Initial draft

Chapter 2

# 5G NR physical layer (An introduction of the Fifth Generation-New-Radio physical layer)

5G stands for Fifth Generation Mobile Communication and it is a revolutionary expansion of the capability of cellular networks. The most significant properties, especially compared to the previous wireless communication technologies, are the ability to provide higher data rates, higher connection density and a far broader range of applications [1]. 5G is referring to a very wide context which is a range of new services envisioned to be enabled by future mobile communication, however, in this chapter, we will discuss to a specific radio-access technology called New Radio-Access Technology, which is the most relevant and concerning part of the machine learning positioning system.

## 2.1 3GPP NR introduction and history

The first version of the NR specifications was available by the end of 2017, which is an early version of 3GPP Release 15, and it could almost meet the commercial requirements on the 5G deployments. It is a limited version named NR Non-Standalone Mode which was rely on LTE core network for initial access and mobility with EPC (Evolved Packet Core) which is possible to connect both the NR radio-access network and the legacy LTE core network, so the LTE eNodeB manages all the control plane data as a master and the NR/gNB handles user plane data as a slave, it is referred to as dual connectivity. Under this kind of situation, it had solved some lower layers communication problems and established a core connection architecture with number of variations based on the routing of user data. It achieves many basic and important functions and lays a solid foundation for the opening of 5g, such as channel coding/modulation, sync/system info. broadcasting/paging, random access channel/procedure, RRM measurement, L1/L2 data/control channels, scheduling HARQ procedures, MIMO Tx schemes, beam management and CSI, RS design and QCL, NR-NR CA and so on [2].

To improve the existing version, to implement more comprehensive functions, to optimize the higher layers architecture effects and the interface to the core network, the development version of Release 15 comes out until the mid of 2018. In addition to solving the remaining issues by the above functions, the most focused and evolving use cases are eMBB which stands for Enhanced Mobile Broadband and URLLC which stands for Ultra Reliable Low Latency Communications. With further study and to achieve the more excellent results, the other network architecture which 3GPP specified this primary core connection architecture as stand-alone architecture is completed gradually. It has an N26 interface to guarantee service continuity which support the ability of interworking between the EPC and 5GC (5G core), and a dynamic switching control plane anchor to hand over the user equipment moving from or out of NR coverage[3], no elements of LTE are utilized. In summary, it is the NR Release 15, the first incarnation of radio access technology which is supporting a wide range of requirements including extremely high data rates and very low latency, despite that it also has many unresolved and not considered issues, such as frequencies beyond 52.6GHZ, mMTC, MIMO enhancements, power saving and so on. However, some of the problems here will gradually be solved in the next version Release 16.

With the ongoing work on Release 16, it is focused on the improvements of already existing features, and new features addressing new deployment scenarios and verticals. It has several enhancements in Release 16 include: cross-link interference mitigation and remote interference management, multiple-input multiple-output enhancements, UE power savings, dual connectivity and carrier aggregation enhancements and mobility enhancements [4]. Besides these mentioned above, Release 16 still study on some important items which are the optimization of technology and expansion of application scenarios, such as positioning, NR-based access to unlicensed spectrum, Non-orthogonal multiple access for NR, Integrated access and backhaul, NR to support non-terrestrial networks, intelligent transportation systems and vehicle to anything communication, industrial IOT and ultra-reliable low-latency communications and so on.

Looking beyond Release 16, NR continue to evolve in Release 17 that 3GPP has passed the midpoint in its work at the end of the first quarter of 2022, it has emphasized on the enhancements of Release 16 and made improvements to features present in Release 16, continue to extend the 5G evolution era to the 5G advanced era which are Release 18/19. Besides it still works on the technologies or scenarios mentioned in previous versions, such as Beamforming and MIMO enhancements from Release 16, Dynamic spectrum sharing improvements from Release 15, it also proposed and improved NR coverage, small data transmission, NR positioning for further specific use, non-public networks, edge computing and data networks analytics more detailed and optimized than the previous two versions. However, the key aspects of Release 17 are the continuous drive to support new verticals and deployment scenarios. So Rel-17 strengthens 5G support for new use cases primarily through new development in five areas: RedCap UE, non-terrestrial networks, frequency bands beyond 52GHz, and the multicast and broadcast service (MBS) [5]. We believe in the future, Release 18 and 19 will create 5G advanced era which will introducing more and more intelligence applications and scenarios into networks and continue to boost the performance.

We can find that the current development of 5G is based on the initial design and research. So, in order to better understand the structure and application methods of the positioning system, we need to explore and understand the principles of the NR basic system, especially on the physical layer that this chapter focuses on.

## 2.2 Waveform, Numerology and Frame Structure

This section of this chapter describes some important theoretical and practical aspects of physical layer protocols and functional processing in 3GPP new radio which is the basis for our understanding of 5G NR. The physical layer is the lowest layer in the RAN protocol architecture, and it use the transmission medium to establish, manage and release physical links for both ends of the communication to achieve transparent transmission of bit streams and ensure that the bit streams are correctly transmitted to the opposite end. The key technology components of the NR physical layer are modulation, waveform, multiantenna transmission and channel coding. In order to understand the structure of NR physical layer better, we will provide an introduction of some important types of transmission waveforms in 5G NR which defines the modulation, frame structure, and other essential parameters that determine how data is transmitted over the wireless channel.

NR waveform employed for eMBB / URLLC and in the licensed-spectrum from below 1GHz up to 52.6GHz, usually is cyclic prefix OFDM which is utilized to address issues related to inter symbol interference and improve the robustness of the signal against multipath propagation in downlink and both cyclic prefix OFDM and DFT-spread-OFDM which works for coverage limited scenarios for uplink transmissions. Additionally, CP-OFDM is targeted at high throughput scenarios and DFT-s-OFDM is targeted at power limited scenarios. In practice, a gNB can select the uplink waveform based on demand and a UE could support both waveforms.

NR has a scalable OFDM numerology to enable diverse services on a wide range of frequencies and deployments. The parameters defined a numerology is subcarrier spacing and cyclic prefix. The subcarrier spacing is scalable and specified as $2^u \times 15$ KHz, where u is an integer and 15 KHz is the subcarrier spacing used in LTE. In 3GPP Release 15, u is equal from 0 to 4, so the four subcarrier spacings are 15KHz, 30KHz, and 120KHz 240KHz which are defined as normal cyclic prefix and 60KHz which has defined as an extended cyclic prefix, all with 7% cyclic prefix overhead. In the normal CP numerology as Figure 1. [2], each symbol length of 15KHz equals the sum of the corresponding $2^u$ symbols at $F_S$, other than the first OFDM symbol in every 0.5 ms and all symbols within 0.5ms have the same length.

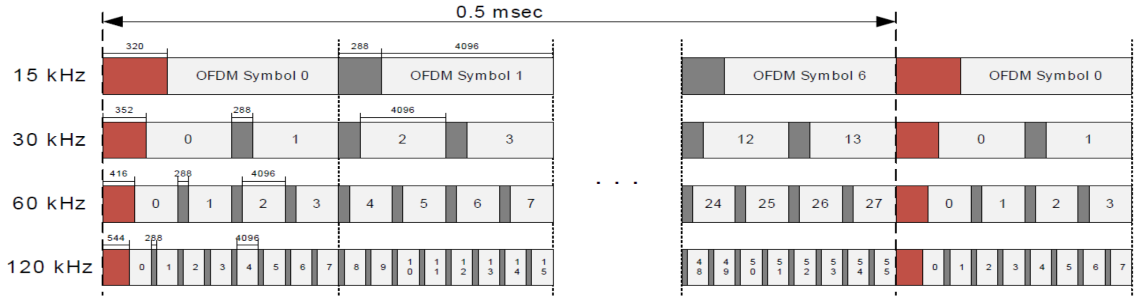


Figure 1. Numerology Example (Normal CP)

Due to the integration of different OFDM-based waveforms and multiplexing different numerologies, we can achieve much better performance and support a wide range of deployment scenarios than a single numerology OFDM. Although it will bring some problems such as high PAPR, inter numerology interference, inter carries interference, inter symbol interference and channel estimation errors, it still can be optimized and reduced to maximize the minimum achievable rate of the users and satisfy the QoS expectations. With the use of small subcarrier spacing, it can provide a relatively long cyclic prefix in absolute time at a reasonable overhead. The more common usage in Release 15 is using TDM and/or FDM for downlink and uplink and it does not require to support downlink reception or uplink transmission of multiple FDM physical channels with different numerologies at the same time [2]. Therefore, carrier aggregation can be used to support very larger bandwidths and can easily be extended to cover much more spectrum than LTE.

In the NR time domain, the frame length of NR is 10 ms and it divided into 10 1 ms subframes. A subframe is composed of an integer number of slots, and each slot consists of 14 OFDM symbols.

Each slot can carry control signals/channels at the beginning and/or ending OFDM symbol(s), as illustrated in Fig. 2 [6], and the slot length scales with the subcarrier spacing which is equal 1ms/$2^u$, u is an integer mentioned above. So, a higher subcarrier spacing leads to a shorter slot duration and it will support lower latency transmission in theoretical aspect.

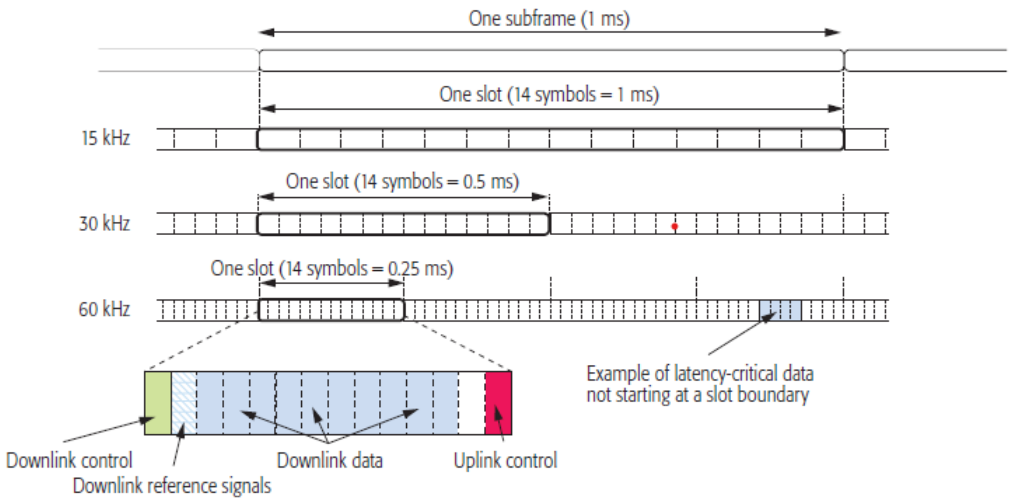


Figure 2. Frame structure (TDD assumed in this example)

Furthermore, if the transmission works over a fraction of a slot which is referred to as "Mini-Slot" transmission, NR will have a more efficient approach to low latency even in unlicensed spectrum. The Mini-Slot structure supports 2, 4, or 7 symbols to be allocated with a flexible start position and it is the minimum scheduling unit. It has three good reasons for allowing the use of Mini-Slot, the first is lowered latency in lower frequency transmission, the second is support of analog beamforming in very high-frequency transmission, the third is to facilitate effective transmission in unlicensed bands [7]. It is widely used in many cases because of these advantages mentioned above, such as support of finer TDM granularity of scheduling for the same/different UEs within a slot, using LTE MBSFN subframes for NR, forward compatibility towards unlicensed spectrum operation and so on.

In NR frequency domain, the smallest physical resource is specified as a resource element which consists of one subcarrier during one OFDM symbol. They are grouped into the physical resource block (PRB) and there are 12 consecutive subcarriers in each PRB. Different subcarrier spacing contains different number of PRBs, for example 2 PRBs of subcarrier spacing 30KHz occupy the identical frequency range as 1 PRB of 60KHz subcarrier as the figure 3. Shows. The resource grids for all subcarrier spacings are overlapped and it defines the transmitted signal space as seen by the UE for a given subcarrier spacing.

## 2.3 Initial/Random Access and Beam Management

5G NR (New Radio) supports very high data rates and lower latency and it divided in FR1 and FR2 frequency bands, FR1 is sub-6 GHz (450 to 6000 MHz); FR2 is millimeter wave band (24.25 GHz to 52.6 GHz). Since millimeter wave bands use very high frequencies, they cause propagation losses and other losses. To compensate for losses, directional communication at this frequency is essential. 5G NR uses an antenna array (MIMO) with many antenna units with smaller wavelengths. Massive antennas provide beamforming gain to the RF link budget, helping to compensate for propagation losses, and large antenna arrays help achieve higher data rates due to spatial multiplexing techniques.

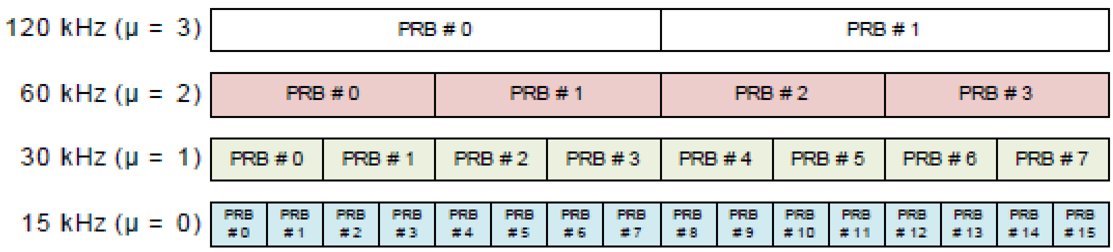


Figure 3. PRB alignment

But the problem is that the radiation range of the large-scale antenna array is no longer circular but has a fusiform shape, which requires that the transmission and reception beams of the transmission link between gNB and UE must be accurately aligned. To achieve alignment of beam pairs with the required end-to-end performance and required latency, beam management is introduced in 5G NR. Beam management is essential in both idle mode (UE and gNB are not connected) and connected mode (UE and gNB exchange data). In the connected mode, the UE can also measure the transmit beam of the gNB to achieve fine refinement; In the idle mode, the UE measures the scanning beam of the gNB to achieve initial access.

When a UE powers on, it needs to search for a suitable cell to launch initial access and the random-access procedure. Initial access are the steps executed to allow a UE that is just powered on to find a cell to camp on and, having found such a cell, the steps that the UE, in the idle or inactive RRC state, uses to access the network and, via a random-access procedure, establishes normal communication, i.e., go to the RRC-CONNECTED state. The random-access procedure is specifically designed to handle the collision risk and lack of accurate timing control [8].

The simplified version of the initial access and contention-based random-access steps are the gNB periodically transmits synchronization signals blocks(SSB) which the UE identifies it within the synchronization signal burst set and require initial access data/basic information to UE firstly, then UE performs initial cell selection and downlink synchronization to establish a connection, thirdly UE keep attempting random-access by transmitting a preamble on the channel until a random-access response or system information is received from the network within a defined window, finally after gNB receives messages from UE and respond with new message to UE, the data and control channels established.

Beam management specifically includes beam sweeping, beam determination, beam measurement, beam reporting, beam recovery, and the reference signals used for beam management are primary synchronization signal (PSS), secondary synchronization signal (SSS), and physical broadcast channel demodulation reference signal (PBCH DMRS) in idle mode and channel state information reference signal (CSI-RS) (DL) and sounding reference signal (SRS) (UL) in connected mode. PSS, SSS, and PBCH are the only always-on signals in New Radio, and the structure of them shows in the figure. 4. It consists of PSS and SSS, which cover 1 OFDM symbol and 127 subcarriers each, and PBCH that occupies 3 OFDM symbols and 240 subcarriers respectively. The center frequency of PSS/SSS is aligned with the center frequency of PBCH. CSI-RS is used by the UE to estimate the channel and report channel quality information (CQI) to the base station. The (SRS) is used to monitor the uplink channel quality. It is sent by the UE and received by the gNB. The UE can configure multiple SRSs for beam management. They contain 1 to 4 OFDM symbols and occupy part of the bandwidth allocated to the UE for transmission.

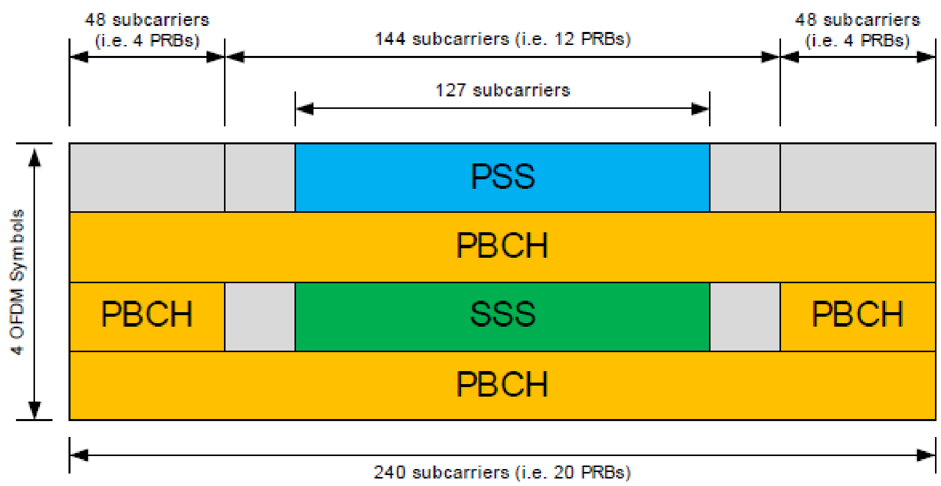


Figure 4. Time-frequency structure of PSS, PBCH, SSS

Beam sweeping means that during a specific time interval, beams are transmitted and/or received in a preset manner to cover a spatial area. In order to expand the beamforming gain, a high-gain directional antenna is usually used to form a narrow beam width. However, a narrow beam width can easily cause an insufficient coverage, especially in the case of a 3-sector configuration. In order to avoid this problem, multiple narrow beams can be used in the time domain to scan within the coverage area to meet the coverage requirements in the area. Using the beam sweeping technology, the beam is transmitted in a predetermined direction at a fixed period. For example, during the initial access process, the UE needs to synchronize with the system and receive minimum system information. Therefore, multiple SSB blocks carrying PSS, SSS and PBCH are scanned and transmitted at a fixed period. CSI-RS can also use beam sweeping technology, but if it wants to cover all predefined beam directions, the overhead is too high. There are two types of CSI feedback, the first type is normal which is codebook-based PMI feedback with normal spatial resolution; The other one is enhanced as type 2 which has explicit feedback and codebook-based feedback with higher spatial resolution. Therefore, CSI-RS is transmitted only in a subset of predetermined beam directions based on the location of the served mobile terminal.

Beam measurement refers to the process in which gNB or UE measures the quality and characteristics of the received shaped signal. During the beam management process, the UE or gNB identifies the best beam through relevant measurements. In the downlink direction, 3GPP defines a beam measurement reporting process based on layer 1 reference signal received power

(L1 RSRP) to support beam selection and reselection. This measurement can be based on SSB or CSI-RS assigned to the UE. The traditional Layer 3 RSRP is reported by the higher layer, while the L1 RSRP in 5G is directly reported at the physical layer, so its reliability and channel capacity are both important. In the uplink direction, the measurement is based on SRS.

Beam determination is the process of gNB or UE selects its own Tx/Rx beam(s). The downlink beam is determined by the UE and the decision criterion is that the maximum received signal strength of the beam should be greater than a specific threshold. In the uplink direction, the mobile terminal transmits SRS according to the direction of gNB, and gNB measures the SRS to determine the best uplink beam. If the gNB side can determine the uplink receive beam based on the UE's downlink beam measurement results, or the gNB side can determine the downlink transmit beam based on the uplink receive beam measurement results, the gNB side can consider the Tx/Rx beams to be consistent; Similarly, if the UE side can determine the uplink transmit beam based on the UE's downlink beam measurement results, or the UE can determine the UE's downlink receive beam based on the UE's uplink beam measurement results, and the gNB supports the UE's beam consistency related characteristic indication information , then the UE side can consider that the Tx/Rx beams are consistent.

After determining the best beam, the UE or gNB will notifies the peer of the selected beam information, this process is called beam reporting. In addition, the gNB and UE sides also need to perform beam error recovery and other related work. When using multi-beam operation, due to the narrow beam width, beam failure can easily cause link interruption between the network and the terminal. When the UE's channel quality is poor, the bottom layer will send a beam failure notification. The UE will indicate a new SS block or CSI-RS and perform beam recovery through a new RACH procedure. The gNB will transmit downlink configuration or UL grant information on the PDCCH to end the beam recovery process.

### 3.4 Downlink and uplink channels

In NR downlink channel, there are 3 downlink physical channels, physical broadcast channel (PBCH) which mentioned in initial access, physical downlink control channel (PDCCH) and physical downlink shared channel (PDSCH) which we will introduce in this section. There are 4 downlink physical signals, primary synchronization signal (PSS) and secondary synchronization signal (SSS) which covered as part of initial access, channel state information reference signal (CSI-RS) and tracking reference signal (TRS).

5G new radio (NR) uses physical downlink control channel (PDCCH) to perform physical layer control functions such as scheduling the downlink (DL) broadcast and DL/uplink (UL) unicast data transmission, signaling various triggers for aperiodic and periodic transmission/reception, resource allocation and power control. PDCCH carries DCI (Downlink Control Information), which includes resource allocation and other control information on one or more UEs. Although the resource allocation unit in NR is similar to LTE, a few new units are introduced in NR in association with the control channels, as discussed in the following.

Resource Element (RE) is the smallest unit of the resource grid made up of one subcarrier in domain and one OFDM symbol in time domain, A PDCCH corresponds to a set of resource elements carrying DL control information [9]; In protocol 38.211, Resource Block (RB) is defined as 12 consecutive subcarriers in the frequency domain; Resource Element Group (REG) corresponds to one OFDM symbol in the time domain and one RB in the frequency domain (1 REG=1 PRB); Control Channel Element (CCE) is the basic unit that constitutes PDCCH which consists 6 REGs, so it includes 72 subcarriers totally which consists 54 data REs and 18 Demodulation Reference Signal REs. QPSK modulation scheme is used for NR PDCCH. NR REG bundles are defined to consist of 2, 3, or 6 REGs, and play a two-fold role: they determine the precoder cycling granularity (which affects the channel estimation performance), as well as the interleaving unit for the distributed REG mapping [9].

Different from the 4G control channel, Control Resource Set (CORESET) which is defined as a set of REGs under a given numerology is a newly proposed concept of time-frequency domain resource set in 5G. Because in 5G, the transmission bandwidth of the system is relatively large and the support capabilities of UEs are different. In order to adapt different bandwidths, while reducing the blind detection complexity of PDCCH, thereby constraining the time-frequency domain resource scheduling of PDCCH through CORESET. CORESET occupies 1–3 OFDM symbols in the time domain, which can be located at any position of the slot. According to different scenarios, the scheduling position of CORESET's OFDM symbols in the time domain is also different. CORESET occupies multiple resource blocks in the frequency domain, and the configured frequency domain resource locations must not exceed the frequency domain range of the bandwidth part (BWP). The granularity of CORESET's frequency domain resource configuration is 6, which can adapt to different REG Bundle situations and effectively reduce resource fragmentation.

The resource mapping methods from CCE to REG in CORESET include interleaved and non-interleaved modes. For interleaving, REG can be mapped within the entire CORESET range through the interleaving formula specified in the 3GPP 38.211 protocol, thereby obtaining frequency diversity gain. In addition, in multi-cell scenarios , assuming that adjacent cells use the same resource mapping method, they will cause interference to each other, and interleaved mapping will be randomly mapped within CORESET according to the interleaves to achieve randomization of interference between cells; for non-interleaved, although it will loss part of the frequency diversity gain, but when the base station knows the downlink wireless channel in advance (especially in TDD mode, the downlink wireless channel is obtained through uplink channel estimation based on channel reciprocity), the PDCCH can be scheduled on the channel with relatively good time and frequency resources in order to obtain a certain scheduling gain.

PDSCH is a DL channel that carries user data, system information, paging information, and control information from layers above. The modulated symbols associated with a codeword mapped in the following order, across layers associated with the codeword, across subcarriers, across OFDM symbols. The modulation of PDSCH is QPSK, 16QAM, 64QAM and 256QAM. It is supported dynamic resources sharing between eMBB and low latency traffic, and through group-common PDCCH, it support indication of time and/or frequency region of impacted eMBB resources to respective eMBB UE (s).

The DM-RS for PDSCH is transmitted together with the PDSCH on Series 1000 antenna ports and subject to the same precoding as the PDSCH. In NR, to help achieve low latency, a front-loaded structure is used whereby the DMRS are located early in the transmission. The front-loaded DMRS symbols has two main mapping structure, one is located at slot based which is fixed OFDM symbol regardless of PDSCH assignment called type A, up to four orthogonal reference signals can be provided with a single-symbol DMRS and the other one is non-slot based which is the first OFDM symbol assigned for PDSCH called type B, up to six orthogonal reference signals can be provided with a single symbol DMRS. In addition, to assist high speed situations, there are additional symbols presenting for broadcast/multicast PDSCH.

The CSI-RS is used by the UE to estimate the channel and report channel quality information (CQI) to the base station. In 5G NR, the uses of CSI-RS have also been further expanded, mainly including: 1) Channel state information measurement, including RI, PMI, CQI, CRI, LI, etc. 2) Beam management, mainly including transmitter beam measurement, receive end beam measurement and transmitter and receiver simultaneous beam measurement. 3) Time-frequency tracking, accurate measurement of time offset, and frequency offset, achieved through TRS signal. 4) Mobility management, through CSI-RS tracking and measurement of the local area and neighboring cells. 5) Rate matching, the main Zero-Power CSI-RS implements RE-level rate matching for PDSCH.

The TRS is a resource set consisting of multiple periodic NZP CSI-RSs and transmitted on the Series 3000 antenna ports [7]. It is UE-specifically managed. It is an NZP-CSI-RS-Resource Set composed of 4 periodic nzp-CSI-RS resources, and this resource set will be configured with the parameter TRS-Info. The set can be configured with a periodicity of 10, 20, 40, or 80 ms. These four CSI-RS resources are distributed in two consecutive slots with 4 OFDM symbols.

In NR uplink channel, there are 3 important uplink physical channels and 1 uplink physical signals we will introduce in the section. They are physical uplink shared channel (PUSCH), physical uplink control channel (PUCCH), physical random-access channel (PRACH), and sounding reference signal (SRS).

PUSCH is the uplink version of the PDSCH, it provides the physical layer to transport user data from the UL-SCH and carries UCI. For the PUSCH channel in NR, the 3GPP standard uses OFDM as the basic transmission mechanism for uplink transmission, and DFT-s-OFDM as an optional solution. Using DFT precoding can reduce the cubic metric, allowing the terminal to obtain higher transmit power, which is consistent with the PUSCH design in LTE. However, DFT-s-OFDM makes the receiver design very complex, and like PUSCH transmission in LTE, PUSCH transmission in NR based on DFT precoding also requires that the frequency domain resources allocated to a terminal must be continuous, that is, to meet the single carrier continuous characteristics. In NR, DFT-s-OFDM waveforms is limited to single-layer transmission, while OFDM-based PUSCH transmission can support up to four-layer uplink transmission. The DM-RS for CP-OFDM PUSCH is the same as used in the downlink, such as gold sequence derived QPSK modulation symbol is used in the uplink for the CP-OFDM case. It is transmitted with the CP-OFDM PUSCH on Series 0 antenna ports and subject to the same precoding as the PUSCH. The DM-RS for DFTS-s-OFDM is based on Zadoff–Chu sequences and supports continuous allocations. Front-loaded DMRS symbols are be located at first OFDM symbol assigned for PUSCH as PDSCH, in addition, for high-speed scenarios, additional DMRS symbols can be configured.

The modulated symbols associated with a codeword mapped in the following order, across layers associated with the codeword, across subcarrier and across OFDM symbols [2]. For PUSCH, CP-OFDM supports these modulations, QPSK, 16QAM, 64QAM and 256QAM, and besides those modulations mentioned above, DFT-S-OFDM also supports π/2-BPSK with modulation order $Q_m$ is equal to 1. There are 2 uplink transmission schemes, for non-codebook-based transmission scheme, the precoding matrix W is equivalent to the identity matrix. For codebook-based transmission scheme, the precoding matrix W is defined as follows: For single-antenna single-layer transmission, W=1; If the signaling Tx-Config is not configured, the precoding matrix W=1.

The PUCCH carries uplink control information (UCI), feeds back H-ARQ acknowledgements to indicate whether the blocks downlink transported are received correctly, reports channel status information and requests uplink resources when uplink data arrives. There are five PUCCH formats which are Format 0 to 4 are specified in NR. Formats 0 and 2 are referred to as short PUCCH formats which occupy a maximum of two OFDM symbols transmitted in one slot, Format 0 is capable of transmitting less than 2 bits and Format 2 can transmit more than 2 bits, they are responsible for the very fast feedback of H-ARQ acknowledgements; Formats 1, 3 and 4 are referred to as long PUCCH formats which occupy from 4 to 14 OFDM symbols and are all capable of transmitting more than 2 bits, they have higher received energy and more reliable reception.

PUCCH Format 0 is used for transmitting H-ARQ acknowledgments and scheduling requests (SRs), is based on Zadoff-Chu sequence of 12 RE with low PAPR and the information is delivered by applying different linear phase rotations in the frequency domain to create different sequences /codes.  For PUCCH-format 0, the configured high-level parameters include the initial cyclic shift which ranges from 0 to 11, the number of occupied OFDM symbols, the starting OFDM symbol index in the time domain, and the PRB position in the frequency domain. There are 12 cyclic shifts which transmits information in PUCCH Format 0, so it can transmit 12 signals. The same PUCCH channel can be used by multiple UEs at the same time. If PUCCH format 0 only transmits H-ARQ acknowledges, the mapping of 1-bit H-ARQ acknowledge into PUCCH Format 0 sequence requires two sequence cyclic shifts, so one PUCCH channel in Format 0 can be multiplexed at most 6 UEs; the mapping of 2-bit H-ARQ acknowledge into PUCCH format 0 sequence are required 4 cyclic shifts, so one PUCCH channel of PUCCH format 0 can multiplex up to 3 UEs; If only SR is transmitted, only one cyclic shift is needed, and one PUCCH channel of format 0 can multiplex 12 UEs.

PUCCH Format 1 is the long format version of Format 0. It occupies 1 PRB in the frequency domain and 4 to 14 OFDM symbols in the time domain. PUCCH Format 1 transmits 1 to 2 bits of information. When only 1-bit H-ARQ acknowledge is transmitted, BPSK modulation is used. When 2 bits H-ARQ acknowledge is transmitted, QPSK modulation is used. When only SR is transmitted, BPSK modulation is used. When 1-bit HARQ-ACK and SR are transmitted simultaneously, QPSK modulation is used. PUCCH format 1 cannot transmit 2-bit HARQ-ACK and SR at the same time. The number of OFDM symbols, the starting OFDM symbol index, the intra slot frequency hopping in the time domain is determined by the high-level parameter. The relationship between PUCCH Format 1 and DMRS is time division multiplexing, and the symbols in the even positions of PUCCH Format 1 are DMRS. Like PUCCH Format 0, PUCCH Format 1 also supports based on sequence cyclic shift.

However, PUCCH Format 2 does not support multi-UE multiplexing. The number of PRBs that can be allocated by PUCCH Format 2 is 1 to 16. There are 4 REs on 1 PRB for DM-RS, and the remaining 8 REs are used to carry UCI. When 1 or 2 OFDM symbols are allocated, the number of REs available on each PRB is 8 and 16 respectively, and the number of bits available on each PRB is

16 and 32 (QPSK modulation). The number of bits available for PUCCH Format 2 can be calculated based on the number of allocated PRBs and the number of OFDM symbols. The subcarrier position of DMRS in the frequency domain is based on PUSCH and satisfies k=3m+1, so DMRS mapped on REs {1, 4, 7, 10} for each PRB.

PUCCH Format 3 is the long version of PUCCH Format 2. Like Format 2, it can transmit more than 2 bits but smaller than N bits, these can be transmitted over 4 to 14 symbols using multiple resource blocks per symbol. PUCCH Format 4 is identical to Format 3 up to the point of modulation output which can transmit more than N bits. They can be configured with intra-slot-hopping and can span over multiple slots. The difference between them is in the modulated symbol mapping. The modulated symbols are divided between (a) the OFDM symbols with 12/*NSF* modulated symbols directed to each OFDM symbol, (b) each 12/*NSF* set spread by a length *NSF* block spreading sequence (*NSF* = 2 or 4) to create a length 12 modulated symbol output, and (c) the length 12 symbol output DFT spread and OFDM modulated resulting in its placement in the resource grid [7].

The PRACH is an uplink channel used to enable the random-access procedure by physically transmitting information from the random-access channel. A random-access preamble is generated by commencing with a length *L* Zadoff–Chu sequence, such a sequence consisting of complex symbols and exhibiting the property of constant power in both the frequency and time domain. Long sequence which L is equal to 839 works only for lower than 6GHz, the subcarrier spacing and bandwidth are 1.25KHz and 5KHz; Short sequence which L is equal 139 is intended for larger than 6 GHZ, the subcarrier spacing and bandwidth are 60KHz and 120KHz.

In 5G, if a base station wants to transmit signals directionally, it must first detect the location of the terminal, the quality of the transmission channel, etc., so that the resources of the base station can be more accurately allocated to each terminal. Therefore, the SRS is configured to allow the gNB to estimate the uplink channel in much the same way that the CSI-RS is configured to allow the UE to estimate the downlink channel. One SRS supports up to 4 antenna ports, the different ports utilize the same basic SRS sequence and the same set of resource elements. The length of an SRS in the time domain can be configured as {1, 2, 4}, with a maximum of 4 consecutive OFDM symbols and the SRS is located on the last six symbols of a slot.

### 3.5 Bandwidth Parts

The frequency points of 5G are divided into two parts: FR1 (f < 6GHz, low frequency) and FR2 (f > 6GHz, high frequency, millimeter wave). The minimum bandwidth of 5G can be 5MHz and the maximum can be 400MHz. If all terminal UEs are required to support the maximum 400MHz, it will undoubtedly place higher requirements on the performance of the UE, which is not conducive to reducing the cost of the UE. At the same time, it is impossible for a UE to occupy the entire 400M bandwidth at the same time. If the UE adopts the sampling rate corresponding to the 400M bandwidth, it will undoubtedly be a waste of performance. In addition, large bandwidth means high sampling rate, and high sampling rate means high power consumption. Under the above background, bandwidth part (BWP) technology perfectly solves the above problems.

A bandwidth part is a set of contiguous physical resource blocks (PRBs) on a given carrier. These RBs are selected from a contiguous subset of common resource blocks of a given parameter set (u, numerology), where defined BWP's u can have the following three different parameters: subcarrier spacing; symbol length; cyclic prefix length. The BWP bandwidth must larger than SS block but may or may not contain SS block; For the same UE, only one BWP in downlink or uplink can be active at the same time, and the UE transmits and receives data and retrieves PDCCH on this BWP. The BWP configuration parameters include numerology which contains CP type and subcarrier spacing, frequency location which is the offset between BWP and a reference point is implicitly or explicitly indicated to UE based on common PRB index for a given numerology, bandwidth size in terms of PRBs and coreset which is required for each BWP configuration in case of single active downlink bandwidth part for a given time instant [2].

There are three types of BWP. The first one is initial BWP, it is used to perform the initial access process and contains requested minimum system information (RMSI), CORESET and RMSI frequency position, bandwidth, spacing carriers, and other parameters. It can set 24~96 different RBs, and the RMSI can be widen to a wider BWP after decoding; The second is activated BWP, it is defined as a UE-specific BWP and can also be used to perform the initial access procedure. This is the first BWP for the UE to start data transmission after RRC configuration / reconfiguration. The first activated BWP should be different from the default BWP; The third type of BWP is default BWP, it is also a UE specific BWP and is configured during RRC reconfiguration, if not configured, it can be assumed that the initial BWP is the default BWP. When the BWP timer expires, each UE will switch back to the default BWP.

Traffic patterns within an active data session may change frequently, because data rates may increase or decrease depending on the type of service or user behavior, such as accessing the Internet and answering phone calls. It becomes important to quickly switch between different BWPs to manage different power consumption at different data rates. The definition of active BWP is a UE is only assumed to receive/transmit within active downlink/uplink bandwidth part using the associated numerology.

BWP activation /deactivation can be accomplished in several different ways [10]: Dedicated RRC signaling: Since the processing of RRC messages requires additional time, with delays up to 10 msec, it is more suitable for semi-static situations. Due to longer handover delays and signaling overhead, the RRC-based approach can be used to configure the BWP set at any stage of the call, or for slow adaptation type services (such as voice) where resource allocation does not change rapidly within the same data session; DCI with explicit indication: It is based on the PDCCH channel and can activate specific BWP through the BWP indicator of DCI 0_1 (uplink grant) and DCI 1_1 (downlink scheduling). This method is more suited for dynamic BWP switching since the latency is as low as 2ms. However, this approach requires an additional consideration of error handling because the UE may not be able to decode the DCI which contains the BWP activation/deactivation commands; Through BWP-inactivity Timer: If a BWP is not explicitly scheduled for the terminal before the timer times out, it will automatically switch to the default BWP; BWP switching is performed through MAC layer signaling during the random access process. If no activated uplink BWP is configured in PRACH, the BWP indicated by the high-level parameter initial uplink BWP is switched to the activated uplink BWP. If it is 5G Cell currently, it will switch to the activated DL BWP according to the BWP indicated by initial downlink BWP; if the activated uplink BWP is configured in PRACH and the cell is 5G Cell, and the activated downlink BWP is inconsistent with the activated uplink BWP, activation needs to be switched DL BWP, ensure that the activated downlink BWP and uplink BWP are consistent. The purpose of this design is to ensure that the terminal can monitor the PDCCH after sending the PRACH.

Although the DCI-based mechanism is more seasonable than the MAC timer-based mechanism, but we need to take additional consideration on the handling of error situations, that is, when the UE cannot decode the DCI containing the BWP activation/deactivation command. To solve this DCI loss situation, a BWP inactivity timer is introduced to activate/deactivate downlink BWP (or DL/UL BWP pair in asymmetric spectrum). Using this mechanism, if the UE is not scheduled within a certain period which means the timer expires, the UE switches its activated downlink BWP (or DL/UL BWP pair) to the default BWP.

During initial access, the UE will have an initial activation BWP, and the new BWP will be explicitly configured during or after RRC connection establishment. The initially activated BWP is the default BWP unless it is configured otherwise. According to 3GPP Release 15, for one UE, there is at most one active downlink BWP and at most one active uplink BWP. When the UE's active BWP is switched on, HARQ retransmission across different BWPs is supported.

In summary, a maximum of 4 BWPs can be configured for the downlink and uplink of the UE, but at a certain time, only one BWP can be activated for the downlink and uplink; The BWP enables the terminal to operate under a narrow bandwidth, when the user needs more data (burst traffic), it can notify the gNB to enable a wider bandwidth; When gNB configures BWP, it includes the following parameters: BWP parameter set (u), BWP bandwidth size frequency location (NR-ARFCN), CORESET (control resource set); For the downlink, the UE will not receive PDSCH, PDCCH, CSI-RS or TRS which are located outside the active BWP; Each DL BWP includes at least one CORESET with a UE-specific search space (USS), and at least one configured DL BWP of the main carrier includes a CORESET with a common search space (CSS); For the uplink, the UE will not send PUSCH or PUCCH outside the activated BWP; Normally, the UE can only receive and transmit within the frequency range where BWP is activated. However, there are exceptions. The UE may perform Radio Resource Management (RRM) measurements or send Sounding Reference Signals (SRS) outside its activated BWP during measurement gaps.

## 3.6 Summary

In this chapter, 5G NR physical layer and technologies have been showed mostly based on Release 15/16 from the discussion above. It offered a wide range of use cases and had a very aggressive performance compared with the previous communication technologies, such as the higher frequency operation and spectrum flexibility due to the numerology and waveforms, the ultra-high data rate, a beam-centric design and a massive number of antenna elements due to the beam management, forward compatible to prepare for the future and lower latency and better performance due to the Mini-slots and the new structures of uplink and downlink channel.

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