5

Radio Network

5.1 Overview

This chapter presents the new 5G radio interface and the principles in the functioning of the 5G radio network. The introduction gives a description of some of the most relevant theories and technologies related to 5G. Then, an overview of the 5G spectrum is given, including discussion of the feasibility of wider bandwidth utilization in theory and practice, planned 5G radio frequency (RF) bandwidths and band allocations, as well as the latest news and expectations of the World Radio Conference (WRC) of the radio section of International Telecommunication Union (ITU-R) as the forum establishes the foundation of the global utilization and rules of the 5G radio frequencies.

Next, the 5G Radio Access Technologies (RATs) are discussed with an explanation of the principles of established and further expected technologies, advanced multiple-in, multiple-out (MIMO), and carrier aggregation (CA). This section includes discussion of the ITU-R RAT candidates, proposed 3GPP design, and how it addresses the ITU-R Recommendations and use cases for 5G.

This chapter also includes introduction to 5G user devices, and new aspects of 5G terminals. Then, the HW of the radio network equipment is described including the most relevant references for further information. One of the rapidly evolving areas in 5G is the antenna system, so it is explained according to the latest knowledge on evolved adaptive antenna systems and other novelty antenna solutions that are feasible candidates to the 5G networks.

As a last part of this chapter, radio resource utilization is discussed, including eco-friendly equipment evolution, low power, dynamic radio resource utilization, evolution of the OFDM from the 4G era to optimally support the more demanding 5G requirements. Also, the Citizens Broadband Radio Service (CBRS) is summarized as it is expected to open new businesses by widening the operator landscape along with the new non-licensed frequency in the United States.

Amongst multiple specifications, the key documents for this chapter are based on the 38-series of the 3GPP technical specifications.

5G Explained: Security and Deployment of Advanced Mobile Communications, First Edition.
Jyrki T. J. Penttinen.

5.2 5G Performance

5.2.1 General

As the 5G is the most versatile set of frequencies ever seen in previous mobile communication generations, also the respective radio network planning will experience major changes. The radio interface of the 5G will experience a major facelift compared to the previous mobile communication systems. The main reason for such a change is the new, completely renovated capabilities of the 5G wireless access that need to be capable of serving use cases that are well beyond previous generations.

The key capabilities include much higher data rates, and much lower latency values. Also, the ability to keep serving the customers with ultra-high reliability, and to support higher energy efficiency and extreme device density, will mean that the radio technology need to be upgraded compared to previous versions, including that of the most advanced Long-Term Evolution (LTE) phase.

The development of the new radio (NR) interface for the 5G will be happening via the further evolution of LTE, combined with completely new radio-access technologies. This native, 5G-specific radio interface is referred to as NR, and along with this evolution, some of the key solutions include the extension of the supported frequencies to higher frequency bands, well beyond 6 GHz region.

There also will be deeper integration of the access and backhaul subsystems. Furthermore, 5G is specifically considering the fluent support of the device-to-device communication, and it thus supports a huge amount of simultaneously communication devices, such as vehicles, machines, intelligent sensors, etc. Yet another key evolution topic of the 5G is the dynamic characteristics of the communications, including flexile duplex and spectrum allocation, relying increasingly on the multi-antenna transmission. It is worth mentioning also the new, clearer separation of the user and control plains [1].

The 5G architecture optimizes the resources and coverage area as it minimizes transmission load, which is not directly related to the user data. The nonuser data include signaling for synchronization, channel estimation, network acquisition, and broadcast of system and control information [1].

The simplified design is essential to serve dense utilization centers containing big amount of network nodes and varying traffic conditions. In addition, the 5G design for the transmission optimizes any deployments. As the network nodes may enter fast, low-energy state upon the load, e.g. when no user-data transmission takes place; it contributes positively to the energy efficiency. An additional benefit of the 5G network design is the positive impact on the high data rate as the interference from others than user data transmissions can be minimized.

5.2.2 Radio Performance Figures

5G, as defined by 3GPP, aims to comply with the strict performance requirements of the International Telecommunication Union's (ITU's) IMT-2020.

Among other advances, also the frame structure of the 5G will be evolving. Nevertheless, the 5G frame structure remains comparable with the 4G. Table 5.1 summarizes the key statements relevant to the frame structure of the radio interface, including a comparison with the previous LTE radio networks.

Table 5.1 The key definitions for the 4G and 5G frame structure and carriers.

Frame structure	4G LTE	5G NR
Radio frame duration	10 ms	10 ms
Subframe duration	1 ms	1 ms
Slot duration	0.5 ms	0.5 ms
Slot format	Predefined	Configurable in a dynamic and semi-statistical way

Table 5.2 The key characteristics comparation of the 4G and 5G radio interface.

Characteristic	4G LTE	5G NR
Channel coding for data	Turbo	LDPC
Channel coding for control	TBCC	Polar
Modulation scheme for uplink	Single-carrier frequency-division multiplexing (SC-FDMA)	DFT-S-OFDM; OFDM (optional)
Modulation scheme for downlink	OFDM	OFDM
Bandwidth (MHz)	1.4, 3, 5, 10, 15, 20	5, …, 100 (sub-6 GHz); 50, …, 400 (above 6 GHz)
Subcarrier spacing (kHz)	15 (unicast, Multimedia Broadcast Multicast Service [MBMS]); 7.5/1.25 (MBMS dedicated carrier)	30, 60, 120; 240 (not for data)
Max. carrier aggregation (CC)	32	16
Max. MIMO antenna ports	8 (SU-MIMO); 2 (MU-MIMO)	8 (SU-MIMO); 16 (MU-MIMO)
HARQ transmission/retransmission	TB	TB, Code block group

There are more notable changes in many other items related to the radio interface. Table 5.2 summarizes other relevant key statements of the 4G and 5G radio interfaces.

5.3 5G Spectrum

5.3.1 Overall Advances of 5G Frequencies

The elemental enhancement of 5G is the ability to handle much faster data rates and to provide higher capacity for simultaneously communicating consumers and machines. To cope with these demands and requirements, 5G networks will provide radio equipment with extended support of bands and bandwidths.

Among other advances in the RF, there will be new frequency bands below and above 6 GHz band. The decision of the globally agreed frequencies will be decided in the ITU-R, while the country-specific deployments depend on each areas' regulator bodies. The current discussion includes many variants up to about 100 GHz bands. In practice, the most favorable frequency strategies support as much and big chunks of contiguous bands as possible. The final decision of each region and country is based on the complete picture of the entities requiring and needing the frequencies.

As there is typically more demand than supply for the frequencies, there might be need for optimized utilization of the frequencies. One of the ways to utilize the bands as efficiently as possible is the so-called white space approach. It refers to shared bands that can be utilized by different stakeholders upon the need. In addition to the traditional modes for business models (mobile network operators (MNOs) purchasing right for licensed frequency utilization) and these novel ideas for more optimal performance via the capacity sharing, there are also potential options for further, new-spectrum chunks such as satellite communication and radio location. Some examples of these sharing modes are seen via the Licensed Shared Access (LSA) that is currently under planning in Europe at 2.3 GHz band, as well as the Citizens Broadband Radio Service (CBRS) in the United States that would rely on the 3.5 GHz band.[2]

As the need for the 5G frequency bands increase along with the expected, much higher utilization of the 5G services as ever before within the previous mobile generations – partially due to the huge increase of the M2M type of communications – the propagation characteristics of the radio waves are the bottleneck. Thus, for the largest coverage areas per radio cell, the frequencies need to be low while the highest capacity coverage areas need to rely on the higher frequencies.

It can be summoned up that the most relevant radio frequencies for the 5G range from about 1 up to 30 GHz, but the technically functional, very near-range cells may be relying on the solutions up to about 100 GHz. The highest frequencies provide much-needed capacity for the limited locations and the lowest frequencies ensure the basic functioning of the 5G services within widest areas.

5.3.2 ITU-R WRC-19 Expectations

The next decisions for the 5G frequency strategies are being prepared for the ITU-R WRC-19 event, which is the last occasion prior to the first commercial 5G deployments that will comply with the ITU IMT-2020 requirements. Meanwhile, the previous ITU-R WRC-15 has identified a set of frequencies to be studied for the feasibility for the 5G. The identified frequencies include 24.25–27.50, 37.00–40.50, 42.50–43.50, 45.50–47.00, 47.20–50.20, 50.40–52.60, 66.00–76.00, and 81.00–86.00 GHz. These frequencies are being studied for the use of the mobile service on a primary basis. There are also frequency bands under study requiring possibly additional allocations to the mobile service on a primary basis, and these bands include 31.80–33.40, 40.50–42.50, and 47.00–47.20 GHz.

In practice, the US Federal Communications Commission (FCC) has been considering bands above 24 GHz for 5G. Other regulators are also investigating the options for the preferred bands above 30 GHz for the mobile industry.

5.3.3 5G Bands

The frequency bands for the LTE are defined in the 3GPP TS 36.104, and the 5G bands can be found in the 3GPP TS 38.104. As can be seen in Table 5.3, the number of the

Table 5.3 The frequency bands and frequency ranges for the LTE as interpreted from the 3GPP TS 36.104.

CH	$f_{\mathrm{UL,\,low}}$ MHz	$f_{\mathrm{UL,\,high}}$ MHz	$f_{\mathrm{DL,\,low}}$ MHz	$f_{\mathrm{DL,\,high}}$ MHz	Mode
1	1920.0	1980.0	2110.0	2170.0	FDD
2	1850.0	1910.0	1930.0	1990.0	FDD
3	1710.0	1785.0	1805.0	1880.0	FDD
4	1710.0	1755.0	2110.0	2155.0	FDD
5	824.0	849.0	869.0	894.0	FDD
6	830.0	840.0	875.0	885.0	FDD
7	2500.0	2570.0	2620.0	2690.0	FDD
8	880.0	915.0	925.0	960.0	FDD
9	1749.9	1784.9	1844.9	1879.9	FDD
10	1710.0	1770.0	2110.0	2170.0	FDD
11	1427.9	1447.9	1475.9	1495.9	FDD
12	699.0	716.0	729.0	746.0	FDD
13	777.0	787.0	746.0	756.0	FDD
14	788.0	798.0	758.0	768.0	FDD
15	N/A	N/A	N/A	N/A	FDD
16	N/A	N/A	N/A	N/A	FDD
17	704.0	716.0	734.0	746.0	FDD
18	815.0	830.0	860.0	875.0	FDD
19	830.0	845.0	875.0	890.0	FDD
20	832.0	862.0	791.0	821.0	FDD
21	1447.9	1462.9	1495.9	1510.9	FDD
22	3410.0	3490.0	3510.0	3590.0	FDD
23	2000.0	2020.0	2180.0	2200.0	FDD
24	1626.5	1660.5	1525.0	1559.0	FDD
25	1850.0	1915.0	1930.0	1995.0	FDD
26	814.0	849.0	859.0	894.0	FDD
27	807.0	824.0	852.0	869.0	FDD
28	703.0	748.0	758.0	803.0	FDD
29	N/A	N/A	717.0	728.0	FDD
30	2305.0	2315.0	2350.0	2360.0	FDD
31	452.5	457.5	462.5	467.5	FDD
32	N/A	N/A	1452.0	1496.0	FDD
33	1900.0	1920.0	1900.0	1920.0	TDD
34	2010.0	2025.0	2010.0	2025.0	TDD
35	1850.0	1910.0	1850.0	1910.0	TDD
36	1930.0	1990.0	1930.0	1990.0	TDD
37	1910.0	1930.0	1910.0	1930.0	TDD
38	2570.0	2620.0	2570.0	2620.0	TDD
39	1880.0	1920.0	1880.0	1920.0	TDD

(Continued)

Table 5.3 (Continued)

CH	$f_{UL, low}$ MHz	$f_{UL, high}$ MHz	$f_{DL, low}$ MHz	$f_{DL, high}$ MHz	Mode
40	2300.0	2400.0	2300.0	2400.0	TDD
41	2496.0	2690.0	2496.0	2690.0	TDD
42	3400.0	3600.0	3400.0	3600.0	TDD
43	3600.0	3800.0	3600.0	3800.0	TDD
44	703.0	803.0	703.0	803.0	TDD
45	1447.0	1467.0	1447.0	1467.0	TDD
46	5150.0	5925.0	5150.0	5925.0	TDD
47	5855.0	5925.0	5855.0	5925.0	TDD
48	3550.0	3700.0	3550.0	3700.0	TDD
49	3550.0	3700.0	3550.0	3700.0	TDD
50	1432.0	1517.0	1432.0	1517.0	TDD
51	1427.0	1432.0	1427.0	1432.0	TDD
52	3300.0	3400.0	3300.0	3400.0	TDD
65	1920.0	2010.0	2110.0	2200.0	FDD
66	1710.0	1780.0	2110.0	2200.0	FDD
67	N/A	N/A	738.0	758.0	FDD
68	698.0	728.0	753.0	783.0	FDD
69	N/A	N/A	2570.0	2620.0	FDD
70	1695.0	1710.0	1995.0	2020.0	FDD
71	663.0	698.0	617.0	652.0	FDD
72	451.0	456.0	461.0	466.0	FDD
73	450.0	455.0	460.0	465.0	FDD
74	1427.0	1470.0	1475.0	1518.0	FDD
75	N/A	N/A	1432.0	1517.0	FDD
76	N/A	N/A	1427.0	1432.0	FDD
85	698.0	716.0	728.0	746.0	FDD

LTE bands has increased steadily along with the new releases of 3GPP technical specifications. The presented list is based on the specification version 15.2.0, dated March 2018.

The bandwidth of the LTE can be 1.4, 5, 10, 15, or 20 MHz, depending on the band number. The carrier aggregation provides further means to combine these bands to achieve wider total bandwidth per single user.

The 5G NR frequency bands are defined in the 3GPP 38.104. Table 5.4 summarizes the 5G NR radio frequencies and bands interpreted from the above-mentioned source, version 15.1.0, which is dated March 2018. As can be seen in the table, many bands are shared with the LTE bands (5G bands n1–n76 and 4G LTE bands 1–76), whereas the rest of the 5G NR bands are new (n77–n84 and n257, n258 and n260).

As has been the case with the LTE development, it can be expected that there will be multitude of new 5G operating bands and channel bandwidths as new 3GPP releases are available. Remarkably, the ITU-R WRC-19 will be an important milestone to decide the

Table 5.4 The NR bands and frequency ranges as interpreted from the 3GPP TS 38.104.

CH	$f_{UL,\,low}$ MHz	$f_{UL,\,high}$ MHz	$f_{DL,\,low}$ MHz	$f_{DL,\,high}$ MHz	Mode
n1	1920.0	1980.0	2110.0	2170.0	FDD
n2	1850.0	1910.0	1930.0	1990.0	FDD
n3	1710.0	1785.0	1805.0	1880.0	FDD
n5	824.0	849.0	869.0	894.0	FDD
n7	2500.0	2570.0	2620.0	2690.0	FDD
n8	880.0	915.0	925.0	960.0	FDD
n20	832.0	862.0	791.0	821.0	FDD
n28	703.0	748.0	758.0	803.0	FDD
n38	2570.0	2620.0	2570.0	2620.0	TDD
n41	2496.0	2690.0	2496.0	2690.0	TDD
n50	1432.0	1517.0	1432.0	1517.0	TDD
n51	1427.0	1432.0	1427.0	1432.0	TDD
n66	1710.0	1780.0	2110.0	2200.0	FDD
n70	1695.0	1710.0	1995.0	2020.0	FDD
n71	663.0	698.0	617.0	652.0	FDD
n74	1427.0	1470.0	1475.0	1518.0	FDD
n75	N/A	N/A	1432.0	1517.0	SDL
n76	N/A	N/A	1427.0	1432.0	SDL
n77	3300.0	4200.0	3300.0	4200.0	TDD
n78	3300.0	3800.0	3300.0	3800.0	TDD
n79	4400.0	5000.0	4400.0	5000.0	TDD
n80	1710.0	1785.0	N/A	N/A	SUL
n81	880.0	915.0	N/A	N/A	SUL
n82	832.0	862.0	N/A	N/A	SUL
n83	703.0	748.0	N/A	N/A	SUL
n84	1920.0	1980.0	N/A	N/A	SUL
n257	26 500.0	29 500.0	26 500.0	29 500.0	TDD
n258	24 250.0	27 500.0	24 250.0	27 500.0	TDD
n260	37 000.0	40 000.0	37 000.0	40 000.0	TDD

global strategy for the utilization of the bands above 6 GHz spectrum while this present list includes the sub-6 GHz bands identified up to date.

3GPP refers this division into sub-6 GHz bands and the bands above 6 GHz as Frequency Range 1 and Frequency Range 2, respectively. More specifically, FR1 covers the frequencies in 450 MHz–6 GHz range while FR2 refers to the frequencies within 24.250–52.600 GHz; as an example, the bands n257, n258, and n260 of Table 5.4 belong to FR2; the rest being in FR1.

The 5G NR is able to support different user equipment (UE) channel bandwidths in a flexible way while it operates within the base station's (BS's) channel bandwidth. As the 3GPP 38.104 states, the base station can transmit to and/or receive from one or more

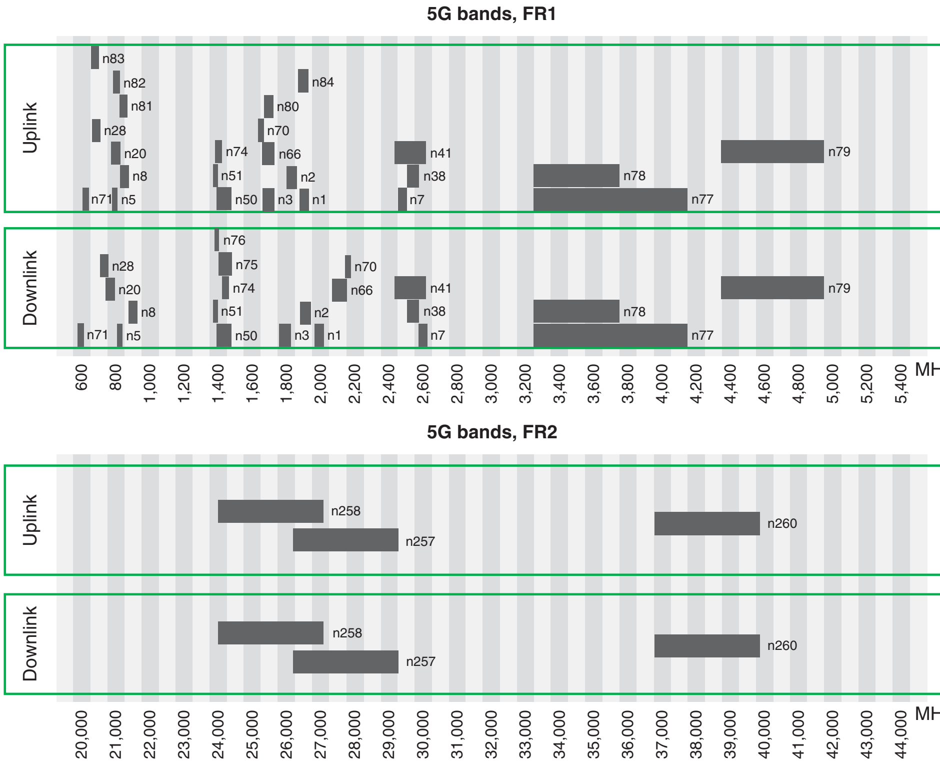

Figure 5.1 The 5G NR bands as defined in 3GPP Release 15.

UE bandwidth parts that are smaller than or equal to the number of carrier resource blocks on the RF carrier, in any part of the carrier resource blocks.

The TS 38.104 specifies multiple transmission bandwidth configurations N_{RB} per base station channel bandwidth and respective subcarrier spacing for FR1 and FR2. The TR1 transmission bandwidth configurations can have bandwidth values of 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, and 100 MHz while the subcarriers can be varied between the values of 15, 30, and 60 kHz. For the FR2 mode, the transmission bandwidth configuration can have bandwidth values of 50, 100, 200, and 400 MHz while the subcarriers can be either 60 or 120 kHz.

Figure 5.1 depicts the 5G bands in graphical format. The more specific requirements for the RF channel utilization, including the guard bands, tolerance values for interfering bands, etc., are found in the 3GPP TS 36.104 and TS 38.104 for 4G LTE and 5G NR, respectively.

5.4 5G Radio Access Technologies

5.4.1 Key Specifications

3GPP defines the 5G radio technology in the 38-series, under the name NR, whereas the core network (CN) is referred to as NGC (next-generation core). Table 5.5 lists some of

Table 5.5 Some of the key technical specifications of 3GPP New Radio (NR) interface.

TS	Title
38.101	User equipment (UE) radio transmission and reception
38.104	Base station (BS) radio transmission and reception
38.201	Physical layer; general description
38.211	Physical channels and modulation
38.300	NR overall description (Stage-2)
38.305	NG Radio Access Network (NG-RAN); Stage 2 functional specification of user equipment (UE) positioning in NG-RAN
38.306	User equipment (UE) radio access capabilities
38.321	Medium Access Control (MAC) protocol specification
38.322	Radio Link Control (RLC) protocol specification
38.323	Packet Data Convergence Protocol (PDCP) specification
38.331	Radio Resource Control (RRC); protocol specification
38.401	NG-RAN; architecture description
38.410	NG-RAN; NG general aspects and principles
38.801	Study on new radio access technology; radio access architecture and interfaces

the fundamental 5G radio technical specifications referenced in this book. The complete list of the 38-series can be found online in [3].

5.4.2 Frequency Bands

For the additional frequency bands and bandwidth variants designed especially for 5G, some of the respective key 3GPP Technical Reports are summarized in Table 5.6.

5.4.3 5G Channel Modeling

As the current radio frequencies are getting increasingly congested while the data rates and capacity demand increase, 5G requires new bands. The mobile communication

Table 5.6 The key technical reports detailing 5G-specific radio frequency bands.

TR	Title
38.812	Study on non-orthogonal multiple access (NOMA) for NR
38.813	New frequency range for NR (3.3–4.2 GHz)
38.814	New frequency range for NR (4.4–4.99 GHz)
38.815	New frequency range for NR (24.25–29.5 GHz)
38.817-01	General aspects for UE RF for NR
38.817-02	General aspects for BS RF for NR
38.900	Study on channel model for frequency spectrum above 6 GHz
38.901	Study on channel model for frequencies from 0.5 to 100 GHz

industry has identified the potential for the range of 6–100 GHz for future 5G networks as it provides means for high capacity and densification of networks. Due to the short communications range, this range is especially suitable for the small-cell deployment scenario.

As an example, the FCC has published rules that provide flexible wireless broadband. FCC allows 3.85 GHz of licensed flexible use at 28–40 GHz bands, and an unlicensed band at 3.5 and 64–71 GHz. There also are plans for adapting 24–25, 32, 42, 48, 51, 70, and 80 GHz for 5G.

The new, much higher frequencies up to 100 GHz require renewed radio propagation models, too. One of the related key studies is found in the 3GPP TR 38.900.

There also have been various channel measurements and modeling efforts such as METIS2020, COST2100, European Telecommunications Standards Institute (ETSI) mmWave SIG, MiWEBA, mmMagic, NYU WIRELESS, and Globecom 2015. The 5G channel modeling is typically based on measurements and ray-tracing concept.

5.4.4 Radio Technology Principles

This section outlines the expected key radio technologies for the 5G that may contribute to achieve the high capacity and radio performance to comply with the strict ITU-R IMT-2020 requirements.

5.4.4.1 OFDM in 5G

The 3GPP has chosen CP-OFDM (Cyclic Prefix-Orthogonal Frequency Division Multiplexing) waveform for 5G NR. The NR and previously defined LTE form jointly the 5G radio access, supporting each other especially in the initial phase of the 5G deployment. While LTE continues supporting frequency bands below 6 GHz, the NR will have a variety of bands over a wide spectrum, from sub-1 up to 100 GHz. The benefit of the joint functioning of the LTE and NR is the possibility of achieving capacity gain via aggregation.

Benefits of OFDM-Based Modulation The Orthogonal Frequency Division Multiplexing (OFDM) modulation has been selected as a base for 5G for several reasons. The following summarizes the key justifications [4]:

- OFDM is spectral efficient both in uplink (UL) and downlink (DL) to comply with high data rate requirements. In addition to the radio interface as such, also backhaul benefits from OFDM-based modulation technique, as well as, e.g. dense urban vehicular communication use case where several vehicles are performing asynchronous broadcasting.
- OFDM provides means for fluent utilization of MIMO, which provides high spectral efficiency via both single-user MIMO (SU-MIMO) and multi-user MIMO (MU-MIMO). Combined with adaptive beamforming technology, the OFDM contributes to the compensation of the radio propagation loss on high-frequency bands.
- OFDM can be optimized for better applicability to peak-to-average-power-ratio (PAPR). In the previous generation's LTE and LTE-Advanced systems, the OFDM has been selected into downlink while the uplink relies on single-carrier

frequency-division multiplexing access (SC-FDMA), which is more adequate in optimizing device's power efficiency. The PAPR of OFDM in 5G can be lowered by applying PAPR reduction techniques with minor impact in performance [5].

- The high-speed use cases require robustness in channel time-selectivity. OFDM supports this via adequate adjustment of subcarrier spacing. It can be assumed that the highest frequency bands will be utilized for small cells. Along with 5G, high robustness is required for supporting the fluent vehicle communications in V2X. It can also be expected that the importance of mobile backhaul will increase.
- OFDM system can be made robust to phase noise by a proper choice of subcarrier spacing.
- The baseband complexity of an OFDM receiver is low.
- OFDM is well localized in time domain, which is relevant in the support of latency-critical ultra-reliable low latency communications (URLLC) and dynamic Time Division Duplex (TDD). The respective use cases include, e.g. the backhaul transmission and V2X communications. Nevertheless, OFDM is not performing optimally in frequency domain. Frequency localization may be important in use cases supporting coexistence of different services having separate waveform types in frequency domain on shared carrier, but in general, frequency localization of a waveform may not be of utmost importance on higher frequencies with available bandwidth.
- The OFDM cyclic-prefix (CP) makes it robust to timing synchronization errors.
- OFDM is a flexible waveform, so it supports a variety of use cases and services over wide range of frequencies when subcarrier spacing and cyclic prefix are adjusted adequately.

OFDM Principle After the evaluation of new candidates to 5G waveforms, the OFDM – familiar from the LTE and LTE-Advanced – was selected as its performance has been proven in practice. It can be further optimized to tackle the strict 5G requirements. The additional benefit of this selection is that for those familiar with the OFDM via LTE (or via many other environments such as Wi-Fi radio interface), there are some minor additions to the already adapted principles. This section presents the OFDM as an elemental base for the 5G, too.

The OFDM refers to the technology that divides a wide frequency band into various narrow frequencies, i.e. subcarriers that carry the actual data between the transmitter and receiver. The multiplexing takes care of the simultaneous transmission of the data on each individual subcarrier. In the LTE and LTE-Advanced systems, the subcarriers have a fixed width of 15 kHz, and depending on the need for the data speed, each device is dedicated dynamically with a variable set of these subcarriers. The idea of using the subcarriers is to obtain a radio channel that is roughly constant (flat) over each given sub-band, which minimizes the negative effects of the fading, as the faded band is typically very narrow and the subcarrier can be reallocated during the fading. This principle makes the equalization much simpler, at the receiver compared to the previous techniques utilized in 2G, 3G, and 4G.

The OFDM symbol duration time is $1/\Delta f$ + cyclic prefix (CP). The cyclic prefix is used to maintain orthogonality between the subcarriers even for a time-dispersive radio channel. In the LTE, a single resource element carries the data by using either

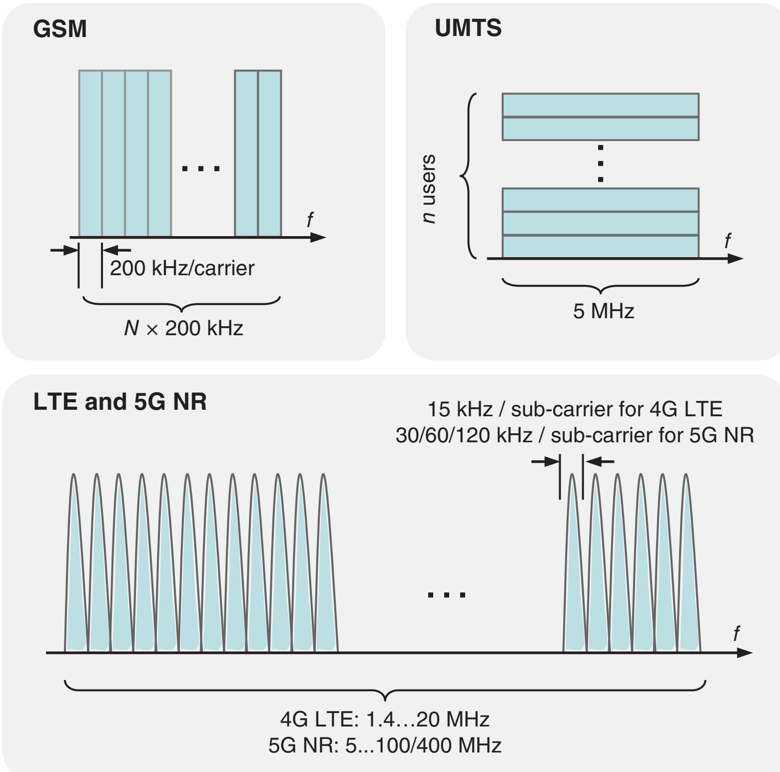

Figure 5.2 The frequency band of OFDM as applied into LTE and 5G NR consists of several subcarriers while the WCDMA of UMTS utilizes one complete carrier for all the code division traffic of a single cell. The LTE and 5G NR allow the additional capacity via carrier aggregation. As a comparison, the GSM system is based on TDMA.

Quadrature Phase Shift Keying (QPSK), 16QAM (Quadrature Amplitude Modulation), or 64QAM modulation.

Figure 5.2 depicts the difference between 3G with a fixed bandwidth of 5 MHz, which is shared between all the admitted users based on code division multiplexing, and the flexible LTE bandwidth, which has finer granularity for defining the frequency band; it is possible to deploy 1.4, 3, 5, 10, 15, or 20 MHz bands in the LTE, and further combine the bands via carrier aggregation concept. As can be seen, one of the benefits of OFDM over Code Division Multiple Access (CDMA) is the dynamic allocation of the subcarriers, which can optimize the frequency band re-farming between LTE and other systems as the utilization of previous systems will decrease. The figure also presents the TDMA (Time Division Multiple Access) principle of the Global System for Mobile Communications (GSM), which, in fact, is a combination of TDMA and Frequency Division Multiple Access (FDMA) formed by eight time slots, or their subdivided resources per each 200 kHz carrier.

For 5G NR, the bandwidth can vary in a wider way, from 5 up to 100 or 400 MHz, depending on the scenario.

OFDM is based on the Frequency Division Multiplexing (FDM). In FDM, different streams of information are mapped onto separate parallel frequency channels. OFDM differs from traditional FDM in terms of the following aspects:

- The same information stream is mapped onto many narrowband subcarriers, increasing the symbol period compared to single carrier schemes.
- The subcarriers are orthogonal to each other to reduce the inter-carrier interference (ICI). Moreover, overlap between subcarriers is allowed to provide high spectral efficiency.
- A guard interval, often called *cyclic prefix*, is added at the beginning of each OFDM symbol to preserve orthogonality between subcarriers and eliminate inter-symbol interference (ISI) and ICI (see Figures 5.3 and 5.4).

In the frequency domain, the overlap between subcarriers can take place as they are orthogonal to each other.

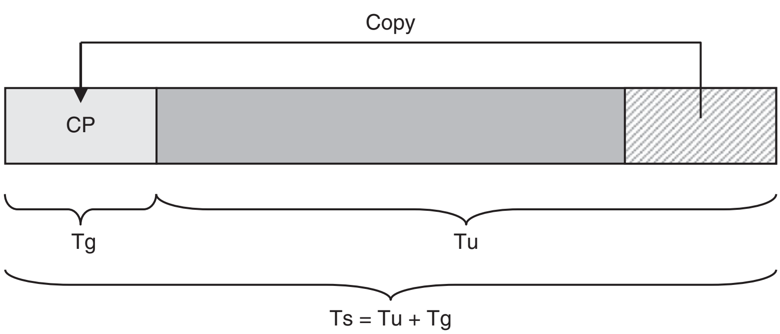

Figure 5.3 The principle of the OFDM cyclic prefix.

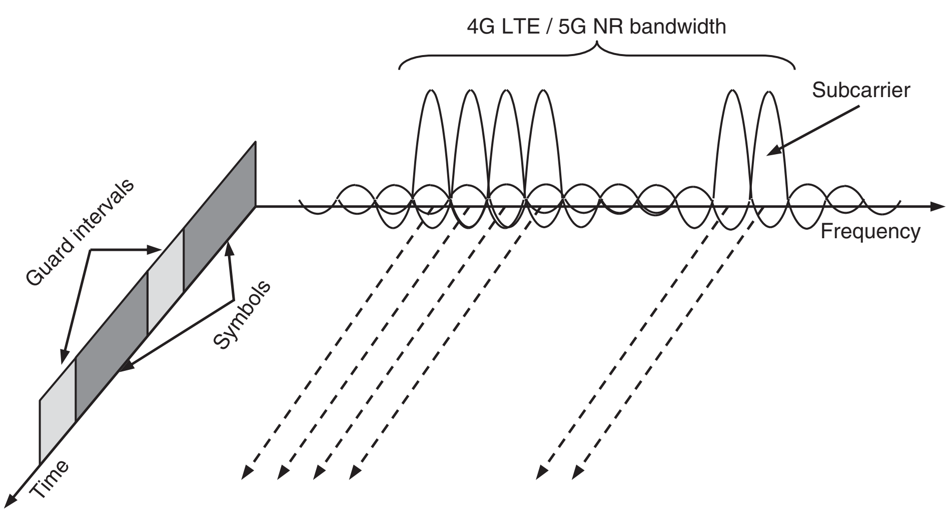

Figure 5.4 Frequency-time interpretation of an OFDM signal.

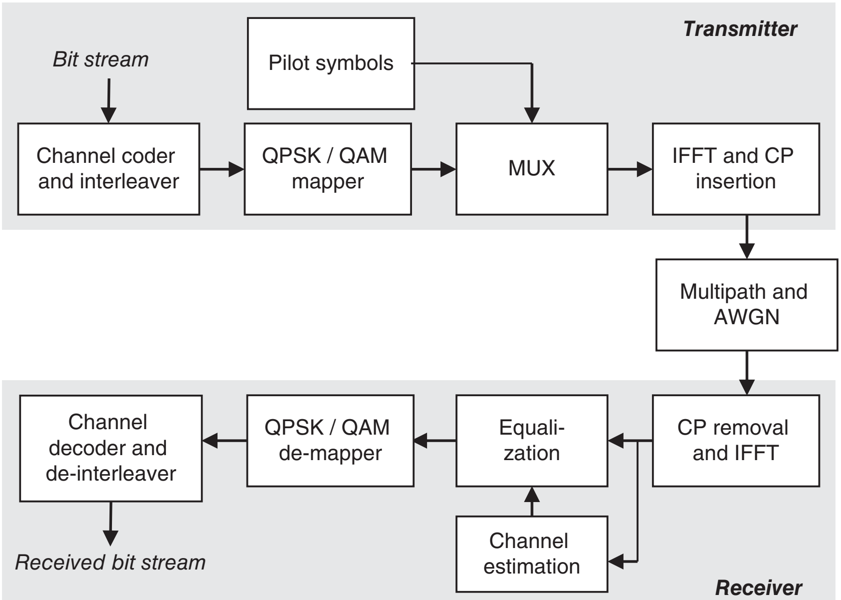

Figure 5.5 SISO OFDM simplified block diagram.

5.4.5 OFDM Transceiver Chain

Figure 5.5 presents a simplified block diagram of a single-input single-output (SISO) OFDM system. On the transmitter side, the modulated (QAM/PSK) symbols are mapped onto N orthogonal subcarriers. This is accomplished by means of an Inverse Discrete Fourier Transform (IDFT) operation. Most commonly, the IDFT is performed with an Inverse Fast Fourier Transform (IFFT) algorithm, which is computationally efficient. Next, the CP is inserted, and a parallel-to-serial conversion is performed prior to the transmission over the air.

At the receiver end, the reversal operations are performed. Once the received signal reaches the receiver, the CP, which is potentially interfered with by previous OFDM symbols, is removed. Then, a fast Fourier transform (FFT) operation brings the data to the frequency domain. This way, channel estimation and equalization are simplified. Note that to be able to carry out the latter operations, known symbols called *pilots* are to be inserted in certain frequency positions/subcarriers at the transmitter side. At the end of the chain, the equalized data symbols are demodulated yielding the received bit stream.

5.4.6 Cyclic Prefix

A guard interval is added in the beginning of each OFDM symbol to minimize negative impact of the multipath channel. If the duration of the guard interval T_g is larger than the maximum delay of the channel $\tau_{\max}$, all multipath components will arrive within this guard time and the useful symbol will not be affected avoiding ISI as can be seen in Figure 5.6.

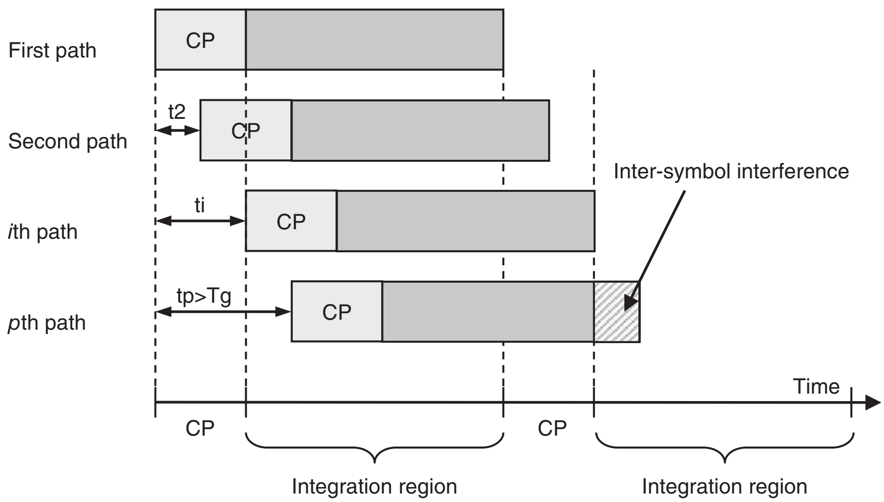

Figure 5.6 Cyclic prefix (CP) avoiding ISI.

One particularization of the guard interval is the so called cyclic prefix. In this case the last N_g samples of the useful OFDM symbol with N samples in total are copied to the beginning of the same symbol. Since the number of cycles of each orthogonality function per OFDM symbol will be maintained as an integer, this strategy also allows to keep the orthogonality properties of the transmitted subcarriers avoiding ICI. Figure 5.6 shows the cyclic prefix concept where

$$T_u = N \times T_0$$

$$T_g = N_g \times T_0$$

$$T_s = (N + N_g) \times T_0$$

The variables refer to the following: T_u is the useful OFDM symbol where data symbols are allocated, T_g is the duration of the cyclic prefix and T_s is the total duration of the OFDM symbol. The insertion of the CP results in Spectral Efficiency Loss (SEL), which is not relevant compared to the benefits that provides in terms of ISI and ICI robustness. The SEL can be interpreted as the loss of throughput that the OFDM transmission system will suffer by the addition of the cyclic prefix, and it can be presented as:

$$SEL = \frac{T_g}{T_g + T_u}$$

The loss of spectral efficiency is directly related to the ratio between the duration of the CP and the total duration of an OFDM symbol.

5.4.7 Channel Estimation and Equalization

In wireless OFDM systems, the received symbols have been corrupted by the multipath channel. To undo these effects, an equalization of the received signal that somehow compensates the variations introduced by the channel must be performed.

If the CP is longer than the maximum delay of the channel and a nonvariant channel over the duration of an OFDM symbol (slow-fading channel), each subcarrier symbol is multiplied by a complex number equal to the channel transfer function coefficient at this subcarrier frequency.

In other words, each subcarrier experiences a complex gain due to the channel. To undo these effects a single complex multiplication is required for each subcarrier yielding low complexity equalization in the frequency domain:

$$y[k] = \frac{z[k]}{h[k]} = d[k] + \frac{w[k]}{h[k]}$$

where $y[k]$ is the equalized symbol in the k^{th} subcarrier, $z[k]$ is the received symbol at the k^{th} subcarrier after FFT and $h[k]$ is the complex channel gain at subcarrier k. $w[k]$ represents the additive white Gaussian noise at subcarrier k.

Note that this equalization has been performed assuming a perfect knowledge about the channel. However, in most of systems that employ equalizers, the channel properties are unknown a priori. Therefore, the equalizer needs a channel estimator that provides the equalization block the required information about the channel characteristics.

To estimate the channel in OFDM systems, *pilot-aided channel estimation* is the most suitable solution for the mobile radio channel. This technique consists in transmitting symbols, often called pilot symbols, known by both the transmitter and the receiver to estimate the channel at the receiver. This approach presents an important trade-off between the number of pilots used to perform the estimation and the transmission efficiency. The more pilots are used, the more accurate the estimation will be, but also the more overhead will be transmitted reducing the data rate.

As an example, Figures 5.7–5.9 depict the mapping of cell-specific reference signals in LTE for different number of antenna ports and with normal CP. The pilot symbols are distributed in frequency- and time-domain and they are orthogonal to each other to provide accurate channel estimation. Figure 5.8 shows the idea of the LTE radio resource block, and following figures show the mapping of the reference signals (Figure 5.10).

In 5G, there also exists 8×8 port configuration.

5.4.8 Modulation

LTE can use QPSK, 16QAM, and 64QAM modulation schemes as shown in Figure 5.11, whereas 5G has option to utilize up to 254QAM. The channel estimation of OFDM is usually done with the aid of pilot symbols. The channel type for each individual OFDM subcarrier corresponds to the flat fading. The pilot-symbol assisted modulation on flat fading channels involves the sparse insertion of known pilot symbols in a stream of data symbols.

The QPSK modulation provides the largest coverage areas but with the lowest capacity per bandwidth. 64-QAM results in a smaller coverage, but it offers more capacity.

5.4.9 Coding

LTE uses Turbo coding or convolutional coding, the former being more modern providing in general about 3 dB gain over the older and less effective, but at the same time more

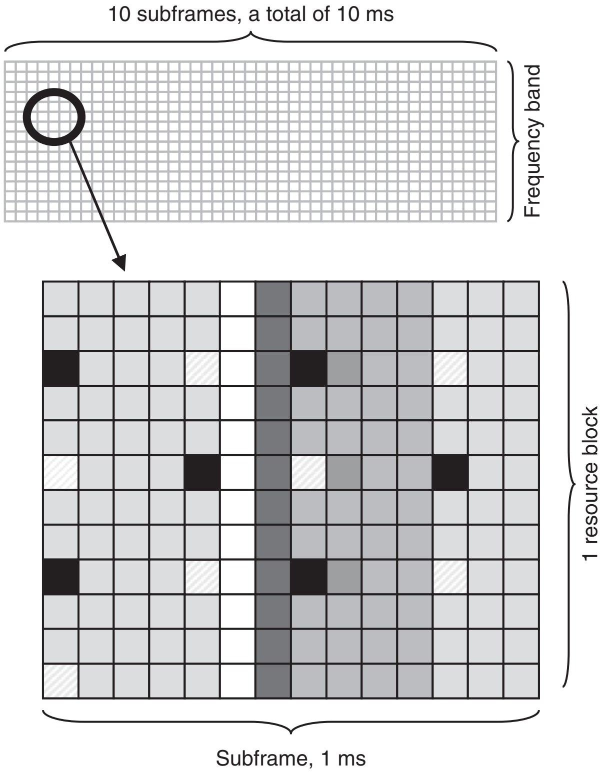

Figure 5.7 The forming of the LTE radio resource block.

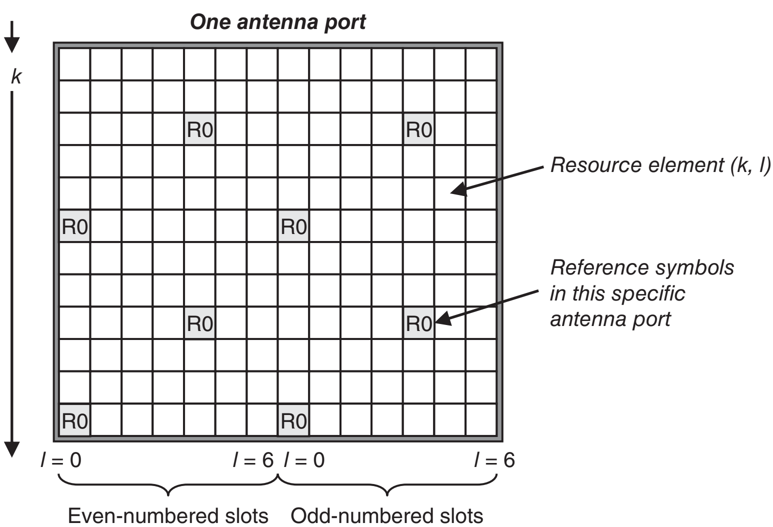

Figure 5.8 Mapping of downlink cell-specific reference signals in LTE with normal CP, i.e. in one antenna port setup of LTE.

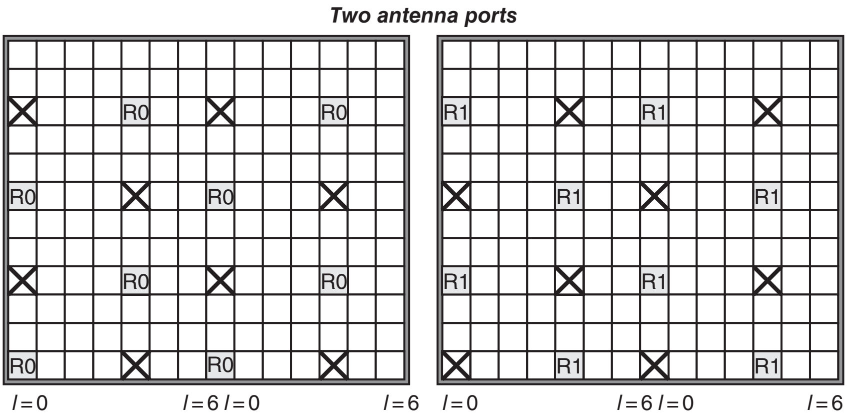

Figure 5.9 Two-port MIMO in LTE. The cross indicates the resource elements that are not used in the respective antenna port.

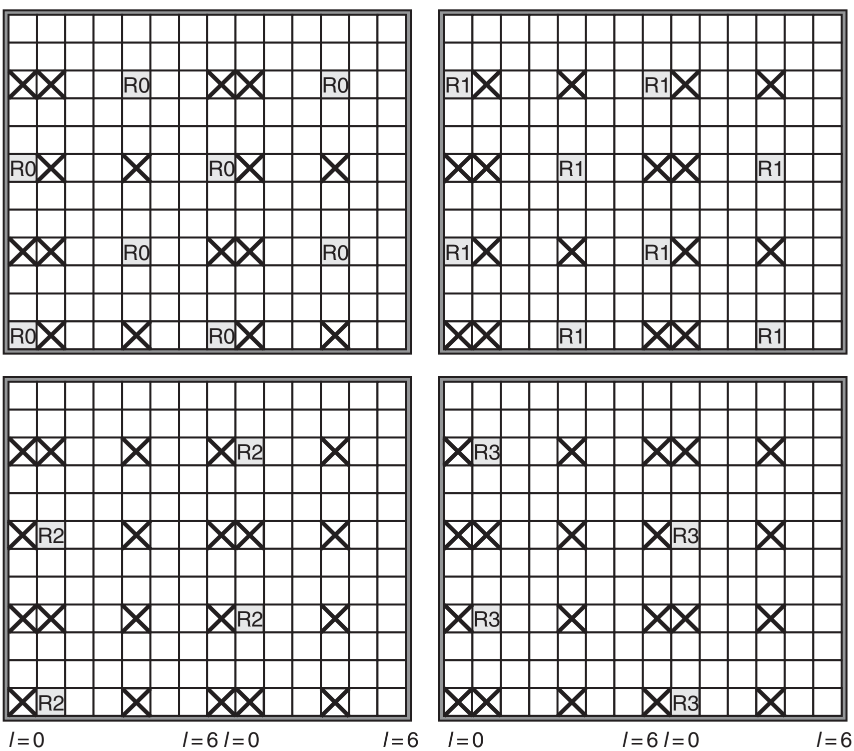

Figure 5.10 Port setup for four antennas.

robust convolutional coding. 5G further optimizes the coding by introducing coding schemes summarized in Table 5.2.

The creation of the OFDM signal is based on the IFFT, which is the practical version of the discrete Fourier transform (DFT) and relatively easy to be deployed as there are

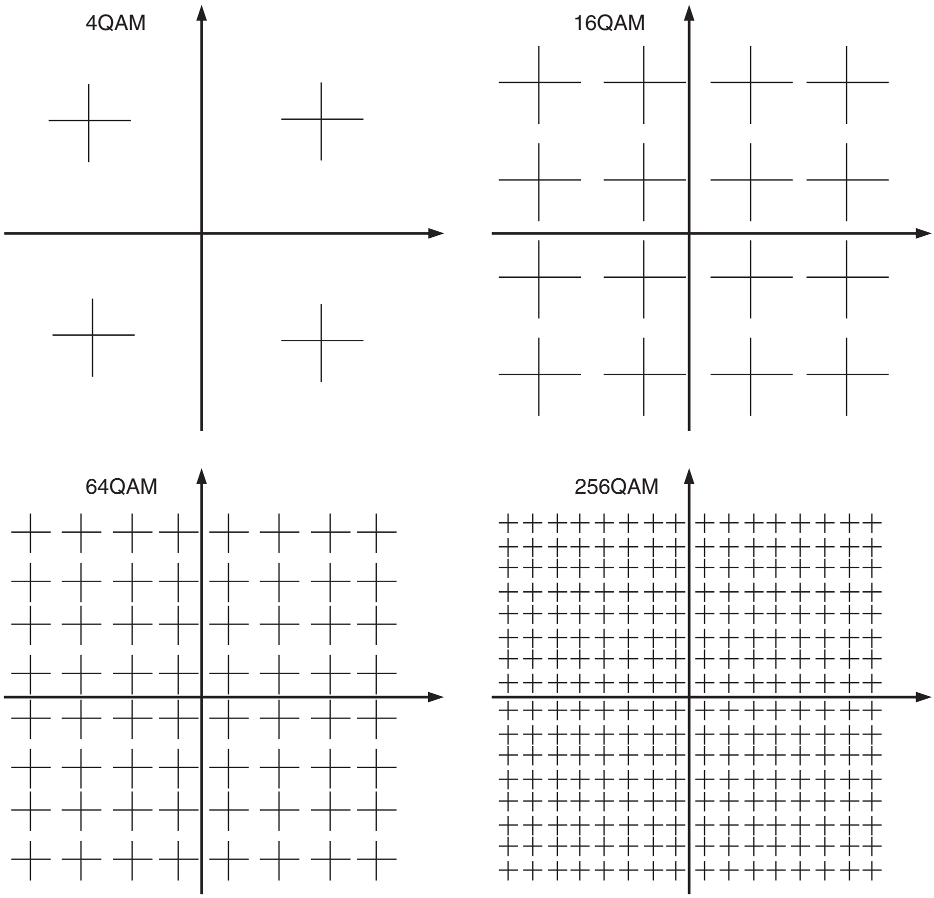

Figure 5.11 The I/Q constellation of the QPSK (4QAM) and set of other QAM variants relevant to 5G.

standard components for the transform calculation. The reception utilizes, on the other side, the FFT for combining the original signal.

5.4.10 Signal Processing Chain

After the coding and modulation of the user data, the OFDM signal is formed by applying serial-to-parallel conversion. This is an essential step to feed the IFFT process. Before bringing the parallel subcarriers of the user data, the subcarrier mapping also takes the needed amount of parallel subcarriers from the other users, i.e. the OFDMA (OFDM Access) is applied. All these streams are fed into the IFFT input in order to do the inversed discrete Fourier transform in a practical way. It is important to note that the process from the serial symbol stream to S/P conversion, sub-carrier mapping process and N-point IFFT process happens in the frequency domain, whereas the process from the IFFT conversion happens in the time domain.

The OFDM symbols are formed by adding the cyclic prefix in the beginning of the symbols in order to protect the signal against multi-path propagated components.

Then, the windowing, digital to analogue conversation, frequency up-conversion, RF processing, and finally the actual radio transmission are performed in the transmitter of the eNodeB. The OFDM transmission is only used in the downlink, so the Long Term Evolution-User Equipment (LTE-UE) does have the OFDM receiver and SC-FDMA transmitter.

5.5 Uplink OFDM of 5G: CP-OFDM and DFT-s-OFDM

As stated in 3GPP TS 38.300, the downlink transmission waveform of the 5G radio interface is conventional OFDM using a cyclic prefix, which is referred to as CP-OFDM. It is the very same as in LTE and LTE-A, as described in the previous section. The uplink transmission waveform of 5G, in turn, is conventional OFDM using a cyclic prefix with a transform precoding function performing DFT spreading that can be disabled or enabled. The latter is referred to as DFT-s-OFDM.

The difference between the 5G and the LTE/LTE-A multiplexing is thus for the uplink; instead of previously utilized SC-TDMA, the 5G is based on OFDM in both downlink and uplink. The DFT spreading that can be applied in 5G uplink optimizes the PAPR performance which was the reason to select the SC-TDMA in the first hand in LTE/LTE-A as the sole conventional OFDM is not optimal for it, especially in the use cases requiring low battery consumption such as low-powered IoT devices.

The requirements of the OFDM in 5G has been defined in 3GPP TS 38.300, Section 5.1. It summarizes the flow of waveform generation for both downlink and uplink (Figure 5.12).

5.6 Downlink

5G supports a closed loop DMRS (Demodulation Reference Signal) -based spatial multiplexing for the Physical Downlink Shared Channel (PDSCH). Furthermore, up to 8 and 12 orthogonal DL DMRS ports are supported for type 1 and type 2 DMRS, respectively. Up to eight orthogonal DL DMRS ports for each UE are supported for SU-MIMO and up to four orthogonal DL DMRS ports for each UE are supported for MU-MIMO.

There is a precoded matrix applied in the transmission of the DMRS and corresponding PDSCH. There is no need for UE to know the precoding matrix to demodulate the transmission.

As defined in 3GPP TS 38.300, the downlink physical-layer processing of transport channels includes the following steps:

- Transport block CRC (cyclic redundancy check) attachment;
- Code block segmentation and code block CRC attachment;
- LDPC (low-density parity check) based channel coding;
- Physical-layer hybrid-ARQ processing and rate matching;
- Bit-interleaving;
- QPSK, 16QAM, 64QAM, and 256QAM modulation schemes;
- Layer mapping and precoding;
- Mapping to assigned resources and antenna ports.

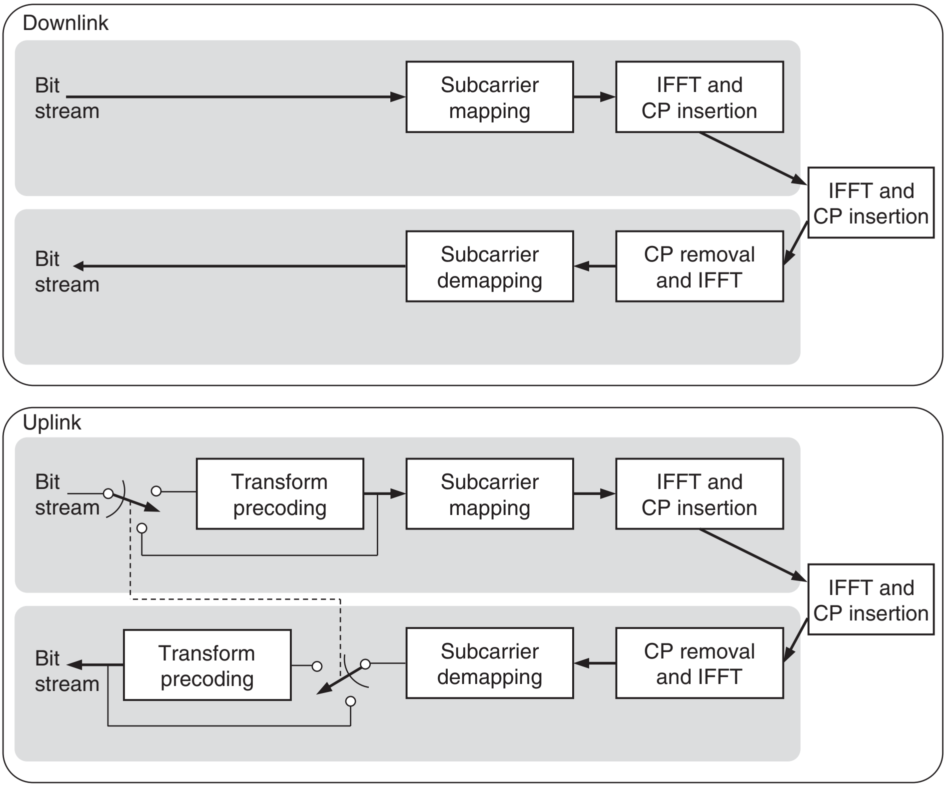

Figure 5.12 The principle of transmitter block for CP-OFDM. The utilization of DFT-spreading in uplink is optional.

To schedule DL transmissions on PDSCH and UL transmissions on Physical Uplink Shared Channel (PUSCH), the UE-specific Physical Downlink Control Channel (PDCCH) is applied. The respective Downlink Control Information (DCI) on PDCCH contains downlink assignments with modulation and coding format, resource allocation, and Downlink Shared Channel (DL-SCH)-related hybrid-ARQ information. It also contains uplink scheduling grants with modulation and coding format, resource allocation, and Uplink Shared Channel (UL-SCH's) hybrid-ARQ information. In the 5G system, the synchronization signal and Physical Broadcast Channel (PBCH) block have primary synchronization signal and secondary synchronization signals (PSS, SSSs).

The UE can rely on band-specific sub-carrier spacing for the SS/PBCH block by default, until network states otherwise.

More detailed description on the DL-SCH physical layer model can be found in the 3GPP TS 38.202, and the PBCH physical layer model is described in 3GPP TS 38.202.

5.6.1 Advanced MIMO

MIMO antenna systems are an integral part of the current 4G deployments. Thus, the evolution of the MIMO can be assumed to continue also in 5G era.

The MIMO antenna systems provide with highly directive antenna pattern forming in a dynamic way. It can be assumed that 5G NR will employ hundreds of antenna elements to increase the performance; this may not be possible with previous mobile communications systems. The MIMO concept also is related closely to the transmitter and receiver antenna beamforming to improve further the performance and to limit interferences. Not only the beamforming is useful for high frequencies, but it can be assumed to form an important base for many low-frequency scenarios to extend coverage and to provide higher data rates.

5.6.2 The ITU-R RAT Candidates

Along with the convergence of the mobile communications, the amount of diverse systems per mobile communications generation has fallen. The systems based on 3GPP specifications have been among the most popular throughout the GSM, Universal Mobile Telecommunications System (UMTS), and LTE evolution, and it seems that the same scenario is continuing as we approach 5G.

In 3G and 4G, there were also other stakeholders providing systems such as cdma2000, an Asian TD-based Wideband Code Division Multiple Access (WCDMA). There were also IEEE standards for WiMAX and WiMAX2 included in the 3G and 4G technologies, as referenced by the ITU. Nevertheless, the significance of these systems has decreased while the LTE and its evolution by LTE-Advanced has increased in relevance and popularity.

Up to the first half of 2018, the IEEE is not considering sending a complete system specification to the ITU-R IMT-20202 process. Nevertheless, 5G networks will rely largely on various protocols defined by IEEE.

5.7 New Radio (NR) Interface of 3GPP

The 3GPP is one of the most concrete standardization bodies driving for the 5G and developing the current 4G technical specifications further for the ITU-R IMT-2020 compliance. This section thus discusses the current understanding of the proposed 3GPP design and how it addresses the ITU-R requirements and use cases for 5G.

The key specification for the NR is the 3GPP 38.300 [6]. Among other aspects, it defines the following key functionalities and principles:

- Protocol architecture and functional split
- Interfaces
- Radio protocol architecture
- Channels and procedures in uplink and downlink
- Medium Access Control (MAC), Radio Link Control (RLC), Packet Data Convergence Protocol (PDCP) and Radio Resource Control (RRC) layers
- Mobility and states
- Scheduling
- UE key functionalities and capabilities
- Quality of service (QoS)
- Security
- Self-configuration and self-optimization

The following sections discuss these aspects apart from the security aspects, which is dealt with more details in a separate chapter later in this book.

5.7.1 Radio Network Architecture and Interfaces

The 3GPP Technical Specification 38.300 defines the 5G radio interface and functionality. The radio network of the 5G has its evolution path. The intermediate step is called non-standalone (NSA) with the base station element called **ng-eNB**. As the 3GPP specifications state, it is a node providing E-UTRA (Evolved UTRA) user plane and control plane protocol terminations toward the UE. It is connected via the Next Generation (NG) interface to the 5G Core Network (5GC). This is thus a 4G eNodeB, which can communicate with the 5G infrastructure.

In the fully evolved standalone (SA) phase, the native 5G radio base station is referred to as **gNB**. It is a node that provides the NR user plane and control plane protocol terminations toward the UE. It is connected via the NG interface to the 5G core network.

The general term for the 5G radio base station is NG-Radio Access Network (NG-RAN) node. It can be either a gNB (which refers effectively to the native 5G base station) or an ng-eNB (which is the intermediate radio base station based on the 4G era). These gNB and ng-eNB elements are interconnected via the *Xn* interface within the radio network. Both elements are connected furthermore via the NG interfaces to the 5G core network. This interface is divided into two parts: user and control interfaces. The control interface is referred to as NG-C, and it connects the radio base stations to the AMF (Access and Mobility Management Function). The user interface is referred to as *NG-U* and it connects the radio base stations to the UPF (user plane function). These interfaces are described in the 3GPP TS 23.501, whereas the functional interface for the control and user plane split as well as the 5G architecture are explained in the 3GPP TS 38.401.

In 5G, the further optimization of the radio resources takes place by separating user and control communications. It refers to the decoupling user data and control planes. This also provides the means to separate the scaling of user plane capacity and control functionality. One example of this is a situation in which user data might be delivered via a dense access node layer while the system information-related messages are delivered via overlaying macro layer.

This separation applies also over multiple frequency bands and RATs. In 5G, this makes it possible to deliver the user data via a dense, high-capacity 5G layer on higher frequency whereas the overlaid LTE layer provides the reliable signaling for call control.

5.7.2 5G Network Elements

5.7.2.1 gNB and ng-NB

Figure 5.13 depicts the NG-RAN architecture of 5G.

The gNB (standalone 5G NodeB) and ng-eNB (non-standalone 4G NodeB) host the following functions:

- Radio Resource Management (RRM)
- IP header management
- AMF management
- Routing functionalities

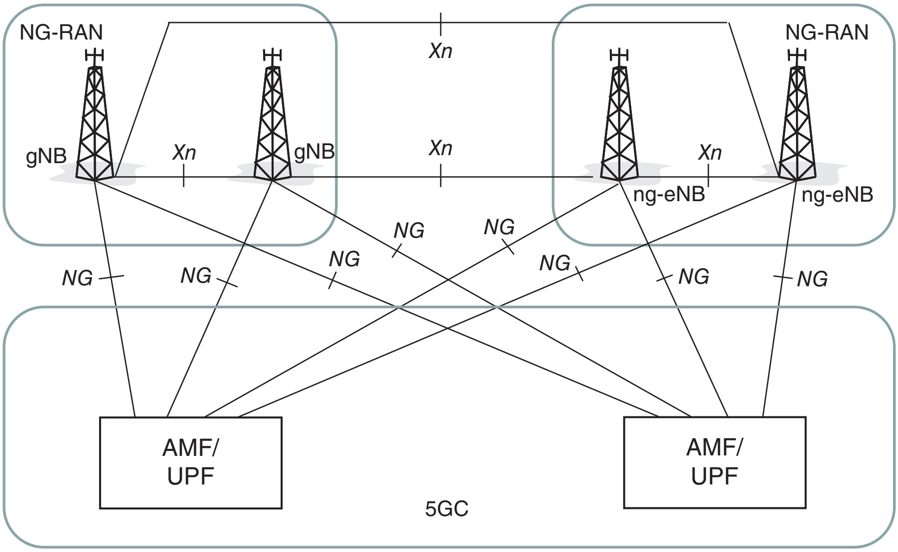

Figure 5.13 The 5G radio network architecture.

- Connection setup and release
- Scheduling functionality
- Measurements
- Packet marking
- Session management
- Network slicing
- QoS functions
- Support of UEs in RRC_INACTIVE state
- Distribution function for NAS messages
- Radio access network sharing
- Dual connectivity
- Tight interworking between NR and E-UTRA

The RRM of the gNB and ng-eNB includes radio bearer and radio admission control, connection and mobility control, and scheduling, which refers to the dynamic resource allocation to a set of UEs in both uplink and downlink. Furthermore, the 5G gNB's IP header management provides data compression, encryption, and integrity protection.

The gNB connects to AMF. The related AMF management from the gNB side refers to the selection of an AMF upon UE attachment in those scenarios when AMF cannot determine the routing information from the UE messaging.

Routing functionality of the 5G NB refers to the routing of user plane data toward a set of UPF elements, and routing of control plane information to AMF.

The connection setup and release performed by the 5G gNB relate to the procedures for initiating and terminating data sessions.

The scheduling functionality of the 5G gNB refers to the ability to schedule and transmit paging messages originated from the AMF, and schedule and transmit system broadcast information originated from the AMF or operations and management system.

The 5G gNB can perform radio interface measurements and deliver respective reports, which assist in the configuration for mobility and scheduling.

The packet marking of the 5G NB refers to the ability to mark the transport level packets in the uplink.

The session management refers to the procedures and functionalities applied during the active data connection.

The network slicing refers to the forming of highly dynamic virtual "sub-networks" with varying capabilities and optimized resource utilization according to the service-based architecture of 5G, taking advantage of the network functions virtualization. In other words, network slicing only consumes those resources from the virtualized environment needed for the specific moment.

The QoS functions refer to the QoS flow management and mapping to data radio bearers.

5.7.2.2 AMF

The AMF refers to as Access and Mobility Management Function. It contains the following key functions as referred in 3GPP TS 23.501:

- NAS signaling termination
- NAS signaling security
- AS security control
- Inter CN node signaling for mobility between 3GPP access networks
- Idle mode UE reachability (including control and execution of paging retransmission)
- Registration area management
- Support of intra-system and inter-system mobility
- Access authentication
- Access authorization including check of roaming rights
- Mobility management control (subscription and policies)
- Support of network slicing
- Session Management Function (SMF) selection

5.7.2.3 UPF

The UPF refers to user plane function. It can perform the following key functions as described in 3GPP TS 23.501:

- Acts as an anchor point for intra- and inter-RAT mobility
- Is external packet data unit (PDU) session point of interconnect to data network
- Performs packet routing and forwarding, packet inspection, and acts in user plane part of policy rule enforcement
- Forms traffic usage reports
- Is uplink classifier supporting routing traffic flows to a data network
- Is branching point supporting multi-homed PDU session
- Manages QoS handling for user plane
- Performs uplink traffic verification, being SDF (service data flow) to QoS flow mapping
- Makes downlink packet buffering and triggers downlink data notification

Table 5.7 The modulation schemes of 5G.

	BPSK	QPSK	16QAM	64QAM	256QAM
Downlink		✓	✓	✓	✓
Uplink, OFDM, and CP		✓	✓	✓	✓
Uplink, DFT-s-OFDM, and CP	✓	✓	✓	✓	✓

5.7.2.4 SMF

The SMF hosts the following main functions, as described in 3GPP TS 23.501:

- Manages session
- Allocates and manages UE IP addresses
- Selects and controls UP function
- Configures traffic steering at UPF routing traffic to proper destination
- Manages control part of policy enforcement and QoS
- Takes care of downlink data notification

5.7.3 Modulation

In 5G, the radio interface supports a set of modulations. For the proper selection of the modulation scheme, a modulation mapper is applied. It receives binary values (0 or 1) as input and produces complex-valued modulation symbols as output. These output modulation symbols can be π/2-BPSK (Binary Phase Shift Keying), BPSK, QPSK, 16QAM, 64QAM, and 256QAM. The modulation schemes supported are listed in Table 5.7.

5.7.4 Frame Structure

This section outlines the 5G channels and procedures both in uplink and downlink as defined by 3GPP. This section also summarizes the functioning of the mobility and states as well as the scheduling based on the 3GPP TS 38.211 (NR; physical channels and modulation) [7].

In 5G, downlink and uplink transmissions are organized into frames, which are derived from the OFDM structure. A single frame has a duration of

$$T_{\mathrm{f}} = (\Delta f_{\max} N_{\mathrm{f}}/100) \cdot T_{\mathrm{c}} = 10\ \mathrm{ms}$$

Each frame has 10 subframes. An individual subframe has a duration of

$$T_{\mathrm{sf}} = (\Delta f_{\max} N_{\mathrm{f}}/1000) \cdot T_{\mathrm{c}} = 1\ \mathrm{ms}$$

The number of consecutive OFDM symbols per subframe varies, depending on the number of the symbol and slot. Furthermore, each frame is divided into two half-frames of five subframes each, with half-frame 0 consisting of subframes 0–4 and half-frame 1 consisting of subframes 5–9. More detailed description of the frame structure and frequency band allocation can be found in 3GPP TS 38.133 and TS 38.213.

5.7.5 Physical Channels

5.7.5.1 Uplink

As defined in [7], an *uplink physical channel* refers to a set of resource elements carrying information that originates from higher layers. 3GPP has defined the following *uplink physical channels* for 5G:

- Physical Uplink Shared Channel (PUSCH)
- Physical Uplink Control Channel (PUCCH)
- Physical Random-Access Channel (PRACH)

The physical layer uses *uplink physical signals* that do not carry information originating from higher layers. These uplink physical signals are the following:

- Demodulation reference signals (DM-RSs)
- Phase-tracking reference signals (PT-RSs)
- Sounding reference signals (SRS)

The UE uses a frame structure and physical resources as dictated by [7] when it is transmitting in uplink. Furthermore, [7] defines a set of antenna ports that are applied in uplink.

5.7.5.2 Downlink

As defined in [7], a *downlink physical channel* refers to a set of resource elements that carry information arriving from higher layers. 5G defines the following downlink physical channels:

- Physical Downlink Shared Channel (PDSCH)
- Physical Broadcast Channel (PBCH)
- Physical Downlink Control Channel (PDCCH)

A *downlink physical signal* refers to a set of resource elements that the physical layer uses, yet these do not carry information originating from higher layers. The downlink physical signals are the following:

- Demodulation reference signals (DM-RS) for PDSCH and PBCH
- Phase-tracking reference signals (PT-RS)
- Channel-state information reference signal (CSI-RS)
- Primary synchronization signal (PSS)
- Secondary synchronization signal (SSS)

5.7.6 General Protocol Architecture

The physical layer channels overview is presented in TS 38.201 (NR; general description) and TS 38.202 (NR; services) provided by the physical layer [8]. These specifications also detail 5G protocol architecture and the functional split of it, and the overall and radio protocol architectures, MAC, RLC, PDCP, and RRC.

The 3GPP specifications describe the NR interface covering the interface between the UE and the network on layer 1, 2, and 3. The TS 38.200 series describes the layer 1 (physical layer) specifications. Layers 2 and 3 are described in the TS 38.300 series.

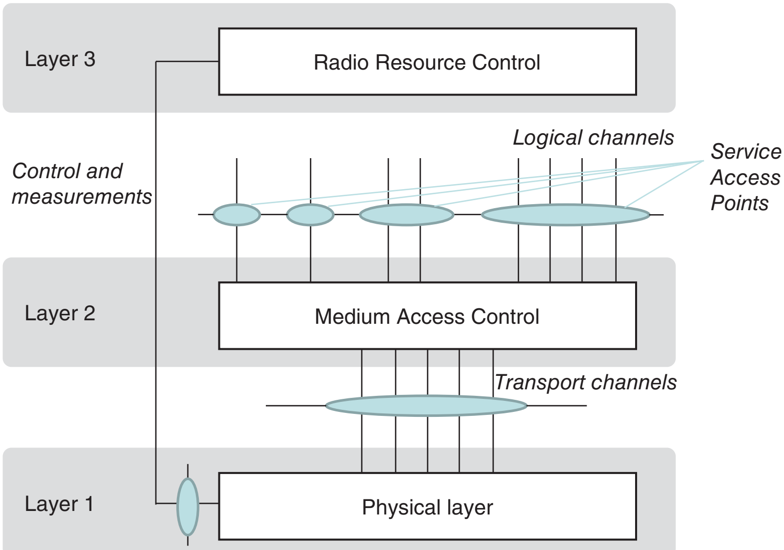

Figure 5.14 The principle of mapping 5G channels.

Figure 5.14 depicts the NR radio interface protocol architecture related to layer 1, which interfaces the MAC layer 2 and the RRC layer 3. The connectivity between layers is done by utilizing service access points (SAPs).

The transport channels between physical radio layer and MAC layer answer the question on how the information is transferred over the radio interface. In the upper layer, between MAC and RRC layers, MAC provides logical channels. They answer the question of what type of information is transferred.

The physical layer offers data transport services to higher layers. The access to these services happens using transport channel through the MAC layer.

5.7.7 Multiple Access

The multiple access scheme for the NR physical layer is based on OFDM with a CP. For uplink, discrete Fourier transform-spread-OFDM (DFT-s-OFDM) with a CP is also supported. To support transmission in paired and unpaired spectrum, both frequency division duplex (FDD) and TDD are enabled.

Layer 1 is based on resource blocks. This provides means for the 5G NR layer 1 to utilize multitude of spectrum allocations. Resource block is based on up to 12 subcarriers.

The duration of radio frame is 10 ms. It contains 10 subframes, and the duration of each is 1 ms. A subframe has one or more adjacent slots, from which each has 14 adjacent symbols.

5.7.8 Channel Coding

The channel coding scheme for transport blocks is quasi-cyclic LDPC codes with two base graphs and eight sets of parity check matrices for each base graph, respectively. One base graph is used for code blocks larger than certain sizes or with initial transmission code rate higher than thresholds; otherwise, the other base graph is used. Before the LDPC coding, for large transport blocks, the transport block is segmented into multiple code blocks with equal size. The channel coding scheme for PBCH and control information is polar coding based on nested sequences. Puncturing, shortening, and repetition are used for rate matching. Further details of channel coding schemes are specified in [5].

5.7.9 Physical Layer Procedures

The physical layer procedures include cell search, power control, uplink synchronization, uplink timing control, random access, and Hybrid Automatic Repeat and Request (HARQ) procedures, antenna beam management, and CSI-related procedures. NR provides support for interference coordination via physical layer resource control in frequency, time, and power domains.

5.7.10 Physical Layer Measurements

Radio characteristics are measured by the UE and the network and reported to higher layers. These include, e.g. measurements for intra- and inter-frequency handover, inter RAT handover, timing measurements, and measurements for RRM. Measurements for inter-RAT handover are defined in support of handover to E-UTRA.

5.7.11 Quality of Service

The 5G aspects on the QoS are defined in 3GPP TS 38.300.

5.8 User Devices

Technical specification 3GPP TS 38.306 V15.1.0 defines the 5G UE radio access capabilities as of Release 15, including new aspects of 5G terminals, local connectivity, evolved battery, display, sensor, memory and processor technologies. Other relevant specifications for the UE's point of view include:

- 3GPP TS 38.300; UE key functionalities and capabilities
- 3GPP TS 38.101-1; NR UE radio transmission and reception, Part 1, Range 1 Standalone
- 3GPP TS 38.101-2; NR UE radio transmission and reception, Part 2, Range 2 Standalone
- 3GPP TS 38.101-3; NR UE radio transmission and reception, Part 3, Range 1 and Range 2 Interworking Operation with Other Radios
- 3GPP TS 38.101-4; NR UE radio transmission and reception, Part 4, Performance Requirements

It should be noted that, as indicated in 3GPP TS 38.300, the UE capabilities in NR do not rely on UE categories. In fact, UE categories indicating peak data rates are only meant for marketing purposes and there is no respective signaling to the 5G network. In practice, the network determines the UL and DL data rate of UE based on the supported band combinations and baseband capabilities, which refer to modulation scheme, MIMO layers, and other characteristics on the RF path.

5.9 Other Aspects

The 3GPP TS 38.300 summarizes some additional aspects respective to 5G, such as self-configuration and self-optimization. It also discusses key security aspects of the 5G, which will be discussed in more detail in Chapter 8.

Along with the 5G deployments, it is expected that more advanced antenna technologies will be taken into use, too. 3GPP TR 37.842 V2.1.0 defines RF requirements for active antenna system (AAS) on the base station, as of Release 13. This specification also acts as a base for the 5G era respective to the AAS.

5.10 CBRS

5.10.1 Background

The CBRS is a framework of new US FCC rules for commercial use of the 3550–3700 MHz band containing a contiguous 150 MHz block for mobile broadband services. 3GPP has extended LTE standards to support the CBRS band. It is governed by FCC to accommodate a variety of commercial uses on a shared basis with incumbent federal and nonfederal users of the band.

Access and operations will be managed by a dynamic spectrum access system like the idea used to manage television white spaces devices. The FCC stated, "Facing ever-increasing demands of wireless innovation and constrained availability of clear sources of spectrum, the Citizens Broadband Radio Service is an opportunity to add much-needed capacity through innovative sharing." [9]

Even if CBRS is not designed especially for 5G, its deployment time schedule coincides closely with the first 5G deployments and it can thus form a part of the initial 5G network infrastructure relying on the 4G technology.

CBRS provides customizable, high-capacity, private LTE networks for consumer and IoT devices. MNOs can increase capacity and coverage. Private operators get more control for special business environments such as factories, warehouses, and airports. Enterprises get seamless, reliable, and scalable LTE radio coverage. CBRS gives added value, especially in large remote sites that otherwise would lack of LTE service.

The FCC has opened 150 MHz spectrum in 3.5–3.6 GHz band. China, Japan, Korea, Europe, and other countries have allocated part or all the band for mobile broadband, and Europe has informed the band will be used in wireless 5G. Other countries are developing the concept as well [10]. ETSI is working on LSA, comparable with CBRS based on authorized shared access (ASA).

Major MNOs have been tested CBRS with special temporary licenses for capacity gain [11]. In the United States, the FCC has made the CBRS frequency available at 3.5 GHz, with 150 MHz bandwidth. The FCC Report Rulemaking 12-354, adopted by the Commission on 17 April 2015, established CBRS for shared wireless broadband use as stated in Part 96 of the Commission's rules [12, 13]. Elsewhere in the world, regulators are making similar frequencies available.

The primary user of the 3.5 GHz bands is Department of Defense, and the FCC is in the process of making the spectrum available for shared commercial use [14].

For practical deployments, the equipment must first be available. As an example, Verizon announced new vendors for CBRS in 2018. Verizon plans to offer private LTE based on CBRS, expecting handsets with CBRS band support to arrive to the commercial markets sometime around the end of 2018.

5.10.2 Use Cases for CBRS

Many of the potential CBRS applications, particularly for priority access licenses (PALs), have substantial commercial value:

- Mobile operator capacity augmentation
- Cable and MVNO (mobile virtual network operator) system augmentation
- Neutral host network for public space
- Wireless Internet service providers (WISPs), particularly in rural areas
- Enterprise LTE, etc.

CBRS allows organizations to establish their own LTE networks via spectrum sharing without purchasing spectrum license. It facilitates new use cases for consumers, enterprises, and IoT [15, 16]. It supports Automation and Industry 4.0, IoT applications in automation, remote mining and farming sites, wireless robotics in product lines, virtual-reality entertainment applications at outdoor sport events, and video surveillance. It also is adequate for mission-critical services, e.g. to monitor electricity distribution grids, and to provide ad-hoc networks for public safety agents.

There have been CBRS trials in 2018, and CBRS commercial deployment is expected latest in the beginning of 2019. The expected forerunners include tier-1 carriers, cable carriers, private LTE carriers (such as mining and transportation companies). The expected device form factors include outdoor and indoor units, smartphones, and tablets.

CBRS Alliance has quarterly meetings to review the CBRS market potential and growth. The subscriber identity module (SIM) cards are agnostic to the CBRS band and service as such, but the new and existing operators may need personalized profiles instead of the generic ones.

5.10.3 The Concept

CBRS is an add-on to the 3GPP LTE network enabling cost-effective mobile broadband in a 3.5 GHz frequency band. There is no need for the CBRS operator to purchase licensed spectrum for the shared option of the CBRS.

The shared CBRS is another variant for the unlicensed LTE, the earlier version being the LTE on unlicensed 5 GHz spectrum (LTE-U), and the LAA (Licensed Assisted Access) which is the standardized version of LTE-U as governed by 3GPP [17].

CBRS can be deployed with operators' existing packet core networks, or enterprises can deploy a private LTE network using small cells and either their own small-scale packet core or through a cloud-hosted packet core, as in the case of Nokia providing this service [18].

Universal SIM (USIM) cards are agnostic for the RF band if the wanted RAT is supported. CBRS is thus merely one variant of LTE system, and the respective USIM works as it has been designed to the LTE networks, communicating with the Home

Table 5.8 The CBRS tiers.

Tier	Users
1	Designed for incumbent users such as federal radar (occasional use e.g. in coast areas), fixed satellite services (Earth station reception), and wireless Internet service providers (ISPs).
2	Refers to the Priority Access License (PAL) holders.
3	For general authorized access (GAA) users allowing access to nonlicensed band. There is a total of 150 MHz spectrum available for the GAA-shared spectrum if the access does not interfere with PAL or incumbent users.

Subscription Server (HSS) to authenticate the user, authorize the access, and encrypt the communications. The principle of the USIM profile of the CBRS is thus the same as in any other MNO environment.

CBRS is a shared spectrum concept based on the FCC rules, providing the possibility for additional stakeholders to operate on unlicensed LTE band 48. While protecting existing national defense users' communications, FCC wants to provide an additional way to consumers for accessing wireless broadband.

Among other stakeholders, Nokia has been driving it actively, and has had a proof of concept with Qualcomm and Google. The results have showed functional high-speed video streaming in car race via CBRS infrastructure.

5.10.4 Frequency Sharing

US FCC has published updated rules for the 3550–3700 MHz spectrum allowing CBRS sharing the band by organizations. CBRS is defined for three-tiers as indicated in Table 5.8.

3GPP has specified the CBRS for LTE networks. Key technical specifications related to the radio interface and services are:

- TS 36.744, CBRS 3.5 GHz band for LTE in the United States (Release 14)
- TS 36.790, LAA (License Assisted Access)/eLAA (enhanced LAA) for the "CBRS" 3.5 GHz band in the United States

CBRS Alliance works on the development of specifications and ecosystem, facilitates the commercialization of LTE CBRS solutions, and develops a certification process for the deployments of CBRS infrastructure [11].

5.10.5 CBRS Interface

The CBRS eNodeB can be connected to the MNO's existing packet core network. It also can be deployed by enterprise as a private LTE network using small cells and either their own small-scale packet core or through a cloud-hosted packet core. One of the architectural models that can be used for offering CBRS is the multi-operator core network (MOCN) as defined by 3GPP [19].

MOCN is the 3GPP standard for radio and core; hosted clients must thus support the 3GPP core network. MOCN provides a neutral host, e.g. CBRS operator with LTE

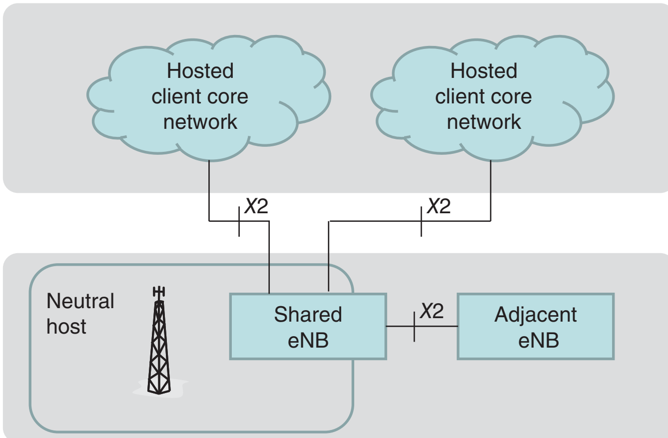

Figure 5.15 The architecture of MOCN.

eNB, connectivity to hosted client core networks (Figure 5.15). Other options include Gateway Core Network (GWCN), in which interworking is at the core network, and multiple operator RAN (MORAN), making the baseband and RF shared [20]. The hosted client must have issued users with universal integrated circuit cards (UICCs) containing 3GPP subscription info and security credentials [19].

As the CBRS is in practice an extension to the RF bands of LTE, it would not change the principle of the security the LTE network provides. LTE-based private networks thus benefit from the native SIM security, as well as emerging non-SIM options.

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