licensee(s), which can use the spectrum under defined conditions subject to an individual agreement and permission by the relevant regulatory authority. These three user modes can occur either in their basic form (see continuous lines in Figure 3-1) or as an evolution of current approaches in the form of "limited spectrum pool" or "mutual renting" (shown through dashed lines in Figure 3-1).

In the "limited spectrum pool" usage scenario, a limited number of known operators obtain authorizations to access a spectrum band dynamically. Mutual agreements between these licensees shall guarantee that in the long-term each participating operator has a predictable minimum value from the shared spectrum. In the "mutual renting" scenario, an operator would rent at least a part of its licensed spectrum resources to another operator, based on mutually agreed rules. Depending on the time period of the spectrum access, the spectrum usage scenarios "limited spectrum pool", "mutual renting" and "vertical sharing" may be considered as exclusive (static) or shared (dynamic) use.

Spectrum access and usage rights granted by general authorization are covered by the "unlicensed user mode", also known as license-exempt usage. This means that such users have no individual license, but the spectrum usage is subject to certain technical restrictions or conditions, for example limited transmission power or mitigation techniques like duty cycle or listen-before-talk. In this user mode, spectrum users cannot claim protection from interference by other users.

In the case when spectrum sharing takes place between systems of different priority, this is referred to as "vertical sharing", whereas spectrum sharing between systems of equal priority is called "horizontal sharing". For example, wireless access systems (WAS) operating in parts of the 5 GHz spectrum have to avoid interference into incumbent radar systems (vertical sharing), and also have to employ mitigation techniques to coexist with other WAS systems (horizontal sharing).

5G systems are expected to support all spectrum usage scenarios indicated in Figure 3-1, in order to facilitate high spectrum usage efficiency. In network operations, several scenarios may occur simultaneously.

3.2.2 Requirements for Different 5G Usage Scenarios

5G is going to support diverse use cases and applications, covering not only the traditional services for mobile subscribers, but also applications for a number of vertical industries like the automotive, energy, eHealth or manufacturing sector. All 5G use cases and applications can be assigned to one or more of the following three main usage scenarios introduced in Chapter 2 [7]:

1) **Enhanced Mobile Broadband (eMBB)**, addressing human-centric use cases for access to multimedia content and data services. This usage scenario embraces a number of use cases and deployment scenarios with quite diverging requirements. For example in a hotspot scenario, extreme high throughputs and low-latency communications are in the foreground, while for wide area coverage the customer Quality of Experience (QoE) with reliable and moderate data rates over the coverage area is in focus.
2) **Massive Machine-Type Communications (mMTC)**, characterized by wireless connectivity of billions of network-enabled devices with prioritization on wide area coverage and deep indoor penetration, typically transmitting non-delay-sensitive data at low rates. Usage scenarios for mMTC are for example smart cities, smart buildings, or sensor networks for farming and agriculture.
3) **Ultra-Reliable and Low Latency Communications (URLLC)**, having stringent requirements on latency and availability. Examples for URLLC are the wireless automation of production facilities, monitoring of critical infrastructures in a smart grid, remote medical surgery, remote robotics, the tactile Internet, or vehicular traffic efficiency and safety.

eMBB applications require a mixture of frequency bands including lower bands for coverage purposes as well as for low to medium data traffic, and higher bands with large contiguous bandwidths to deal with the expected extremely high traffic demand. Exclusive licensed spectrum is essential to guarantee coverage obligations and a minimum QoS for the customers. Spectrum authorized by other licensing regimes, for example LSA or unlicensed access, is a supplementary option to increase the overall spectrum availability.

mMTC applications mainly demand frequency spectrum below 6 GHz, and spectrum below 1 GHz is needed in particular for wide area coverage and reliable outdoor to indoor penetration. Therefore, exclusive licensed spectrum is the preferred option. However, also higher frequency bands and other licensing regimes might be considered, subject to the specific mMTC application requirements.

URLLC applications require high and reliable spectrum availability. Thus, licensed spectrum is considered most appropriate for these kinds of services. For communications for automotive safety and efficiency, see also Chapter 14, the frequency band 5875-5925 MHz harmonized for ITS is an option. Particularly for high-speed vehicles and in rural environments, spectrum below 1 GHz is well suited.

3.3 Spectrum Bandwidth Demand Determination

Radiocommunication networks are deployed over a specific geographical area to provide one or multiple services characterized by the offered QoS, using a chunk of spectrum according to the aforementioned authorization and usage options. Since spectrum is a finite resource, it is of paramount importance to determine the spectrum bandwidth demand for each radio service in order to be able to fulfil the service requirements.

3.3.1 Main Parameters for Spectrum Bandwidth Demand Estimations

The required bandwidth for any specific radiocommunication network, i.e. also the future 5G networks, greatly depends on the following three parameters:

1) **The targeted QoS**. This parameter may differ to a large extent, depending on the service provided by the network. For 5G, the mix of the three main usage scenarios (eMBB, mMTC and URLLC) needs to be considered. One key aspect to be taken into account for QoS is the prediction of traffic patterns for different services.
2) **The area spectral efficiency**. This parameter is expressed in bit/s/Hz/cell and describes how efficiently, in terms of the data rate per bandwidth per cell, the available spectrum is used. Innovations currently under standardization or research will greatly impact the achievable area spectral efficiency in 5G and its foreseeable evolution. The area spectral efficiency can be increased by enhancing the achievable single link spectral efficiency within an individual transmission reception point (TRP), for instance through higher order modulation and coding schemes, massive multiple input-multiple output (MIMO) or interference cancelation technologies, as covered in detail in Chapter 11. Also, the coordination of several TRPs present in the area, for instance in the form of advanced inter-cell interference coordination (ICIC) and coordinated multi-point (CoMP) can increase the area spectral efficiency, as detailed in Chapter 12. These latter approaches can strongly benefit from C-RAN deployments and software-defined networking (SDN), as discussed in Section 6.8.
3) **Physical deployment of network, TRPs and user distributions.** The number of network TRPs in high traffic density areas has been substantially increased in current legacy networks, with the provision of different levels of small cells, in order to maintain the QoS with the same amount of spectrum bandwidth. However, this high density deployment has a clear impact on both capital expenditures (CAPEX) and operational expenditures (OPEX) associated with the provision of the service, which could be unsustainable from an economic point of view. Realistic estimations on user density distributions and TRP deployments are needed in order to perform an adequate evaluation of the required spectrum bandwidth. Parameters like the speed of users or moving TRPs will also have an impact on the final achievable spectral efficiency of the associated links and thus the required bandwidth.

In the following sub-sections, an overview of current approaches and their applicability to 5G is given, and a statistical procedure with a technology and frequency band agnostic approach is introduced.

3.3.2 State of the Art of Spectrum Demand Analysis

Currently, the spectrum requirement analysis for new terrestrial IMT radiocommunication networks such as 5G is evolving from [8]. The parameters for the bandwidth demand analysis introduced in Section 3.3.1 are implemented in this tool in the following manner:

1) The targeted QoS is characterized by the parametrization of the requirements of twenty different service categories. The parameters associated to these service categories are the foreseen traffic models of different services based on market forecasts, defined by: session arrival rate [session/s/user], mean device bit rate [kbps] and mean session duration [s/session].
2) The area spectral efficiency is directly associated with each of the four different TRP layers considered: macro cells, micro cells, pico cells and hot spots, with different values associated to the three considered deployment scenarios (dense urban, sub-urban and rural). Therefore, each TRP is characterized by the area spectral efficiency [bits/s/Hz/cell] value used in the respective radio access technology (RAT), taking into account the estimated traffic per area.
3) The physical deployment scenarios are characterized by the service environment and by the user density [users/km^2]. Depending on the service environment, three main scenarios are considered: dense urban (with three different densities), sub-urban (with two different densities) and rural. Furthermore, each user in a scenario is associated with a probability of being in one of the following three mobility states: stationary (0-5 km/h), low mobility (5-50 km/h), and high mobility (50-250 km/h).

The results of studies on estimated spectrum requirements for terrestrial IMT (pre-5G technologies) in the year 2020, as provided in [8], are shown in Table 3-1.

Spectrum demand estimates for 5G (IMT-2020) are even higher. For example, with a technical performance-based framework for spectrum bandwidth demand analysis, a demand of about 7 GHz of additional spectrum in bands above 6 GHz is estimated for a dense urban information society scenario, and more than 14 GHz for a virtual reality office environment [6].

3.3.3 Spectrum Demand Analysis on Localized Scenarios

When planning mobile networks, mobile network operators (MNOs) aim to achieve a targeted QoS using the limited assigned bandwidth within one or several bands, with minimum deployment and operational costs. Usually, advanced radio frequency propagation tools are used, based on ray tracing techniques and thus being capable of evaluating the achievable signal-to-interference-plus-noise ratio (SINR) once TRP positions, carrier frequency and technology parameters are set.

The SINR values for randomly distributed locations in a TRP coverage area follow a Gaussian curve. Usually, the figure of merit of a new technology is evaluated as the achievable increase of the

Table 3-1. Estimated spectrum requirements for pre-5G technologies in the year 2020 [8].

User Density	Total requirement by 2020 (MHz)	pre-IMT & IMT-2000 (MHz)	IMT-Advanced (MHz)
Low	1340	440	900
High	1960	540	1420

mean value of this Gaussian curve for any specific scenario. This approach is also used in 3GPP benchmarking. For example, in [9], the performance degradation of the SINR distribution for different channel calibration errors in a 32 TRP scenario (assuming a downlink CoMP joint transmission technique) is described as variations in the Gaussian SINR values.

Based on this principle, a method for the spectrum demand analysis in a limited coverage area, with statistical model assumptions for the SINR has been developed [6]. The main parameters for spectrum bandwidth demand estimations are implemented as follows:

1) The targeted QoS is characterized by the achievable throughput for user sessions, taking into account that for each session type various levels of QoS are established, since services like video streaming may be delivered in different qualities, linked to different compressing levels. Moreover, for each type of user equipment (UE), a different probability to be connected with a different session type (data transfer, video streaming, web browsing, etc.) can be applied by a throughput requirement statistical model.
2) The area spectral efficiency is calculated for each scenario. The TRPs deployed in the scenarios (assuming a heterogenous, layered deployment with macro, micro and pico cells) are characterized - for each frequency band considered in the scenario - by the statistical distribution of the achievable SINR in their coverage area. In order for a UE to be schedulable, the UE-TRP link must present a spectral efficiency above the value established as the minimum level. The radio links to the various types of UEs considered in the scenarios (at each carrier frequency) are characterized by: a degradation coefficient (from values achievable applying Shannon theorem), the maximum values of spectral efficiency (depending on the number of antennas involved in the MIMO system), and a minimum value for SINR below which the UE is considered out of coverage.
3) The physical deployment scenarios are characterized by the user density (i.e., users/km^2) and the TRP positions. Three different levels of user densities are considered: general density over the full scenario, high density spots with increased density (campus, office areas, etc.), and ultra-dense hot spot areas. The TRPs are deployed according to these three levels, taking into account a realistic deployment of the macro layer, i.e. including random phase and distance errors from the canonical regular grid used in 3GPP evaluations, leading to realistic coverage areas provided by the Voronoi cells (see Figure 3-2) in accordance with the distance to actual positions of TRPs in the scenario.

Since the achievable QoS may vary greatly depending on the statistical models included in the evaluation tools, a Monte Carlo computational approach is required to get a reliable evaluation of the QoS, achievable with different bandwidths available in different frequency bands.

3.4 Frequency Bands for 5G

3.4.1 Bands Identified for IMT and Under Study in ITU-R

The widespread usage of smartphones and tablets is causing a continuing growth in mobile data communication. According to [10], mobile data traffic will increase with an estimated compound annual growth rate (CAGR) of 47% from 2016 to 2021. In order to cope with such a huge mobile traffic demand, spectrum regulators are working together with involved industries in order to

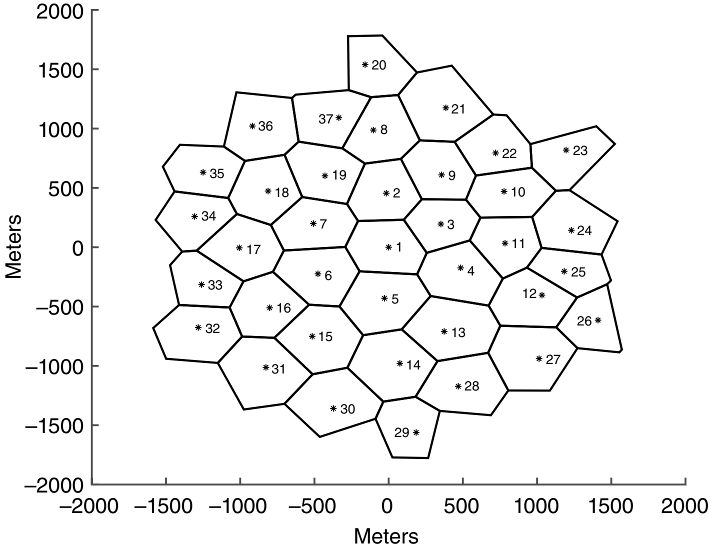

Figure 3-2. Voronoi cells in a 37 cell scenario, with 0.5 km inter-site distance (ISD) and 20% error in phase and distance.

identify bands to make sufficient spectrum available for 5G, focusing on bands that have the potential to be harmonized globally. In consideration of the diverse usage scenarios, technologies and applications enabled by 5G, access to different spectrum bands with different characteristics is required:

- spectrum at lower frequencies to enable coverage of wide areas;
- spectrum at higher frequencies with larger bandwidths to provide necessary capacity and enable higher data rates;
- spectrum at very high frequencies (above 24 GHz) and with very large bandwidths, for providing ultra-high capacity and data rates.

Concerning spectrum above 24 GHz, the World Radiocommunication Conference in 2015 (WRC-15) approved by its Resolution 238 [1] to conduct studies in the respective groups within the ITU Radiocommunication sector (ITU-R), in order to determine spectrum needs and to define sharing and compatibility conditions in the frequency ranges between 24.25 GHz and 86 GHz, as listed in the right column of Table 3-2. Most of these bands already have an allocation to the mobile service on a primary basis, except the bands 31.8-33.4 GHz, 40.5-42.5 GHz and 47-47.2 GHz, which may require such an allocation in addition.

Based on the results of the studies mentioned above, according to agenda item 1.13, the WRC-19 will consider the identification of these frequency bands for the future development of International Mobile Telecommunications (IMT), including possible additional allocations to the mobile service on a primary basis.

In order to conduct the appropriate studies, a Task Group (TG 5/1) was established in ITU-R under the Study Group 5 as being responsible for WRC-19 agenda item 1.13, while the ITU-R Working Party 5D was tasked to conduct and complete the studies with regard to spectrum needs, technical and operational characteristics including protection criteria, and deployment scenarios for

Table 3-2. Bands identified for IMT and under study in ITU-R [1].

Global identifications (in all three regions) for IMT		Regional (in one or two regions) or national identifications for IMT		Under study for IMT-2020 (RESOLUTION 238 in WRC-15)
Band	**Bandwidth**	**Band**	**Bandwidth**	**Range**
450-470 MHz	20 MHz	470-960 MHz	490 MHz	24.25-27.5 GHz
1427-1452 MHz	25 MHz	1452-1492 MHz	40 MHz	31.8-33.4 GHz
1492-1518 MHz	26 MHz	3300-3400 MHz	100 MHz	37-40.5 GHz
1710-1885 MHz	175 MHz	3600-3700 MHz	100 MHz	40.5-42.5 GHz
1885-2025 MHz	140 MHz	4800-4990 MHz	190 MHz	42.5-43.5 GHz
2110-2200 MHz	90 MHz			45.5-50.2 GHz
2300-2400 MHz	100 MHz			50.4-52.6 GHz
2500-2690 MHz	190 MHz			66-76 GHz
3400-3600 MHz	200 MHz			81-86 GHz
Σ	**966 MHz**	**Σ**	**920 MHz**	

the terrestrial component of IMT. These studies were completed by March 2017. TG 5/1 is also responsible for the input to the Conference Preparatory Meeting (CPM-19) concerning WRC-19 agenda item 1.13.

For the sharing and compatibility studies to be performed, the protection criteria of the radio services which have already a service allocation in the respective band or adjacent to this band have to be taken into account, and all relevant interference scenarios need to be considered. According to the TG 5/1 work plan, the results of the sharing and compatibility studies will be finalized in 2018.

3.4.2 Further Potential Frequency Bands

Beside the frequency bands above 24 GHz under study for IMT-2020 (see right column of Table 3-2), spectrum below 6 GHz is required to fulfil the requirements of all potential 5G use cases. For this purpose, bands identified for IMT (see Table 3-2), but not yet in usage by cellular mobile systems, offer the best opportunities. Examples are the 600/700 MHz bands considered in US and Europe, and the 3.3-3.8 GHz range from which parts are in focus for 5G in Europe, China, Japan and South Korea. The range 4.4-4.9 GHz, although predominantly not identified for IMT, is under consideration in Japan and China [11].

Spectrum at 28 GHz is one of the main potential candidates for first deployments of 5G above 24 GHz, as the band 27.5-28.35 GHz is put into focus for initial 5G commercialization in the US [12] and in other large markets such as Korea (26.5-29.5 GHz) and Japan (27.5-29.5 GHz)[11]. There is also some interest from the mobile industry in investigating bands in the range of 6-24 GHz [4], although corresponding proposals were not supported by WRC-15.

Applications for which spectrum bands are already harmonized [13] may also be realized with 5G technology, for example traffic safety applications within the band 5875-5925 MHz in support for the automotive sector, or wireless industrial applications within the band 5725-5875 MHz for the factories sector. Further applications with already harmonized frequency bands are for instance Public Protection and Disaster Relief (PPDR) or Programme Making and Special Events (PMSE).

3.4.3 5G Roadmaps

The European Commission signed an agreement with the 5G Infrastructure Association, representing major industry players, to establish the 5G PPP, in order to accelerate research developments in 5G technology, supported by a public funding of around €700 million through the Horizon 2020 Programme, and the same amount from the private side. Furthermore, the telecommunications industry will invest five to ten-times this amount in 5G deployments outside the partnership [14]. The EU industry is set to complement this investment to more than €3 billion. Moreover, the European Commission adopted an Action Plan [2] for a coordinated 5G deployment across all EU member states, targeting early network introduction by 2018, and moving towards commercial large scale introduction by the end of 2020. In order to support this timeline, spectrum should be made available in the 5G pioneer bands [3]: at 700 MHz, within 3.4-3.8 GHz, and at 26 GHz. Corresponding activities at national level have been initiated, e.g., in Germany [15] and in the UK [16].

In the US, the Federal Communications Commission (FCC) adopted a Report and Order [12] with new rules to enable rapid development and deployment of next generation 5G technologies and services in spectrum bands above 24 GHz. These new rules open up nearly 11 GHz for flexible, mobile and fixed wireless broadband, comprising 3.85 GHz of licensed spectrum in the bands 27.5-28.35 GHz, 37-38.6 GHz, 38.6-40 GHz, and 7 GHz of unlicensed spectrum at 64-71 GHz. In addition, a government research initiative has been launched [17], including an $85 million investment in advanced wireless testing platforms by a public-private effort, and an additional $350 million over the next seven years in academic research that can utilize these testing platforms. An auction for spectrum in the 600 MHz band in March 2017 resulted in 70 MHz for licensed use and 14 MHz for wireless microphones and unlicensed use [18], to be freed from television usage by early 2020.

In South Korea, a pilot 5G mobile service is planned for the 2018 Winter Olympics in Pyeongchang in February 2018, and the rollout of 5G commercial services is foreseen for 2019 [19]. In Japan, commercial 5G networks are expected by 2020 in time for the Summer Olympics in Tokyo, or possibly even for the rugby world cup in 2019 [11]. In China, 5G trials are scheduled in two phases, first technology trials from 2015 to 2018, and second product trials from 2018 to 2020, with 5G commercial deployment envisaged by end of 2020 [20]. Note that further details on 5G pilots and early commercial 5G deployments in the different geographic regions are provided in Chapter 17.

3.5 Spectrum Usage Aspects at High Frequencies

In this section, the propagation challenges at high frequencies are discussed first in order to give an understanding of the operational environments. Then, the capabilities of beamforming for compensating the propagation loss at high frequencies are investigated, followed by an analysis of suitable deployment scenarios in various frequency ranges. Finally, the coexistence of 5G with fixed service links and system operations under license-exempt operation at high frequencies is evaluated.

3.5.1 Propagation Challenges

The system coverage of wireless networks becomes worse at higher carrier frequencies due to the increase of propagation loss. While propagation modelling is covered in detail in Chapter 4, the key challenges related to propagation at high carrier frequencies are shortly listed here. Depending on the deployment scenario, different propagation aspects are involved, as for instance captured in [21] and also studied in [22].

The base line propagation loss, as detailed in Section 4.2.1, is derived from the frequency dependent free space loss which is distance-dependent. For high frequencies, depending on the locations of user terminals and base stations (BSs), further propagation components are to be considered in addition, leading to more severe propagation challenges.

In the scenario where user terminals are located indoors and served by outdoor macro BSs, for instance, the building penetration loss, which is typically dependent on the type of material of the outer building walls, is the main challenge, see Section 4.2.3. The incident angle of the main antenna beam to the building entry is another important component which is usually modeled as angular loss. Since macro BSs are usually placed on the rooftop of a building, the main radiation is above or around the edge of the building, causing additional loss known as diffraction loss, see Section 4.3.3. Inside the building, internal wall losses may occur. In addition to these losses related to environment and deployment, also the human body loss may need to be considered, depending on the position of the user device. When user terminals are located outdoors, e.g., in streets, the coverage is not affected by building loss, angular loss, and indoor wall loss. However, due to the placement of macro BSs on rooftops, the coverage is still affected by the diffraction loss and the body loss. In the scenario where indoor users are served by indoor BSs, free space loss, internal wall loss and body loss are affecting the coverage.

3.5.2 Beamforming and 5G Mobile Coverage

With the increase of the carrier frequency, the physical size of one antenna element can be reduced due to decreasing wavelength. Therefore, by keeping the antenna size, the number of antenna elements can be increased, resulting in higher beamforming gain. However, as the propagation loss also increases over the frequency, it is not obvious that the beamforming gain is sufficient for compensating the propagation loss.

In theory, the relation between the power gain G of an antenna, the effective antenna area A, and the wave length λ is as follows [23]:

$$G = \frac{4 * \pi * A}{\lambda^2} \tag{3-1}$$

Since the wave length is inversely proportional to the carrier frequency, the antenna gain in dBi grows over the frequency f according to the following formula when A is fixed:

$$G_{dBi} = K + 20 * \log_{10}(f) \tag{3-2}$$

with $$K = 10 * \log_{10} \frac{4 * \pi * A}{c^2} \tag{3-3}$$

where c is the speed of light

For Equation (3-2), the antenna gain increases logarithmically with the carrier frequency when the antenna size is kept unchanged. However, the key frequency-dependent propagation components in the outdoor to indoor scenarios might increase more rapidly over frequency than the antenna gain. In [21], it is indicated that the building penetration loss in decibel (dB) increases linearly over frequency. For instance, the loss of concrete wall material is given by $5 + 4f$ (dB).

In reality, the antenna gain at high frequencies might be more limited for a number of reasons. First of all, the beamforming gain might not be continuously increasing over frequency due to hardware limitations or antenna design. Particularly, this would apply for hand-held devices. Therefore, there will be an upper limit on the number of antenna elements. For instance, it is currently assumed in 3GPP that each TRP is capable to have up to 256 elements in the 30 GHz range, and up to 1024 elements in the 70 GHz range [24]. However, the number of elements may be limited to 32 elements for the UE antenna. In high mobility scenarios, the use of antenna beams smaller than the angular extent of the intended coverage area requires beam steering and tracking functionalities. Even if channel state information (CSI) is available at the transmitter (Tx) and the receiver (Rx) for optimal beamforming, the optimal beam pointing to a mobile user becomes increasingly challenging due to smaller beam widths in higher frequency ranges. Furthermore, regulatory limits for transmission power and electro-magnetic field (EMF) exposure are to be taken into account.

3.5.3 Analysis of Deployment Scenarios

In this sub-section, a rough coverage analysis for carrier frequencies up to 100 GHz is performed. For the downlink coverage, three different deployment scenarios, with node types and user locations leading to different propagation characteristics, are examined: outdoor to indoor (O2I), outdoor to outdoor (O2O), and indoor to indoor (I2I).

As mentioned in the previous subsection, there is still uncertainty about the hardware capabilities which might evolve over time. Therefore, analyzing the coverage at high frequencies is a challenging task. Especially, the realizable beamforming gain and the power amplifier efficiency are not easily predictable. Thus, a required system gain is defined as the required average transmit power plus the Tx/Rx beamforming gain in order to reach a certain performance target, and the system gain is estimated over frequencies. Although this metric may not provide the coverage feasibility directly, because the realizable transmission power and the Tx/Rx beamforming gains are still needed, it gives good guidance on the coverage sensitivity at high carrier frequencies to achieve a specific target data rate. In principle, one can conclude that the higher the value of the required system gain, the more difficult it is to achieve the intended target.

In Figure 3-3, the system gain is shown as a function of the carrier frequency for different deployment scenarios. In this example analysis, a performance target of 50 Mbps was chosen by assuming a channel bandwidth of 100 MHz and a 2x2 MIMO stream at a given thermal noise power with a noise figure of 5 dB. Two different building types are assumed in the O2I scenario: a modern building type consisting of 70% infrared rejection glass windows and of 30% concrete wall, which is similar to a modern building with coated windows, and a classical building type with 30% of standard windows and 70% of concrete, which represents classical buildings in Western Europe. For the O2I and the O2O non-line-of-sight (NLoS) case, a cell edge user located 100 m away from a macro BS is considered. Users in the I2I scenario are assumed to be 10 m away from an indoor BS.

The results show that the O2I scenario is the most challenging one, and most sensitive with regard to a change of the carrier frequency. This indicates that the spectrum up to 30 GHz appears suitable

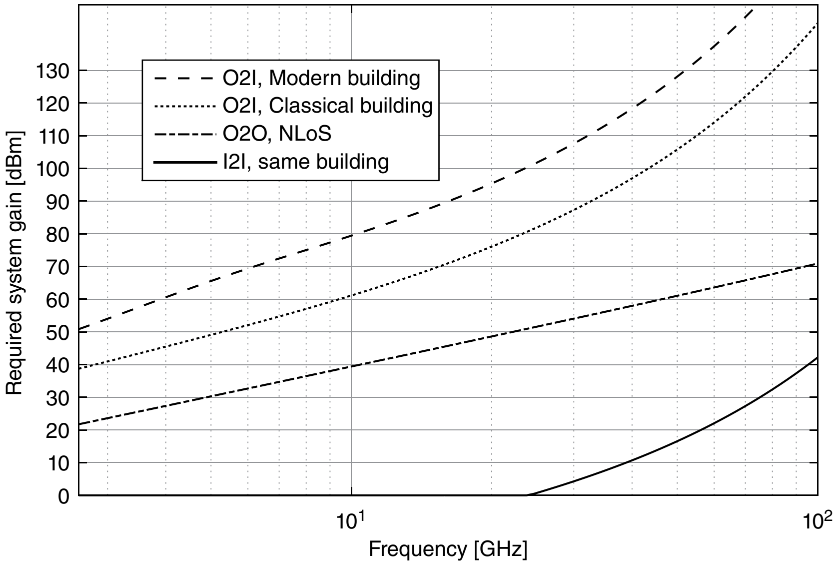

Figure 3-3. Required system gain for different deployment scenarios in relation to frequency ranges [22].

for O2I coverage. In addition, there is a very large variance on the O2I coverage feasibility due to the variety of building types and materials. Compared to the O2I case, the O2O and I2I scenarios have more relaxed requirements on the transmit power and beamforming capability so that carrier frequencies above 30 GHz could be still suitable. However, the beamforming capability is essential to compensate the propagation loss at high frequencies.

3.5.4 Coexistence of 5G Systems and Fixed Service Links

The fixed service is heavily used in some of the 5G candidate frequency bands above 6 GHz. Therefore, the coexistence of rooftop 5G macro-cell systems and fixed links operating in adjacent channels is to be investigated.

In Table 3-3, the aggregate adjacent channel interference at the fixed service receiver is shown [22], in dependence of the dish size of the fixed link receiver and the traffic load level within the 5G system. These results are based on system-level coexistence evaluations in a realistic three-dimensional (3D) dense urban city with a random height of buildings. In the simulations, the macro BSs and the fixed service link stations were placed on rooftop. A 3D ray-tracing-based propagation model was assumed for explicitly modeling diffraction and reflection. In addition, frequency dependent building penetration and wall loss were included. The antenna used in the study assumes UE specific beamforming such that the BS adjusts the beam direction towards a specific UE in a scheduling instance.

The 99th percentile of the aggregate adjacent channel interference in dBm/MHz received at the fixed service receiver is selected as the worst case. The estimated adjacent channel interference level is lower than the typical thermal noise level. In addition, an increase in the dish size of the fixed service station decreases the interference level further due to the higher directivity of the antenna,

Table 3-3. Aggregate adjacent channel interference at the fixed service receiver [22].

Fixed link receiving station dish size (m)	Load level within the 5G system	99% of adjacent channel interference (dBm/MHz)
0.3	Low	−133.7
0.3	High	−119.83
3.5	Low	−140.9
3.5	High	−127.74

allowing for a better selection of the wanted signal. The simulations were performed at a carrier frequency of 15 GHz. At higher frequencies, the potential for interference would be less, as the implementation of smaller beams creates more spatial separation in the 5G system, thus enlarging coexistence feasibilities.

3.5.5 Coexistence under License-exempt Operation

5G is designed to operate in different spectrum usage scenarios (see Section 3.2.1), including the “unlicensed user mode”. Listen-before-talk (LBT) is one well-known mitigation technique to enable the coexistence of wireless systems under license-exempt operation [25]. This section investigates the usage of LBT and its impact when high gain beamforming is used at high carrier frequencies.

Figure 3-4 illustrates the downlink system level performance of street micro cells in a dense urban deployment scenario, with and without applying LBT. Two networks, each with four access points (APs) and forty UEs, are considered. The APs are wall mounted and the UEs are

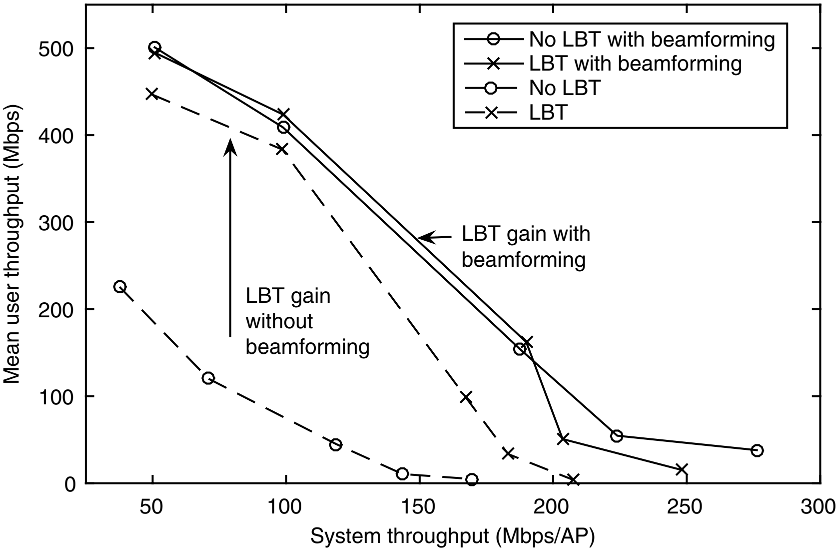

Figure 3-4. Impact of beamforming on coexistence under license-exempt operation [6].

distributed randomly outdoor in the streets. In case that beamforming is applied, it is implemented with 100 antenna elements at the BS.

It can be concluded that in general higher system load results in lower throughput per user, but generates an increase of the overall system throughput which is measured by aggregating the traffic from multiple users in the whole system. If beamforming is not applied, it can be observed that a better performance can be achieved with LBT. However, when beamforming is implemented, the impact of LBT becomes marginal. This implies that there is the potential of using high gain beamforming as a mitigation technique for inter-network spectrum sharing at high frequencies.

3.6 Spectrum Management

In order to cope with the versatile spectrum requirements of 5G, a flexible and effective spectrum management system is required. Additionally, in the advent of software-defined networking (SDN) and network function virtualization (NFV), mobile network operators are looking for new ways for further network optimization. Various levels of sharing such as radio access network (RAN) sharing with spectrum resource virtualization, infrastructure sharing, multi-operator core network (MOCN), multi-operator radio access network (MORAN), see also Section 6.7, entail the need for efficient information exchange and network management. Again, sophisticated solutions for radio resource management will be highly beneficial. In this section, evolutionary paths for the practical implementation of dynamic spectrum management are discussed, concluded by the introduction of a possible functional architecture covering both, the operator and the regulator domain.

3.6.1 Evolutions in Dynamic Spectrum Management

Accurate cooperation between MNOs and national regulatory authorities (NRAs) in terms of effective management of RAN and spectrum resources will be possible only in the presence of a stable, dedicated spectrum management system (SMS) being able to efficiently manage the utilization of spectrum resources available under diverse authorization schemes (e.g., exclusively licensed, LSA, license-exempt, see Section 3.2.1), i.e. to coordinate and control the realization of agreements, and to enforce the execution of decisions made. In consequence, such a SMS has to provide numerous functionalities to different stakeholders. On one hand, it should be fully automated, realized fully in a software manner, allowing for accurate and real-time access to shared resources. In order to achieve this goal, a set of standardized interfaces and protocols have to be defined and incorporated into the overall wireless network architecture. On the other hand, rules and policies on how the spectrum and other resources are managed might be modified in various ways, and these modifications can be implemented into the system either automatically or manually by qualified personnel. For example, new policies on spectrum sharing may be provided by the NRA in form of new regulations, or may be the result of mutual agreements between MNOs cooperating in LSA mode. Naturally, the features of a SMS have to be supplemented by effective access to the storage functionalities. The rules for spectrum management, for example those defining the way how operators share spectrum in LSA mode or how the NRA defines the spectrum access policies, have to be effectively stored and should be easily accessible for authorized users of the SMS. In consequence, the presence of dedicated databases or other forms of big data processing and management solutions have to be implemented as well.

Two key solutions for vertical spectrum sharing already exist: an architecture based on the LSA approach, and a three-tier sharing model controlled by a dedicated Spectrum Access System (SAS). The first one is implemented in Europe by a dedicated standard for the band 2.3-2.4 GHz [26], and the second one is promoted in the USA for the dynamic management in the 3.5 GHz band [27]. Both systems comprise of a central coordination entity equipped with some intelligence for proper decision making, by using dedicated protocols with a set of messages to be exchanged with the stakeholders. Moreover, the central coordination entity is able to query ancillary databases which are used for storing context information about the ambient environment. One may notice that these two solutions are not well advanced in terms of opportunities for its users, in particular as they are limited to certain frequency bands and to certain rules of spectrum sharing. Thus, in order to move a step forward towards effective dynamic spectrum management, the application of radio-environment maps (REM) are proposed in the research community.

REMs, also referred to as geolocation databases (GLDB), are considered as an advanced and dedicated tool for effective storage and management of available rich context information, which may be helpful for efficient flexible spectrum access [28]. The REM approach has been considered as a real and pragmatic solution for the problem of unreliable spectrum sensing algorithms which were developed mainly in the context of cognitive radio. REMs are applied as an entity for guaranteeing reliable access to various types of gathered information, and in consequence, for facilitating flexible spectrum access. Most frequently, the databases are considered in the context of storage of interference maps between two radio systems operating in a certain geographical area. Moreover, these structures can store information about the location of wireless transceivers, their transmit parameters and coverage area. Fast and reliable access to such accurate information will enable better spectrum management and thus lead to more efficient spectrum utilization. In a broader sense, REM databases can contain not only interference or coverage information, but may be used also for keeping typical traffic distribution of the mobile users, dedicated and unique, yet anonymized history maps associated with each user. In such a map the traffic distribution over time and space may be provided. In order to realize sophisticated spectrum management, a dedicated REM management system is needed, equipped with an entity responsible for database queries and management, and a dedicated engine for the analysis of the data on users and inference. Thus, a REM based spectrum management system seems to be highly similar to the generic concept of the SMS considered earlier.

The future SMS has to be discussed also in the context of effective coexistence between cellular mobile and Wireless Local Area Network (WLAN) deployments. Mobile data offloading from cellular to other types of networks is one solution for effective management of high user-data traffic. MNOs and hardware manufacturers are widely considering coexistence and even cooperation between technologies operating in licensed and in license-exempt spectrum, for example the License Assisted Access (LAA) scheme using carrier aggregation to combine LTE in the license-exempt 5 GHz spectrum with LTE in licensed bands. With this aggregation, where control and signaling information is transmitted in the licensed spectrum, higher user data rates can be supported, while the user experience remains seamless and reliable. The convergence of cellular and non-cellular networks is supported by technical developments in both research and standardization communities. In 3GPP-based networks, the presence of the Access Network Discovery and Selection Function (ANDSF) entity, as well as Local IP Access (LIPA) or Selected IP Traffic Offloading (SIPTO), are the exemplary steps toward this direction. In the IEEE community, the introduction of the Wi-Fi Certified Passpoint™ and the Hotspot 2.0 concept, together with advanced databases and the dedicated Access Network Query Protocol (ANQP), pave the way for tighter cooperation between cellular and non-cellular networks. Further information can be found in [29] and [30]. The discussion above leads to the following conclusions: First, there are already technologies and technical solutions available for an effective management of traffic between these two types of networks. Second, there is a strong need for a RAT-independent SMS. The latter should be treated as a solution for the effective organization of various types of spectrum resources and RATs. Again, the application of such a RAT-agnostic SMS requires the presence of a dedicated inference engine, standardized protocols and interfaces for message exchange, as well as accurate databases.

Finally, one may observe that in fact most of the contemporary wireless networks are based on IP-centric solutions. Thus, MNOs may benefit from the virtualization of their resources. Indeed, SDN together with the application of NFV opens the door for a fully software-controlled management and optimization of networks. In such a context, the data of mobile users connected to the network may be managed by means of virtualized entities. One can even claim that if the service-level agreements (SLAs) between end-users and service providers are fulfilled, the way how the data is transported, i.e., over cellular or non-cellular connection, is of secondary importance. As the virtualization techniques are now widely applied to various types of networks, one may again assume that there is a need for an advanced, flexible spectrum management system that will be able – in a wide sense – to coordinate and control the usage of spectrum resources from a common pool. A comprehensive discussion on wireless network virtualization may be found for instance in [31].

3.6.2 Functional Spectrum Management Architecture

Advanced spectrum management systems are already under consideration in different research projects [6], [32]. A possible functional architecture of a holistic SMS is illustrated in Figure 3-5, embracing the key functionalities required from a regulatory (NRA domain) as well as from an operational (MNO domain) point of view.

SMS functionalities within the NRA domain:

- **Regulatory Spectrum Coordination**: From NRA perspective, the management and coordination of spectrum requires the existence of a central coordination point which is permitted to perform any necessary action to guarantee proper execution of NRA rules. This entity has to handle also the communication with the MNO domains.
- **System Management**: As already mentioned, the SMS should be able to incorporate any modifications of the existing (applied) spectrum management policies or to include new ones. These policies may be prepared in human- and/or machine understandable form, and be provided either in an automated way, or implemented by qualified personnel, while the system management is providing functions to perform operation administration, and maintenance tasks.
- **Spectrum User Authorization**: From the NRA perspective it is evident that the SMS system should provide functionality for secure user authorization. Thus, this entity is containing MNOs licensing and registration information.
- **Data storage**: Information of interest from the perspective of NRA (such as spectrum resources, protection and usage rules, etc.) has to be stored in an efficient form. Dedicated repositories and databases shall be available in the SMS, which may create a fragment of the overall REM-based structure.
- **Monitoring functionality** (including reporting and information entry): In order to realize fair and effective management of the spectrum, but also to avoid violation of policies provided by the

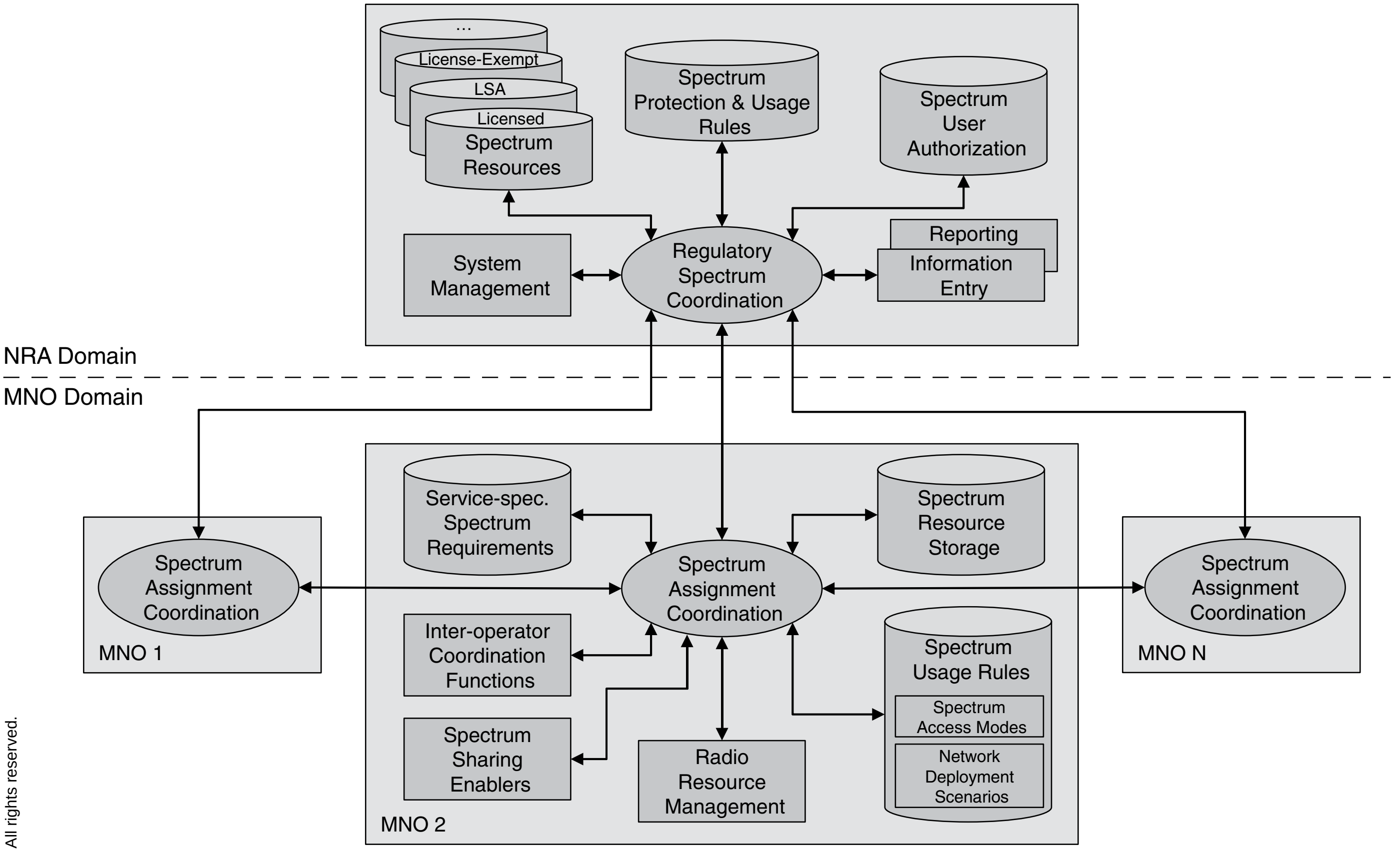

Figure 3-5. Functional architecture of a holistic spectrum management system.

stakeholders, advanced monitoring functionalities have to be available to the NRA. These modules will provide updates to the Regulatory Spectrum Coordination entity, which in turn will provide updates to the databases.

SMS functionalities within the MNO domain:

- **Spectrum Assignment Coordination**: This entity plays a central coordination role. It is responsible for spectrum assignment (radio resource management) by utilizing information from various data bases and spectrum sharing enablers if applicable. It also coordinates the mutual dependencies between operators (defined and stored in the databases), and communicates with the Regulatory Spectrum Coordination entity in the NRA domain.
- **Dedicated interfaces due to ownership issues**: There will be a dedicated client of the SMS system per each MNO due to the fact that each one needs to manage sensitive information (e.g., data related to customers, business etc.). However, in a virtualized scenario, such a spectrum management application (client) needs to communicate with other involved stakeholders to exchange necessary data for proper spectrum management. Thus, both dedicated interfaces between the involved MNOs and between MNOs and the NRA, and advanced inter-operator functionalities have to be incorporated in the system.
- **Policy analysis**: some of the policies may be generic (e.g., those provided by the NRA and defining the rules of thumb for a certain services, frequencies or geographical areas), whereas others may be more specific (such as those defined by the mutual agreements between two MNOs). As the SMS is assumed to be RAT-agnostic (i.e., various RATs may be used simultaneously), there is a risk that these policies may be somehow mutually depended, or even incoherent. In order to avoid any problems related to this aspect, the SMS should be equipped with a dedicated reasoning and inference engine being able to apply advanced inference and machine learning algorithms.
- **Access to Databases**: Information received from the NRA but also from other MNOs, or gathered by dedicated monitoring modules, have to be stored in the databases. These databases may be part of broader REM-based structure. In case of network virtualization, these databases will include for example service-specific requirements or rules related to spectrum usage. Three types of repositories are included in Figure 3-5: Service-Specific Spectrum Requirements, Spectrum Resource Storage, and Spectrum Usage Rules.

It is to be noted that the above split of functionalities does not provide any conclusion on how the SMS is implemented. In particular, although the spectrum coordinator entities are centralized in a logical way, in practice there may be a number of coordination modules, each responsible for a certain geographical area. Moreover, a hierarchical deployment scenario may be considered, where the long-term analysis (such as reasoning for potential policy updates, analysis of the traffic, application of LSA rules etc.) may be implemented in the core network, and short term decisions (such as scheduling, vertical and horizontal handover management, etc.) will be placed in the RAN.

3.7 Summary and Outlook

In 5G networks, data rates from a few kbps up to several Gbps will need to be supported. A significant amount of additional spectrum, preferably globally harmonized, needs to be made available for mobile communications to cope with the predicted extreme high mobile traffic for specific usage scenarios. Therefore, a number of frequency ranges between 24.25 GHz and 86 GHz are studied with regard to coexistence feasibilities between the services currently in operation and future 5G implementations. Furthermore, initiatives have been established in different regions and countries to foster the timely availability of 5G. For instance, the European 5G Action Plan is promoting pan-European multi-stakeholder trials and early deployment in major urban areas and along major transport paths.

For eMBB applications, a mixture of frequency bands is required: lower bands for coverage purposes and for low to medium data traffic, and higher bands with large contiguous bandwidth to deal with the expected extremely high traffic demand. For mMTC applications, mainly frequency spectrum below 6 GHz is demanded, and spectrum below 1 GHz for wide area coverage and reliable outdoor to indoor penetration. For URLLC applications, high and reliable spectrum availability is required, for which licensed spectrum is considered most appropriate. In order to ensure high QoS, good system performance, and incentives for investment in network infrastructure, exclusively licensed spectrum on a technology-neutral basis is essential. Shared spectrum and license-exempt spectrum can play a complementary role to increase capacity and user experience.

The implementation of diverse spectrum usage scenarios, using frequencies from below 1 GHz up to almost 100 GHz with possibly diverging authorization schemes, requires a flexible and effective spectrum management, both in the regulatory domain as well as within the operational system. Based on already established approaches like LSA, sophisticated architectures are under development in different research projects.

The bandwidth required for a radio communications network depends mainly on the following three parameters: (1) the targeted QoS, (2) the area spectral efficiency, and (3) the physical deployment and distribution of transmitters and receivers. Since the achievable values of QoS may vary greatly, a Monte Carlo computational approach is required, in order to obtain a reliable evaluation of the QoS achievable with different bandwidths available at each frequency band.

The move of mobile services to higher frequencies goes along with less favorable propagations conditions, in particular for outdoor-to-indoor coverage. The higher propagation loss with increasing carrier frequency might be compensated to some extent by the implementation of advanced antenna systems like beamforming, but this effect will in practice be restricted by hardware design and electro-magnetic field exposure limits. Beamforming can be considered also as a mean to ease coexistence between radiocommunication services operating in higher frequency bands.

There is a trend towards using even higher frequency bands than currently under consideration in ITU-R. For example, in the Horizon 2020 project TWEETHER [33] a wireless distribution system in the W-band (92-95 GHz) is studied, to be linked to fixed fiber networks and to mobile networks deployed in bands below 6 GHz, in order to have finally a hybrid solution providing seamless connectivity with high capacity and wide coverage. Even at 300 GHz, a range which may have a potential for ultra-fast future wireless short range services, data transmission of 12.5 Gbps could be experimentally demonstrated with a wireless link operating generated and modulated with photonic technologies [34].

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4

Channel Modeling

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4.1 Introduction

The emerging 5th generation (5G) cellular systems raise unprecedented requirements on data rates, link reliabilities, end-to-end (E2E) latencies, and the support of a portfolio of different scenarios and service types. To satisfy 5G requirements, cutting-edge technology components are proposed both in academia and in industry. First, targeted frequency bands are expanded from legacy below 6 GHz to above 6 GHz millimeter-wave (mmWave) bands, which are able to provide large frequency resources to boost throughput. Second, recently massive multiple-input multiple-output (MIMO) technology has appealed to the communication community due to its promising capability of greatly improving spectral efficiency, energy efficiency, and robustness of the system by equipping a base station (BS) with a large number of antenna elements (typically tens or even hundreds). Third, massive machine-type communications (mMTC) are emerging to provide scalable, energy-efficient and smart services for sensors, healthcare, and consumer goods. The design and evaluation of these technology components demand an accurate and efficient channel model.

The most widely used channel model family is the well-known 3rd Generation Partnership Project (3GPP) spatial channel model (SCM) and Wireless World Initiative New Radio phase II (WINNER II) family, which follows the geometry-based stochastic channel model (GSCM) approach. As shown in Figure 4-1, the SCM/WINNER II family has been continually evolving for more than a decade. Each evolution of the family introduces further key features, such as time variation modeling in the SCM extension (SCME), support of wider bandwidth and more scenarios in the WINNER II and International Mobile Telecommunications-Advanced (IMT-A) channel models, three dimensional (3D) propagation modeling in the WINNER+ channel model and 3GPP 3D-SCM [1], and early 5G support in the Mobile and Wireless Communications Enablers for the Twenty-twenty Information

5G System Design: Architectural and Functional Considerations and Long Term Research, First Edition.
Edited by Patrick Marsch, Ömer Bulakçı, Olav Queseth and Mauro Boldi.

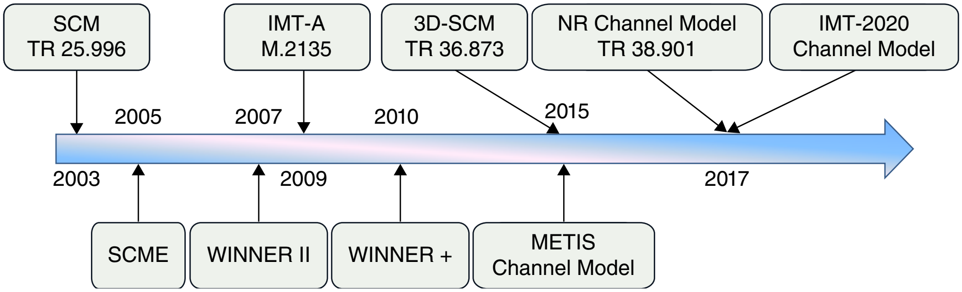

Figure 4-1. Evolution of the SCM/WINNER II channel model family.

Society (METIS) channel model [2]. Among these evolved models, the 3GPP 3D-SCM was most popular, as it was previously utilized in the standard for system evaluation. In the 3GPP 3D-SCM, like other members of the SCM/WINNER II family of channel models, the scattering environment between the BS and user equipment (UE) is abstracted by a number of effective clusters. These clusters are characterized by angular spectrum, delay spectrum, and cluster power. An important feature of 3GPP 3D-SCM is that both azimuth and elevation angles are modeled, capturing the essence of 3D channel properties. Large-scale parameters (LSPs) such as path loss parameters, shadow fading, line-of-sight (LOS) factor, delay and angular spreads are determined stochastically based on measurements. Beside channel generation, the concept of user dropping is also applied, where a drop is defined as one simulation run with constant channel parameters for a certain set of cells or sectors, BSs and UEs over a period of time.

However, 5G requirements in the 3GPP New Radio (NR) standard introduce new challenges to channel models. For example, NR is expected to support mmWave bands, massive MIMO and new use cases, which are not sufficiently supported by existing channel models. As a result, 3GPP has developed the channel model for NR [3] with a supported frequency range from 0.5 to 100 GHz. The support of large antenna arrays and up to 2 GHz bandwidth enables the NR channel model to capture essential characteristics of mmWave channels. Additionally, mmWave propagation aspects such as blockage modeling and atmosphere attenuation are considered. The NR channel model should take various types of links into account to satisfy scenarios ranging from ordinary cellular scenarios to mMTC communications and high mobility scenarios. The modeling of space-time-frequency consistency is also regarded as an important additional feature for multi-user MIMO (MU-MIMO), dual connectivity and beam tracking simulations. In the NR channel model, in addition to the extension of GSCM, a map-based approach is proposed to enable site-specific simulations. For the purpose of evaluating 5G proposals, the International Telecommunication Union (ITU) working group 5D (WP5D) proposed the IMT-2020 channel model [4] which further extended the NR channel model by considering more scenarios and including optional parameter tables and features.

In this chapter, core features of new channel models, such as path loss modeling and fast fading generation, are initially described in Section 4.2. Then, additional features such as the modeling of large antenna arrays, blockage, scattering, etc. are introduced in Section 4.3. Finally, the chapter is summarized in Section 4.4, where also potential future research directions for channel models capable of meeting the requirements of the evolving 5G system are described.

4.2 Core Features of New Channel Models

The core features in this chapter form the basic building blocks of channel coefficient generation. These include the path loss model, LOS probability modeling, outdoor-to-indoor (O2I) penetration loss modeling, and fast fading modeling.

4.2.1 Path Loss

Path loss, the electromagnetic signal power attenuation from the transmitter to the receiver, is a major measure of the propagation channel quality and is important for assessing the wireless system performance. Path loss models in different scenarios for cellular applications have been extensively studied during the past for bands below 6 GHz. In recent years, focus has been shifted to bands from 6-100 GHz for developing 5G mmWave small-cell networks. The general finding for path loss from numerous measurements in mmWave bands is that, due to high penetration and scattering loss, there is usually more excess attenuation (i.e., excluding free space path loss) on non-line-of-sight (NLOS) paths when compared to existing cellular bands. This results in a sharp difference in the path loss exponent between LOS and NLOS mmWave links.

The two classical models for path loss, i.e., the float-intercept (FI)[1] and close-in (CI) models have been used in the literature and in different study groups and projects [3] [5] [6], and have been parameterized for various environments and frequency bands from 0.5 up to 100 GHz. The path loss (in dB) in FI and CI models is a function of link distance d (in meters) and carrier frequency f_c (in GHz), and given as

$$PL^{\mathrm{FI}}\left(f_c,d\right)=10\alpha\log_{10}\left(\frac{d}{1\mathrm{m}}\right)+\beta+10\gamma\log_{10}\left(\frac{f_c}{1\mathrm{GHz}}\right)+\mathrm{N}\left(0,\sigma^{\mathrm{FI}}\right) \tag{4-1}$$

$$PL^{\mathrm{CI}}\left(f_c,d\right)=\mathrm{FSPL}\left(f_c,1\mathrm{m}\right)+10n\log_{10}\left(\frac{d}{1\mathrm{m}}\right)+\mathrm{N}\left(0,\sigma^{\mathrm{CI}}\right) \tag{4-2}$$

where σ^{FI} and σ^{CI} are the standard deviation of path loss (i.e., shadowing fading term) in FI and CI models, respectively. The parameters α, β and γ in Eq. (4-1) are the path loss decay component, FI path loss at $d = 1\,\mathrm{m}$, and the frequency dependency coefficient, respectively. The term γ is dismissed in Eq. (4-1) when a single frequency is modeled. In Eq. (4-2), FSPL(f_c, 1m) is the free-space path loss at $d = 1\,\mathrm{m}$, and n is the path loss exponent. Table 4-1 and Table 4-2 present the curve-fitting omnidirectional path loss model parameters using FI and CI models. These are obtained from numerous measurements and ray-tracing simulations in outdoor and indoor environments, respectively, reported in [5], [6] and [7]. The curve fitting process is done via minimizing the standard deviation of the measured or simulated path loss data using the above model equations, where the model parameters are the variables to be optimized. It is emphasized here that the applicable ranges of antenna height, link distance, and frequency are different in [5], [6] and [7]. In addition, different data fusion methods are used in the models for the scenarios where measured data is collected from multiple campaigns.

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[1] The term "alpha-beta-gamma" (ABG) is also used for the floating-intercept model.

Table 4-1. Parameters of path loss models for different outdoor scenarios.

Model scenario and frequency range		Model type	*n* or *α*	*β*	*γ*	*σ*
UMi Street Canyon in [7] Frequency range: 2-73.5 GHz	LOS	FI	2	31.4	2.1	2.9
		CI	2	–	–	2.9
	NLOS	FI	3.5	21.4	1.9	8.0
		CI	3.1	–	–	8.1
UMi Street Canyon in [5] Frequency range: 2-86 GHz	LOS	FI	1.92	32.9	2.08	2.0
	NLOS	FI	4.5	31	2.0	7.82
UMa in [5] Frequency range: 2-73.5 GHz	LOS	FI	2.8	11.4	2.3	4.1
	NLOS	CI	2.7	–	–	10

Table 4-2. Parameters of path loss models for different indoor scenarios.

Model scenario and frequency range		Model type	*n* or *α*	*β*	*γ*	*σ*
Indoor in [5][2] Frequency range: 2-86 GHz	LOS	FI	1.38	33.6	2.03	1.18
	NLOS	FI	3.69	15.2	2.68	8.03
InH Indoor Office in [6] Frequency range: 2-73 GHz	LOS	CI	1.73	–	–	3.02
InH Shopping Mall in [6] Frequency range: 2-73 GHz	LOS	CI	1.73	–	–	2.01

In the standardized 3GPP NR channel model [3], additional refinements are considered for urban micro (UMi) Street Canyon, indoor hotspot (InH), and urban macro (UMa) scenarios to incorporate 3D link distance, effective antenna heights, and LOS breakpoint into the path loss. Here, the same model parameters are used for the whole range of applicable frequencies, i.e. from 0.5 to 100 GHz (see Table 7.4.1-1 in [3]). ITU-R Recommendation P.1411-8 models path loss differently for ultra-high frequency (UHF), super-high frequency (SHF) up to 15 GHz, and mmWave frequency ranges, while additional losses caused by atmospheric gases and rain, and directive antennas are considered for the latter [8]. Specifically, using the CI model, the directional path loss when both transmit and receive antennas are pointing to each other in LOS condition is given by

$$PL(d) = PL_0 + 10n\log_{10}\left(\frac{d}{d_0}\right) + L_{\mathrm{gas}} + L_{\mathrm{rain}} \tag{4-3}$$

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[2] Indoor scenario in [5] is a merged scenario including office, lecture room, and airport.

where PL_0, L_{gas}, L_{rain} are the path loss at the reference distance d_0, and attenuations caused by the atmospheric gases and by rain, respectively. The model is parameterized for the urban LOS scenario with different building types (high-rise and low-rise) and for transmit (receiver) antenna half-power beam widths of 30 (10) degrees in the 28 GHz band, or 15.4 (15.4) degrees for 60 GHz bands (see Table 6 in [8]).

The above FI and CI have the same set of optimized parameters including the path loss exponent and shadow fading standard deviation for the whole range of applicable frequencies. Recent works have also investigated the frequency dependency of the path loss exponent in the CI model [6], or all of the parameters in [9]. Specifically, in [9], each of $(\alpha,\beta,\gamma,\sigma)$ in the FI model or (n,σ) in the CI model are functions of carrier frequency, and given as

$$\chi = a - b\log_{10}\left(\frac{f_c}{1\text{GHz}}\right) \tag{4-4}$$

where χ represents a parameter of interest, and a and b are model parameters. The frequency-dependency of these path loss model parameters in the range of 0.8 to 60.4 GHz was revealed in [9] for the Street Canyon scenario for both LOS and NLOS conditions. Using the new frequency-dependent model parameter set, it was shown in [9] that both FI and CI models outperform the ITU-R M.2135 UMi models in term of path loss prediction accuracy.

4.2.2 LOS Probability

As different path loss model parameters are applied for LOS and NLOS links, it is important to identify whether a link is in LOS or NLOS condition. There are several different analytical models to characterize LOS probability, including the random shape theory model [10], the LOS ball model [11], and the standardized 3GPP and ITU-R models [3], [8]. In the ITU recommendation, the LOS probability for UMi and InH are calculated based on the link distance d as

$$P_{\text{LOS}}(d) = \min\left(\frac{d_1}{d}, 1\right)\left(1 - e^{-\frac{d}{\alpha}}\right) + e^{-\frac{d}{\alpha}} \tag{4-5}$$

and

$$P_{\text{LOS}}(d) = \begin{cases} 1 & \text{if} \quad d \le d_1 \\ e^{-\frac{d-d_1}{\alpha}} & \text{if} \quad d_1 < d < d_2 \\ P_0 & \text{if} \quad d \ge d_2 \end{cases} \tag{4-6}$$

respectively, where d_1 is the distance up to which LOS is guaranteed, α is the decaying parameter, and d_2 is the distance at which $P_{\text{LOS}} = P_0$. In 3GPP, a similar exponential model is used, but the parameters are different for different environments. They include UMa Street Canyon, UMi Street Canyon, rural macrocell (RMa) and indoor office, where antenna heights are assumed to be at 25 m, 10 m and 3 m, respectively (see Table 7.4.2-1 in [3]).

In [12], a linear model and a more generic exponential model are considered, where the LOS probability for a link distance d is respectively given by

$$P_{\mathrm{LOS}}(d)=\begin{cases} 1 & \text{if} \quad d \le d_1 \\ \dfrac{(d_2-d)(1-P_0)}{d_2-d_1}+P_0 & \text{if} \quad d_1 < d < d_2 \\ P_0 & \text{if} \quad d \ge d_2 \end{cases} \tag{4-7}$$

and

$$P_{\mathrm{LOS}}(d)=(1-P_\infty)\exp\left(-\left(\frac{d}{\alpha}\right)^N\right)+P_\infty \tag{4-8}$$

where $P_\infty = P_{\mathrm{LOS}}\,|_{d\to\infty}$ and N is the exponent. The models were parameterized for open square, shopping mall and indoor office scenarios using accurate point cloud models, and were demonstrated to have a very good agreement with available measurements.

Except for the results in [12], the curve-fit parameters in the above models are mainly obtained from measurements in existing cellular bands and independent of the carrier frequency. It is essential to investigate the environment-specific LOS probability in higher frequency bands, as the clearance of blockages from the first Fresnel zone of a link is smaller. Specifically, a link is obstructed-LOS or NLOS if there is at least one obstacle, having the total link distance to the BS and UE satisfying [12]

$$d_{\mathrm{BS}-p}+d_{\mathrm{UE}-p}<d_{\mathrm{BS-UE}}+\frac{\lambda}{2} \tag{4-9}$$

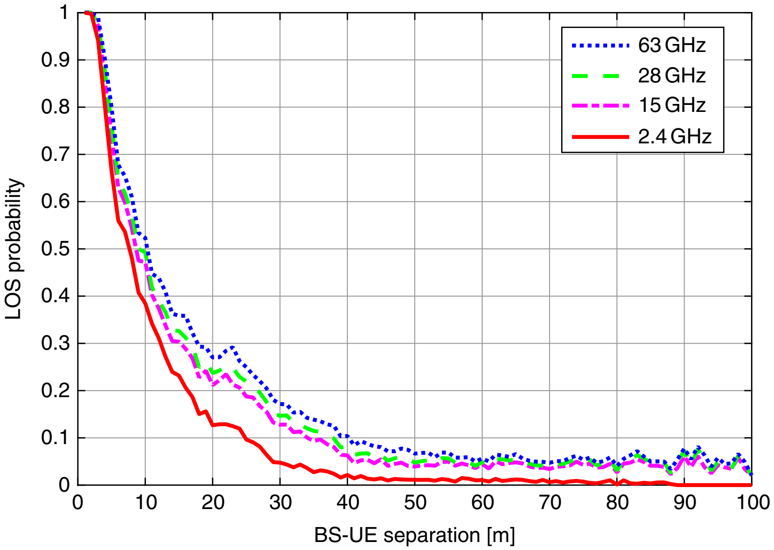

Figure 4-2. LOS probability in a shopping mall at different frequencies [12].

where $d_{\text{BS}-p}$, $d_{\text{UE}-p}$ and $d_{\text{BS}-\text{UE}}$ are the 3D distances between the BS to the obstacle, between the UE to the obstacle, and between the BS and the UE, respectively, and λ is the wavelength of the carrier frequency. It was revealed in [12] that while significantly different LOS probabilities are applied for below and above 6 GHz, the same model parameters can be used for mmWave bands, as only small variations in probability values were found in those bands.

4.2.3 O2I Penetration Loss

For O2I link analysis and coverage evaluation, the signal attenuation through building walls and objects inside the building needs to be added into the basic path loss, producing total path loss. The O2I path loss can in general be expressed as [8]

$$PL_{\text{O2I}} = PL_{\text{bpl}} + PL_{\text{bel}} + PL_{\text{in}} + \text{N}\left(0, \sigma_{\text{dB}}^2\right) \tag{4-10}$$

where PL_{bpl} is the basic path loss (formulated and modeled as in Section 4.2.1), PL_{bel} is the building entry loss through external walls, PL_{in} is the indoor path loss dependent on the depth into the building, and σ_{dB} is the standard deviation of the O2I path loss.

The building entry loss level is highly dependent on building materials and structures, incidence angle, and varies across frequencies. For a rigorous characterization, the penetration loss through a building wall or window can be calculated using the Fresnel transmission coefficients [13], given that the wall or window material and structure are accurately modeled. Using the model parameters for electrical properties of the materials given by the ITU recommendation (see Table 3 in [13]), the calculated penetration losses with a perpendicular polarization of a single-layer concrete and glass wall are shown in Figure 4-3. As can be seen from the subfigures, the loss is material-dependent, and increases with the slab width, incidence angle[3] (left subfigure) and frequency (right subfigure).

The curve-fitting model parameters for the electrical properties of popular materials in the frequency range of 1-100 GHz provided in [13] can be used for calculating site-specific building penetration loss. In reality, however, the calculation is often just an approximation, since the building material structure is much more complex, as it is not just single or homogeneous, but normally a combination of different materials. Therefore, an accurate profile of the building walls and windows is not always available, as it becomes hard for such a calculation to predict the overall penetration loss, especially for such a large environment. It is observed by measurements that compound material can have very different electrical properties, and hence cause a different transmission loss as compared to homogeneous material. For example, coated-glass windows in modern office buildings cause a signal attenuation as strong as 30 dB at mmWave frequencies, much higher than the 10 dB signal attenuation of the non-coated glass windows exhibited at the same frequencies [5].

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[3] This trend does not apply for an incidence angle close to the pseudo-Brewster angle due to the effect of a minimum reflection coefficient for the perpendicular polarization [13].

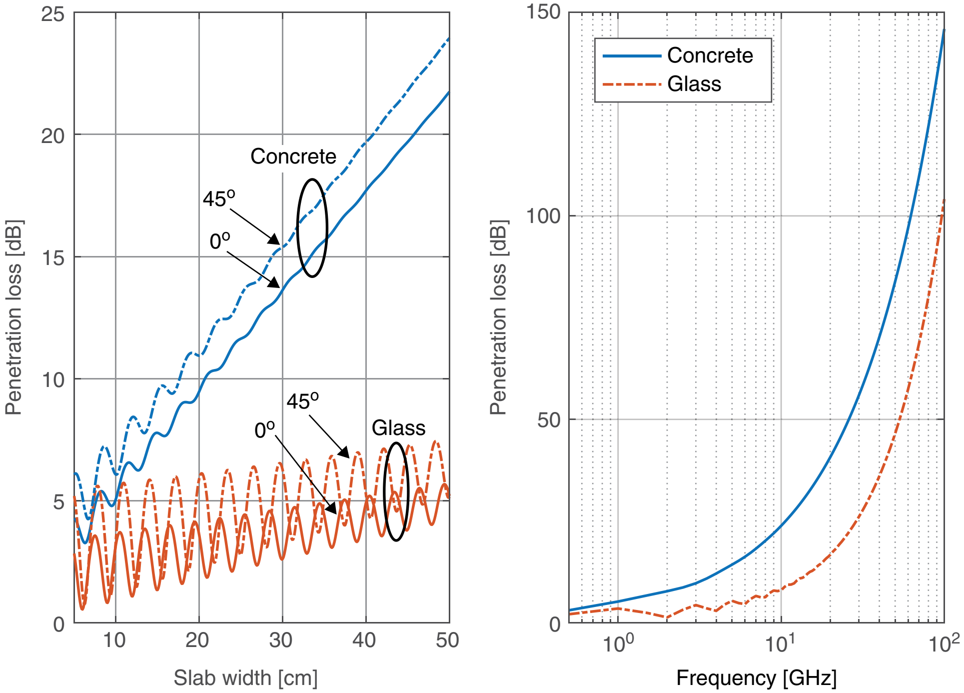

Figure 4-3. (Left) Calculated penetration loss at 2 GHz for transverse-magnetic (TM) polarization with incident angles of 0° (solid) and 45° (dashed); (Right) Calculated penetration loss for TM polarization for concrete of 15 cm width, and glass slabs with incident angle of 0°.

The experiment-based 3GPP building entry loss model takes into account the penetration losses through different building materials and the loss from the non-perpendicular incidence angle loss formulated as

$$PL_{bel} = PL_{npi} - 10\log_{10}\sum_{n=1}^{N} p_n 10^{-\frac{L_{m_n}}{10}} \tag{4-11}$$

where PL_{npi} is the non-perpendicular incidence loss, p_n and L_{m_n} are the proportion of and the loss through the n -th material, respectively, and N is the total number of materials. A simple linear model for L_{m_n} taking into account the frequency dependency based on curve-fitting to the measurements is provided in [1] for popular materials including concrete, wood and glass.

The 3GPP total O2I loss model in Eq. (4-11) was parameterized for UMi and UMa with different types of high-loss and low-loss buildings, for a frequency range from 0.5 up to 100 GHz [3]. It should be noted that the 3D-SCM O2I penetration loss and the NR O2I penetration loss are modeled under different modeling frameworks. The former is generated in a *link-specific* manner, i.e., each link between a BS and UE has an individual O2I penetration loss value. Conversely, the latter is *UE-specific*, i.e., each UE has an O2I penetration loss value which is shared by all links between BSs and the UE. In [5], the O2I loss model is basically the same as the corresponding model agreed in

3GPP with the additional refinements, including a lognormal frequency-dependent spread and elevation angle dependence. The model was parameterized for the UMi scenario for the frequency range of 10-60 GHz [5].

4.2.4 Fast Fading Generation

When considering a channel with N clusters, the MIMO channel impulse response between the uth receive antenna and the sth transmit antenna $h_{u,s}(t,\tau)$ at time t and delay τ can be expressed as

$$h_{u,s}(t,\tau)=\sum_{n=1}^{N} h_{u,s,n}(t)\delta(\tau-\tau_n) \tag{4-12}$$

where $h_{u,s,n}$ is the complex coefficient between the uth receive antenna and the sth transmit antenna of the nth cluster, τ_n is the delay of the nth cluster, and $\delta(\cdot)$ is the Dirac function defined by $\delta(x)$ which equals 1 if $x=0$ and equals 0 otherwise. The complex coefficient $h_{u,s,n}$ of the nth cluster is obtained by summing the contributions of M subpaths as

$$h_{u,s,n}(t)=\sum_{m=1}^{M}\sqrt{P_{n,m}}\mathbf{F}_{\mathrm{RX},u,n,m}^{\mathrm{T}}\cdot\mathbf{\Gamma}_{n,m}\cdot\mathbf{F}_{\mathrm{TX},s,n,m}\cdot e^{j\varphi_{n,m}} \tag{4-13}$$

where $P_{n,m}$ is the power, $\mathbf{F}_{\mathrm{RX},u,n,m}$ and $\mathbf{F}_{\mathrm{TX},s,n,m}$ are the antenna patterns of the receive and transmit antenna elements, $\mathbf{\Gamma}_{n,m}$ is the 2×2 polarization matrix, and $\varphi_{n,m}$ is the aggregate phase term including the phase difference due to antenna positions and the Doppler phase shift.

Prior to generating these channel coefficients, the small-scale parameters need to be computed. Cluster delays are randomly generated according to the power delay profile (PDP). Then, cluster delays are mapped to compute cluster powers. The strongest two clusters are divided into sub-clusters to support up to 100 MHz bandwidth. Next, arrival angles and departure angles are calculated based on the angular spectrum and cluster powers. With these angles, antenna patterns of the receive and transmit antenna elements can then be calculated. After generating the polarization matrix and the aggregate phase term, the final channel coefficients can be computed according to Eq. (4-12).

4.3 Additional Features of New Channel Models

To fully evaluate 5G systems, a set of additional features can be included during the channel generation procedure. In this subsection, these additional features as well as their impacts on the 5G system design will be introduced.

4.3.1 Large Bandwidths and Large Antenna Arrays

One benefit of deploying 5G networks in mmWave bands is the large bandwidth these can provide, as already discussed in Section 3.4. Meanwhile, mmWave bands also bring severe propagation loss which needs the massive array gain of large antenna arrays to compensate. Hence, support of large bandwidths and large antenna arrays in the 5G channel model is required. The key impact of large bandwidths and large antenna arrays is that they introduce finer resolutions in both the temporal and spatial domains, resulting in more resolvable subpaths in each cluster. Although intra-cluster subpaths are already supported in legacy channel models, only the strongest two clusters are so far considered to have subpaths, and an equal power distribution is assumed across these subpaths. Moreover, legacy channel models consider up to 400 paths in a channel impulse response, and the maximum number of paths is irrelevant to bandwidth or antenna array size. However, measurement campaigns in [5] in mmWave bands have shown that in order to capture 95% of the channel power, the number of paths to consider is significantly larger than those in below 6 GHz bands, when large bandwidths and large antenna arrays are applied. This is because wavelengths in mmWave are smaller, and diffusive reflected paths are more significant than in below 6 GHz bands. The increase in resolvable paths implies a richer scattering environment in large bandwidth and large antenna array scenarios.

In the 3GPP NR channel model [3], the modeling of intra-cluster delay and angular spreads was enhanced to better support large bandwidths and large antenna arrays. Unlike legacy channel models, where the number of subpaths per cluster is constant, the number of subpaths per cluster M in the NR channel model is proportional to the bandwidth, size of antenna aperture, and carrier frequency. Subpath-specific power, delay, and angles are generated according to distributions obtained via measurements. Another fundamental difference to the 3GPP 3D-SCM [1] is that intra-cluster delay and angle are independently generated. Both delays and intra-cluster angular offsets are generated by uniformly distributed random variables (r.v.s). Subpath powers are obtained via Monte Carlo sampling in the temporal-spatial spectrum. After all necessary small-scale parameters are generated, the overall channel impulse response with large bandwidth and antenna array support can be expressed as the sum of the subpaths

$$h_{u,s}\left(t,\tau\right)=\sum_{n=1}^{N}\sum_{m=1}^{M}h_{u,s,n,m}\left(t\right)\delta\left(\tau-\tau_{n,m}\right) \tag{4-14}$$

where $h_{u,s,n,m}$ is the complex coefficient between the uth receive antenna and the sth transmit antenna of the mth subpath within the nth cluster, given as

$$h_{u,s,n,m}\left(t\right)=\sqrt{P_{n,m}}\mathbf{F}_{\mathrm{RX},u,n,m}^{\mathrm{T}}\cdot\mathbf{\Gamma}_{n,m}\cdot\mathbf{F}_{\mathrm{TX},s,n,m}\cdot e^{j\varphi_{n,m}}. \tag{4-15}$$

It should be noted that intra-cluster characteristics are highly dependent on the clustering algorithm used during post-processing. Typical clustering algorithms such as the Kmeans++, the agglomerative algorithm and the time cluster and spatial lobe clustering algorithm approach were introduced in [6].

Due to spatial and temporal richness and intra-cluster characteristics in mmWave channels, the number of radio frequency (RF) chains in massive MIMO systems with hybrid beamforming should be carefully chosen to reach a balance between implementation complexity and utilization of the richness of the mmWave channel, as elaborated further in Section 11.5. Also, frame structures of different numerologies should be adaptive, i.e., the length of (shortened) transmission time intervals (TTIs) and subcarrier spacings should be designed according to the richness of the channel, as detailed in Section 11.6.

4.3.2 Spatial Consistency

The modeling of spatial consistency is an important feature in the 5G channel model. Spatial consistency describes how the channel evolves as a function of the spatial location in a continuous manner, which is important for beam tracking system design for mmWave. When two users are located near each other, their channels should experience similar characteristics, such as similar angles of arrivals and delay spreads. In legacy channel models, channel characteristics of these two users are generated independently resulting in an overestimated MU-MIMO gain. In the 5G channel model, this defect is solved by introducing correlations in the channel characteristics of these two users. The correlation of two users is calculated as

$$\mathrm{R}(\Delta x) = \exp\left(-\frac{|\Delta x|}{d_{\mathrm{corr}}}\right) \tag{4-16}$$

where Δx is the distance between the two users in the horizontal plane and d_{corr} is the environment-dependent correlation distance. The values of d_{corr} for parameters such as cluster-specific parameters, LOS states, and indoor states are different. Typical values of d_{corr} are between 10 and 60 meters. There are two spatial consistency modeling methods in the NR channel model: one is the spatially correlated random variable based method, and the other is the geometric stochastic approach.

In the spatially correlated random variable based method, the generation of small-scale parameters is based on two-dimensional (2D) spatially correlated random variables. As a result, clusters of co-located UEs are expected to have similar delays and angle information. In the NR channel generation procedure, random variables are either Gaussian distributed or uniformly distributed. Although the method of generating these random variables is not specified in the NR channel model, a computationally efficient method is to generate spatially correlated Gaussian random variables via the Gaussian random field method, and then map them to [0, 1] using the cumulative distribution function (CDF) of the Gaussian distribution to obtain spatially correlated and uniform random variables.

Consider a $n \times n$ matrix representing the discrete points in the area of interest, and let $\mathbf{R}$ be the correlation matrix where $[\mathbf{R}]_{ij} = \exp\left(-|\Delta x_{ij}| / d_{\mathrm{corr}}\right) \forall i, j \le n$ is the correlation value between the point (i, j) and point (1, 1) in the area of interest. Then, compute its 2D fast Fourier transform (FFT) by $\mathbf{G} = \mathrm{FFT2}(\mathbf{R})$, where FFT2 is the 2D FFT operator. Next, generate a zero-mean unit variance Gaussian matrix $\mathbf{V}_{\mathrm{iid}}$ with independently and identically distributed (i.i.d.) entries. The matrix $\mathbf{V}$ storing correlated Gaussian random variables can then be calculated by

$$\mathbf{V} = \mathrm{real}\left\{\mathrm{FFT2}\left\{\mathrm{sqrt}(\mathbf{G})\right\} \circ \frac{\mathbf{H}_{\mathrm{iid}}}{n}\right\} \tag{4-17}$$

where $\mathrm{real}\{\cdot\}$ obtains the real part of a matrix, $\mathrm{sqrt}\{\cdot\}$ computes the element-wise square root of a matrix, and $\circ$ is the Hadamard product which computes the element-wise product of two matrices. In this case, any two entries in $\mathbf{V}$ will have the target correlation value. According to the property of a Gaussian copula, spatially correlated uniform random variables with the same correlation matrix $\mathbf{R}$ can be obtained by mapping the spatially correlated Gaussian random variables to [0, 1] via the CDF of a standard Gaussian distribution.

The spatially correlated random variable based method provides a more accurate solution to spatial consistency modeling and is already used in LSP generation. This is extended to small-scale channel parameters. However, the spatially correlated channel parameters will be stored with respect to different positions and require large storage space.

The geometric stochastic approach assumes that the last bounce of a cluster is known, and updates the cluster delays, cluster power, and cluster angles according to the relative motion of the UE. This approach is similar to the one introduced in the SCME, which may lead to less accurate descriptions of 2D spatial consistency. For example, assume that two users are far apart at the beginning of the simulation. When these two users now move into proximity, the geometric stochastic approach may not necessarily guarantee that the correlations of their channel parameters match the target correlation values. However, a benefit of the geometric stochastic approach is that it updates small-scale channel parameters during channel generation, without requiring any extra storage space such as the spatially correlated random variable based method.

Beside the two aforementioned methods used in 3GPP, the COST 2100 channel model [14] introduced a concept known as *visibility region* to model spatial consistency. A visibility region is a circular area with a smooth power transition boundary and is randomly placed in the area of interest. Each cluster is associated to a visibility region. A UE can see this cluster if it is within its visibility region. When the UE is moving, it can transit from one visibility region to another smoothly, such that spatial consistency is maintained. The COST 2100 channel model later generalized this idea to both the transmitter and receiver sides to support dual mobility and even massive MIMO.

Better spatial consistency support in the 5G channel model allows more accurate performance evaluations of MU-MIMO and coordinated multi-point (CoMP) systems. Also, the design of beam tracking algorithms would need to estimate the variation of the channel in a continuous manner.

4.3.3 Blockage

Geometry-induced blockage is a static condition, caused by obstructing objects in the map environment. In this situation, the propagation is dominated by diffraction and diffuse scattering in those locations that are blocked. This results in additional loss, but also in different channel statistics as compared to those based on shadow fading.

The knife edge diffraction (KED) theory provides a relatively simple and robust mean for calculating the diffracted fields at surface edges. Blocking studies in literature have accounted for blockage between a transmitter and a receiver by means of the KED approach. Each blocking object is approximated by a rectangular screen as shown in Figure 4-4. The total blockage attenuation will be

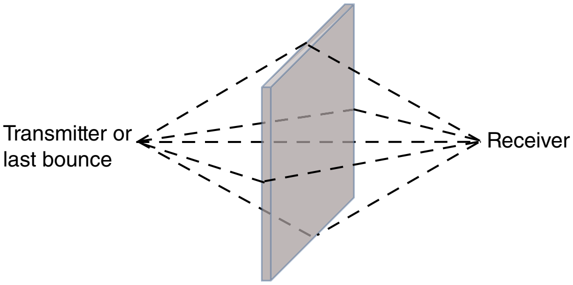

Figure 4-4. Schematic of knife edge diffraction blockage model [16].

calculated using the four links from the four edges of the screen and the link between the transmitter or the last bounce and the receiver. To model more complex shapes, a combination of multiple rectangular screens may be used. In particular, this approach has been adopted by [3]. However, a change of receiver and transmitter location will imply that as a path changes, the angle of the screen will also change. In order to avoid the shadowing variation, each screen can be continuously rotated so that it is perpendicularly oriented with respect to each path.

In [5], a substantially improved blockage model has been developed based on the KED blockage model. This model accounts for the fast fading through the summation of the complex amplitudes of the paths from the four edges of a rectangular screen. This approach has been validated with 5G radio access measurements considering blocking by a truck [15]. It was shown that summing up the complex amplitudes results in a better agreement with measurement data before and during the blocking, and avoids an underestimation of attenuation in deep shadowing zones. Also, this model has been validated towards measurements of human body shadowing.

A blockage object can significantly degrade signal strength in a certain angular area. As such, wider beams may perform better than narrow beams in case of blockage, since wider beams can capture or propagate signals in more directions. This is counter-intuitive, as it is normally encouraged to use narrow beams in 5G systems. Also, fast beam finding and tracking methods are essential in the overall system design, such that the system can flexibly sense strong reflected paths and switch beamforming directions to these paths, as elaborated further in Section 13.2.5.

4.3.4 Correlation Modeling for Multi-Frequency Simulations

In 5G NR, UEs may receive data simultaneously from different BSs operating at different frequency bands, as detailed in Section 6.5. One typical example is to receive control signaling at below 6 GHz channels while boosting data throughput through the usage of mmWave bands. These two links at different frequencies may not be fully independent as they may share similar LOS states, blockage objects, and even some LSPs. Therefore, correlation modeling for multi-frequency simulations is needed in the channel model.

In the NR channel model, a procedure is added to handle this. First, after user dropping, LOS angles for all frequencies are determined identically based on geometry. Second, if soft LOS states are considered, they are frequency-dependent. Otherwise, LOS states of all frequencies are the same. Third, LSPs are the same for all the frequencies, except for possibly frequency-dependent scaling, according to the LSP table. For example, in the 3GPP NR channel model, first- and second-order statistics of the delay and angular spreads are modeled as linear functions of the frequency (in logarithmic scale). Depending on the parameter and the type of the environment (outdoor or indoor), the frequency-dependency in the 3GPP NR channel model is strong for some LSPs, while it is rather weak or not modeled at all for others (i.e., the mean and variance values of LSPs are constant over the considered frequency range, from 0.5 to 100 GHz). The frequency-dependency of LSPs, however, is still a topic of ongoing research, and new models with additional refinements may be needed in the future. As can be seen from Figure 4-5, data from numerous recent multi-frequency channel measurement campaigns in the mmMAGIC project [5] shows smaller variations of channel delay spread with frequencies in both UMi Street Canyon and Indoor Office scenarios. To have a fair comparison and avoid biased conclusions, a set of technical requirements for comparability including equal measurement bandwidths, equal antenna patterns, equal dynamic ranges for analysis in delay and angle domains, equal angle resolutions, the same environment and same antenna locations are

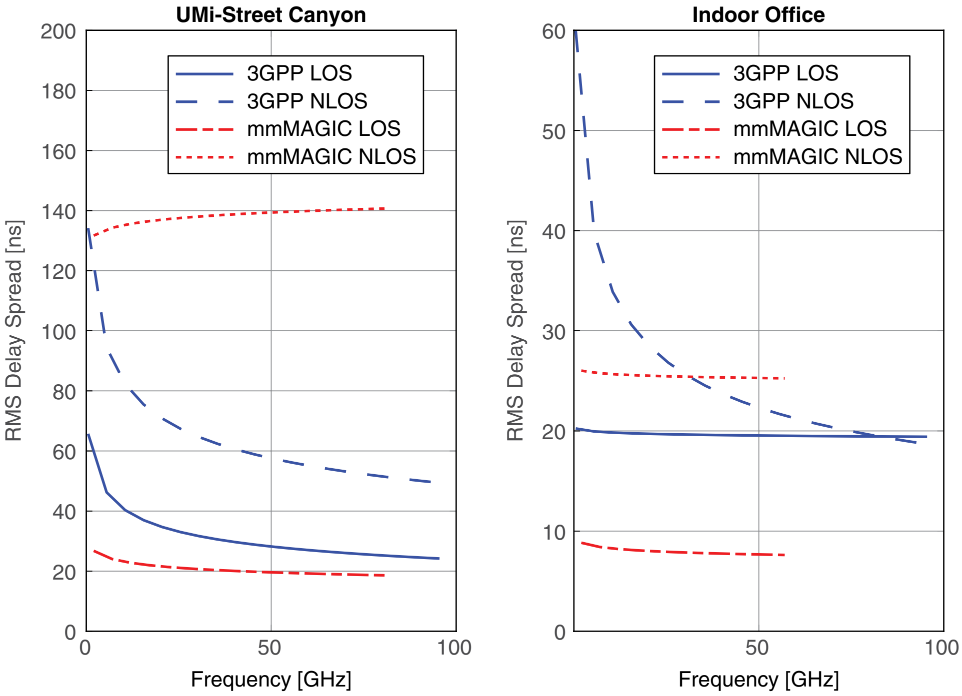

Figure 4-5. RMS delay spread versus frequency in UMi-Street Canyon (Left) and Indoor Office (right) in the 3GPP NR channel model [3] (0.5-100 GHz) and the mmMAGIC channel model [5] (2-96 GHz for outdoor and 2-60 GHz for indoor).

defined. These requirements are assured in all multi-frequency channel measurement campaigns in [5]. According to results in [5], the frequency trend of the channel delay spreads is small, and the linear relations between the channel delay spreads and the frequency are not statistically significant. This suggests that for a simpler approach, the same model parameters for LSPs can be used across considered frequency bands, from 2-86 GHz.

After necessary LSPs are obtained, channel coefficients of multi-frequency links can be generated. The accurate modeling of the root mean squared (RMS) delay spread is essential, as it can highly influence the design of the cyclic prefix of orthogonal frequency division multiplexing (OFDM) symbols. Additionally, if blockage is taken into account in the simulation, the locations of blocking objects are assumed the same across all frequencies. The procedure of multi-frequency simulation provides an evaluation framework for dual connectivity and carrier aggregation. The additional correlation introduced in the procedure helps to avoid a biased estimation of throughputs of multi-frequency links due to overestimating diversity gains of these links.

4.3.5 Ground Reflection

Although the LOS path can provide good channel quality, the superposition of the ground-reflected path and the LOS path can significantly degrade the received signal power even in LOS condition. In channel models for below 6 GHz channels, e.g., 3D-SCM, ground reflection is considered by using a two-slope LOS path loss model. The two slopes are separated by a breakpoint at a distance to the transmitter which is proportional to the carrier frequency. The LOS path loss exponent is approximately 2 before the breakpoint. Due to the ground-reflected path, the path loss exponent then increases to approximately 4 after the breakpoint. Gaussian distributed random shadow fading is added to the LOS path loss, which partially models the effect of superposition of reflected and scattered paths. However, this is not sufficient in above 6 GHz channels, where the ground-reflected path creates a deterministic fading pattern. In below 6 GHz channels, most of the area of interest lies after the breakpoint. However, as frequency increases towards mmWave spectrum, and cells become smaller and smaller, the value of the breakpoint surges, and most of the area of interest is before the breakpoint. A comparison between UMi path loss with and without explicit ground reflection modeling is illustrated in Figure 4-6. It can be observed that the path loss exponent has a hard transition from 2 to 4 at the breakpoint in the UMi path loss model without ground reflection. When ground reflection is explicitly modeled, a smooth transition of the path loss exponent and a deterministic fading pattern can be seen.

Explicit ground reflection modeling has been included as an additional feature in the NR channel model. A separate ground-reflected path is added to the original LOS channel impulse response. It should be noticed that the ground-reflected path is likely to be superimposed to the LOS path due to limited bandwidth during system evaluation using the NR channel model. The complex coefficient, delay and angles are determined geometrically.

Ground reflection has a significant impact on the overall system design. For instance, the deployment of relatively static links, such as mmWave wireless backhaul, should avoid deeply faded locations caused by the ground-reflected path. The modeling of ground reflection can help system

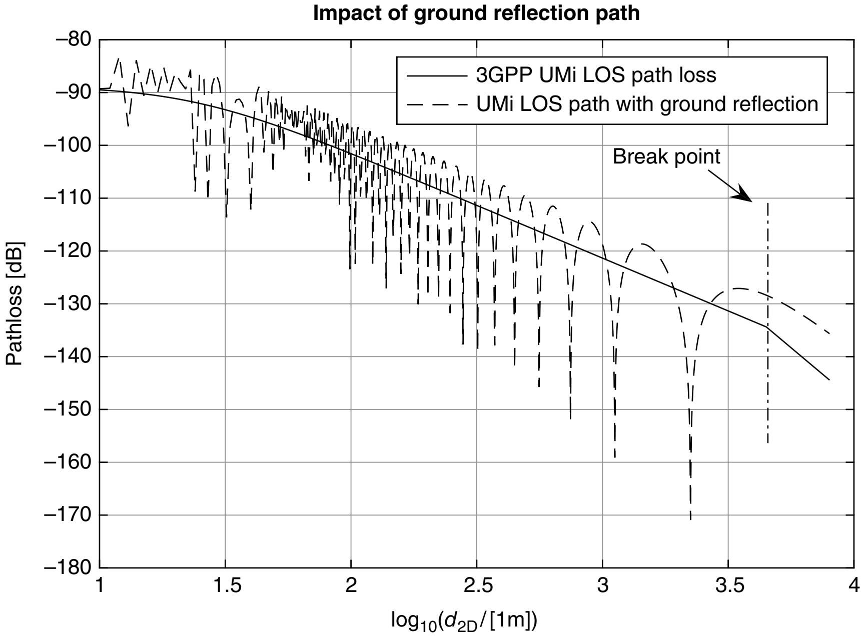

Figure 4-6. Comparison between UMi LOS path loss with and without ground reflection modeling.

designers to predict these locations and take necessary actions such as more robust link adaptation. Also, dual connectivity among different frequency bands, possibly based on carrier aggregation, can help to overcome the deep fade caused by ground reflection, see also Section 6.5.

4.3.6 Diffuse Scattering

Diffuse scattering occurs when waves impinge on a rough surface where the roughness of the surface is comparable to the wavelength. The standard deviation of surface-roughness σ_h of rough construction materials such as concrete, bricks and asphalt is of the order of 1–2 mm. The condition of roughness is usually defined by the Rayleigh criterion $\sigma_h < \lambda / 8\cos(\theta_i)$ [17], where λ is the carrier wavelength and θ_i is the incidence angle. Due to the decrease in wavelength, mmWave channels are less likely to satisfy the Rayleigh criterion, meaning that the diffuse scattering effect in mmWave channels is more significant than in below 6 GHz channels. More precisely, higher frequencies result in a smaller specular reflectivity of the surface, and each impinging ray may be backscattered into many low-amplitude rays having random propagation directions. Based on this assumption, one can hypothesize stronger dense multipath components (DMCs) at mmWave frequencies compared to lower frequencies. However, some studies have shown that the ratio of the power of the DMCs to that of the specular component is similar [18] or even lower than for lower frequencies.

The small-scale variations instigated by the propagation mechanism of diffused scattering have been investigated through the process of wall reflection measurements at a central frequency of 60 GHz and a bandwidth of 2 GHz [5]. As a metric of comparison, the notion of *power concentration*, which can be defined as the angular span corresponding to 90% of the power in the angular profile, was used. Therefore, the impact of diffused scattering is smaller with higher power concentration, since a high concentration implies that most of the received power is found within a small range around the incident angle. The measured results in [5] showed that scattering caused by the surface roughness can be characterized by a Nakagami-m distribution. When reflections from rough surfaces, such as brick walls, were analyzed, it was found that the value of this metric appears quite large, implying that the effect of diffused scattering is quite significant and should be taken into account for deterministic channel prediction tools such as ray-tracing.

Diffuse scattering may increase the richness in mmWave channels, and hence the design of beamforming techniques in 5G should take this characteristic into consideration, see Section 11.5.

4.3.7 D2D, Mobility, and V2V Channels

Vehicular communications have recently drawn a significant increase in interest in the framework of intelligent transportation systems (ITS), where vehicles are envisioned to collect data on traffic dynamics and share these with each other and possibly with the road infrastructure via wireless links, as covered in detail in Chapter 14. In this context, one of the most important points is to have accurate channel models that are able to predict the peculiarities of vehicular propagation channels. Vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) channels have been widely investigated in the frequency range below 6 GHz, mainly motivated by the deployment of the 3GPP vehicle-to-everything (V2X), IEEE 802.11p and ITS-G5 standards. In mmWave bands, the V2V channels, and more generally, device-to-device (D2D) channels with mobility at both ends of the communication link, are so far poorly investigated.

A generic channel model based on a simplified or analytical channel representation could be easily extended to the D2D case. For instance, the map-based model proposed by the METIS project [2] can be used to generate a channel trace according to the transmitter and receiver positions. The authors in [19] employ a combined two-ring model and ellipse model, where the received signal is constructed as a sum of LOS, single- and double-bounced rays. In addition, this model is able to include vehicular traffic density information, and therefore mobile scatterers, to analyze their impact on channel characteristics. This has been extended to 3D in [20] using a two sphere model and an elliptic-cylinder model. The approach used in [21] to model V2V channels below 6 GHz was to define static and moving scatterers, the latter representing vehicles, and calculate the multipath components whose statistics were derived from measurements. The same approach could be extended to mmWave frequency bands, but the parametrization of the model should be corroborated by measurements. Vehicular channel angles-of-arrival at 60 GHz have been measured in [22], [23]. In [24], path loss characteristics have been derived at mmWave frequencies for LOS conditions and moving vehicles, and in the case of blockage by multiple vehicles. In [25], V2V channel measurements at 60 GHz and 1 GHz bandwidth were performed with antennas close to the bumpers. The results show that the channel impulse response is composed by a direct component, which is the sum of the LOS path and the one reflected from the ground, and delayed contributions coming from guard rails on the roads.

4.3.8 Oxygen Absorption, Time-varying Doppler Shift, Multi-Frequency Simulations, and UE Rotation

Dry air and water vapour can generate specific attenuation at frequencies up to 1000 GHz, which can be evaluated by means of a summation of the individual resonance lines from oxygen and water vapour. Significant oxygen absorption can be observed around 60 GHz [26]. Since the legacy 3D-SCM did not consider this frequency band, 3GPP added oxygen absorption modeling in the NR channel model to better support mmWave band modeling. A frequency-dependent oxygen loss can be added to each cluster in the frequency range of 53 to 67 GHz. This oxygen loss is cluster-specific and is proportional to the propagation distance of the cluster. As a result, it can impact the delay spread of channels at around 60 GHz. The impact of this gas attenuation is strongly dependent on the targeted application. While for point-to-point long range communication (e.g., backhaul) it should be included, in short range applications, like small cells and indoor hotspots, it could be neglected.

A time-varying Doppler shift is modeled to capture the phase change of a UE whose motion is not with constant velocity. The Doppler term within $[t_0, t]$ can be computed via the aggregated Doppler phase as

$$\exp\left\{ j2\pi \int_{t_0}^{t} \frac{\hat{\boldsymbol{r}}_{\mathrm{rx},n,m}^{T}(\tilde{t}) \cdot \boldsymbol{v}(\tilde{t})}{\lambda_0} d\tilde{t} \right\} \tag{4-18}$$

where λ_0 is the carrier wavelength, $\hat{\boldsymbol{r}}_{\mathrm{rx},n,m}^{T}(\tilde{t})$ is the direction vector of the mth ray in the nth cluster at the receiver, and $\boldsymbol{v}(\tilde{t})$ is the velocity vector of the receiver.

In mmWave bands, directive antennas are expected to be deployed at both the UE and the base station, as discussed in Section 11.5. As a result, the received signal power is sensitive to the orientation of the UE because of narrow beams. When the antenna beams are not aligned or are blocked, significant attenuation can be observed. This is modeled by rotating the bearing angle, downtilt angle and slant angle of the UE in the NR channel model.

4.3.9 Map-based Hybrid Modeling Approach

Besides the GSCM approach, another highlight of the NR channel model is the introduction of the map-based hybrid modeling (MBHM) approach. This approach aims at generating channel coefficients considering the digital map of the network layout. A ray tracing technique is used in the MBHM. Each ray-traced path (also known as deterministic cluster) from the transmitter to the receiver is tracked by modeling its interactions with the propagation environment. These interactions can be categorized into five types including LOS, reflections, diffraction, penetration and scattering. After importing the 3D digital map of the network layout and identifying the interaction type of each deterministic cluster, electric field calculations can be performed to determine its path power, angle and delay. Additionally, a configurable number of random clusters are generated following a similar procedure of the GSCM. The final channel output is then based on the combination of deterministic and random clusters. MBHM is able to provide site-specific channel characteristics, which can better support system design and network deployment.

4.4 Summary and Outlook

Bringing appealing features to the evolution of cellular systems, the upcoming 5G systems have introduced challenges to the modeling of propagation environments for 5G evaluations as well. Legacy channel models targeted below 6 GHz bands only and did not sufficiently describe 5G propagation channel characteristics, and were hence required to be extensively enhanced. The 3GPP NR channel model and IMT-2020 channel model have been developed based on the legacy 3D-SCM by additionally considering new frequency bands and new features. This includes better support for larger bandwidth and antenna arrays, more accurate modeling of space-time-frequency consistency, blockage, oxygen absorption, ground reflection, diffusive scattering, and new map-based hybrid modeling approaches.

More recently, attention has been paid to study path loss models for up to 100 GHz carrier frequency. Although classic FI and CI models are used, new path loss parameters for various scenarios such as UMa, UMi, and InH have been proposed between 6 GHz and 100 GHz. Another important environment-specific property of the channel is the LOS probability, as the clearance of blockages from the first Fresnel zone of a link is smaller in higher frequency bands. The NR channel model further introduces a O2I penetration loss model which can be characterized by simulation parameters to represent the use of metal-coated glass in buildings and the deployment scenarios.

A key characteristic in mmWave bands is the frequency-dependency of channel parameters. In the 3GPP NR and IMT-2020 channel models, frequency-dependency of delay and angular spreads is quite significant. However, recent measurements in [5] show that there is a downward trend in delay spread in indoor environments as frequency increases, while frequency-dependency is insignificant in O2I or outdoor environments. As delay spread has a large impact on the cyclic prefix length of OFDM symbols, it is important to take this into account when designing different numerologies in 5G systems. The impact of ground reflection becomes significant in mmWave bands, resulting in a deterministic fading pattern. Static links, such as those related to low-mobility users or wireless backhaul, can suffer from deep fading caused by ground reflection. An explicit modeling of ground reflection can help predict fading patterns and design necessary measures to compensate deep fading. Large bandwidths and large antenna arrays increase the richness of mmWave channels in delay and spatial domains. Intra-cluster delay and angular spreads can influence the design of hybrid beamforming techniques and decisions on TTI lengths and subcarrier spacing. Blockage effects become significant in higher frequency bands, which results in additional loss in signal power. The KED theory is used in the development of blockage modeling in the NR and IMT-2020 channel models. However, this model underestimates the loss in deep shadowing zones. Further enhancements have been proposed in the literature by accounting for the fast fading due to summing of the complex amplitude of paths from the edges of the blockage object, which provides a more accurate estimate of the signal loss in deep shadowing zones. For the evaluation of user mobility, multi-user multi-node communications and beam tracking design for 5G communication, it is important to include a spatial consistency procedure in the channel modeling. Investigations on reflections and scattering lead to the conclusion that a Nakagami-m distribution can adequately model the random fluctuations caused by surface roughness of various building materials.

The evolution of 5G will continue including more features and use cases. A number of improvements to channel modeling should be considered accordingly. For future work, a unified path loss model from 0.5 MHz to 100 GHz should be studied. Similarly, the link-specific O2I penetration loss model in 3D-SCM and the UE-specific O2I penetration loss model in the NR channel model should also be unified under the same modeling framework. The modeling of space-time-frequency consistency needs to be enhanced. Spatial consistency in the 2D plane has been considered in the NR channel model. However, in order to fully support vertical applications such as drone-to-drone communications and non-terrestrial networks, 3D spatial consistency needs to be considered as well. In 5G, dual connectivity in multiple frequency bands is a promising concept to separate control plane and user plane. The control plane, for instance, can be transmitted via below 6 GHz channels, and the user plane can be conveyed in mmWave bands for throughput boosting, as detailed in Section 6.7.2. However, there exists inconsistency between below and above 6 GHz channels in the NR channel model, hence a better frequency-consistent channel model should be developed. Furthermore, current state-of-the-art MBHMs focus mainly on cellular applications and have been validated only for below 6 GHz bands for outdoor or 28-30 GHz bands for indoor and static scenarios, and should be further extended for new vertical applications. Finally, new measurement campaigns are always encouraged to study channel characteristics such as time-variability of scattering clusters, shadowing, dynamic blockage or movement effects in dual mobility scenarios, aerial scenarios and other vertical applications.

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