5G Air Interface – Part II
LTE and NR
Physical layer
LTE and 5G NR are based on OFDM (or the related SC-FDM)

But what Multiple Access and Duplexing mechanisms are used?

For **MA** an orthogonal version of FDMA is used
- signals from/to different users occupy different frequencies
- the SubCarrier Spacing must be exactly the OFDM symbol rate

For **duplexing** there are two alternatives:
- Frequency Domain Duplexing
  - different frequency bands are used for the UL and DL
    - for example n1: UL 1920-1980 MHz, DL 2110-2170 MHz
- Time Domain Duplexing
  - a single frequency band is used
    - for example n38: 2570-2620 MHz for both UL and DL
The basic OFDM paradigm can be readily extended to OFDMA by allocating time-frequency Resource Elements to different UEs.

In the DL direction, the base-station transmits to all UEs and each needs to know which REs it needs to extract. In the UL direction, each UE transmits only in its REs in order not to interfere with other UEs in the cell.
OFDMA UL

UEs are only allowed to transmit

- at precisely the frequencies and times allocated by the base-station

This requires:

- locking on to base-stations RF frequency
- offsetting with respect to the base-station’s framing

In order to maintain orthogonality, each UE must transmit at

- precisely the correct symbol rate
  - necessitates accurately locking on to base-station’s frequency
- precisely the correct symbol switch times as seen at the base-station
  - if UE simply offsets in time with reference to received framing
    its transmission will be received with a timing delay of 1 μs / 300 m
  - the cyclic prefix needs to be long enough to absorb delays
  - the base-station can send timing advance commands to offset UL
- full time synchronization not required for FDD
  but is required for TDD operation
The entire transmission occupies a frequency range of system bandwidth and guard bands occupy about 10%:

- for LTE: 1.4, 3, 5, 10, 15, or 20 MHz
- for 5G R15 under 6 GHz:
  - 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100 MHz
- for 5G R15 above 6GHz:
  - 50, 100, 200, 400 MHz (and maybe higher later) and guard overhead is 1 or 2%
SubCarrier Spacings

In LTE: SCS = 15 kHz (the OFDM symbol duration = 66.7 μs w/o CP)
5G introduces a scalable numerology with SCS with Δf = 2^μ * 15 kHz
(i.e., SCS = 15, 30, 60, 120, 240, 480)
but not all SCS options are available for all RF bands

<table>
<thead>
<tr>
<th>μ</th>
<th>SCS</th>
<th>RF</th>
<th>CP</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>15</td>
<td>&lt; 6GHz</td>
<td>normal</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>&lt; 6GHz</td>
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<tr>
<td>2</td>
<td>60</td>
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<td>normal/extended</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>&gt; 6 GHz</td>
<td>normal</td>
</tr>
<tr>
<td>4</td>
<td>240</td>
<td>not in R15</td>
<td>normal</td>
</tr>
<tr>
<td>5</td>
<td>480</td>
<td>not in R15</td>
<td>normal</td>
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</table>

Of course OFDM requires the symbol rate to equal the SCS
so the symbol durations are shorter for higher μ
5G NR options

LTE defined system bandwidths of 1.4, 3, 5, 10, 15, 20 MHz

5G has more options, and higher bandwidth efficiency (>98%!)

- for RF bands under 6 GHz
  - 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100 MHz

- for RF bands above 6GHz
  - 50, 100, 200, 400 MHz (and maybe higher later)

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<table>
<thead>
<tr>
<th>SCS (slot)</th>
<th>20 MHz</th>
<th>50 MHz</th>
<th>100 MHz</th>
<th>200 MHz</th>
<th>400 MHz</th>
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<td>3300</td>
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<tr>
<td>1 ms</td>
<td>FFT 2048</td>
<td>FFT 4096</td>
<td>FFT 4096</td>
<td>FFT 4096</td>
<td>FFT 4096</td>
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<tr>
<td>30 kHz</td>
<td>660</td>
<td>1644</td>
<td>3300</td>
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<tr>
<td>500 μs</td>
<td>FFT 1024</td>
<td>FFT 2048</td>
<td>FFT 4096</td>
<td>FFT 4096</td>
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<tr>
<td>60 kHz</td>
<td>324</td>
<td>816</td>
<td>1644</td>
<td>3300</td>
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<tr>
<td>250 μs</td>
<td>FFT 512</td>
<td>FFT 1024</td>
<td>FFT 2048</td>
<td>FFT 4096</td>
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<tr>
<td>120 kHz</td>
<td>408</td>
<td>816</td>
<td>1644</td>
<td>3300</td>
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<tr>
<td>125 μs</td>
<td>FFT 512</td>
<td>FFT 1024</td>
<td>FFT 2048</td>
<td>FFT 4096</td>
<td>FFT 4096</td>
</tr>
</tbody>
</table>

For example:

- **subcarriers**: FFT size guard overhead
- **LTE**: SCS=15kHz/8W=20MHz used only 1200 subcarriers (OH = 10%)
Scalable SCS, bands, and bandwidths

Only certain combinations of SCS and bandwidth are allowed in given bands

<table>
<thead>
<tr>
<th>NR Band</th>
<th>SCS kHz</th>
<th>5 MHz</th>
<th>10-12 MHz</th>
<th>15 MHz</th>
<th>20 MHz</th>
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<td>n5</td>
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<td>Yes</td>
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...
Scalable symbol durations

The symbol duration in OFDM must be $1 / \text{SCS}$

So, each 15 KHz OFDM symbol duration (including CP) precisely equals
- 2 symbol durations with SCS = 30 KHz
- 4 symbol durations with SCS = 60 KHz
- $2^\mu$ symbol durations with SCS = $2^\mu \times 15\text{kHz}$

and this is true even for the first symbol in the subframe which has a different CP (in order for the subframe to be precisely $\frac{1}{2} \text{ms}$)

So different numerologies can co-exist (we’ll see how soon)
OFDMA time macro-structure

Along the time axis the transmission is divided into *frames*. For both LTE and 5G the frame is always 10 ms. in duration and each frame is subdivided into 10 *subframes* (1 ms. each) and each subframe is subdivided into 2 *slots* (each 500 μs.) and each slot contains 6 or 7 *OFDM symbols* of 66.7 μs. + (long or normal) Cyclic Prefix duration.
Cyclic Prefix

In OFDM the CP is used to convert the analog *linear* convolution into a digital *cyclic* one.

In OFDMA it has the additional task of compensating for delay differences and multipath reflections.

Note that the CP must absorb only the difference between the minimum path and the longest since the time advance should absorb the minimum.

In LTE the OFDM symbol is $1 / 15 \text{ kHz} = 66.7 \mu\text{s}$.

For regular cases there are 7 OFDM symbols in a 500 $\mu\text{s}$ slot.

the CP lasts $4.7 \mu\text{s}$. so that $7(66.7+4.7)=500 \mu\text{s}$.

which can absorb a path differential of $4.7 \times 0.3 = 1.4 \text{ km time of flight}$.

The long (extended) CP lasts $16.7 \mu\text{s}$. so that $6(66.7+16.7)=500 \mu\text{s}$.

This CP can absorb $16.7 \times 0.3 = 5 \text{ km of flight time}$ and is used only for very large cells.
Resource Blocks

Each SCS * symbol-duration square is called a Resource Element.

It is neither practical nor necessary to allocate at the granularity of individual REs.

For LTE the smallest unit that can be allocated to a user is a Resource Block, although usually many RBs are simultaneously allocated to a UE depending on user needs and cell resource availability.

1 RB is: 12 channels (12*15kHz = 180 kHz) times 1 slot (½ msec = 6/7 symbols) altogether 72 or 84 Resource Elements.

<table>
<thead>
<tr>
<th>LTE</th>
<th></th>
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<tbody>
<tr>
<td>BW (MHz)</td>
<td>usable BW (MHz)</td>
<td>subchannels</td>
<td>RBs</td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>1.08</td>
<td>72</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2.7</td>
<td>180</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4.5</td>
<td>300</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>600</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>13.5</td>
<td>900</td>
<td>75</td>
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</tr>
<tr>
<td>20</td>
<td>18</td>
<td>1200</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>
**LTE Bottom up**

6 or 7 symbols make up a *slot*

2 slots (1 ms) make up a *sub-frame*

For FDD a frame is made up of 10 subframes (20 slots = 10 ms)

For TDD 5 subframes make up a half-frame (10 slots = 5 ms)

and 2 half-frames make up a frame (10 ms)

Put in another way (for 7 symbols / slot)

- $T_s = 0.325$ ns. is the rate at which we sample the OFDMA signal
- $T_{symbol} = 2048 \times T_s = 0.067$ ms. is the OFDM symbol duration
- $T_{slot} = 7 \times T_{symbol} = 15360 \times T_s = 0.5$ ms. is the slot duration
- $T_{subframe} = 2 \times T_{slot} = 14 \times T_{symbol} = 1$ ms.
- $T_{frame} = 10 \times T_{subframe} = 10$ ms. is the duration of a frame

![Diagram showing LTE frame structure](image_url)
5G nested RBs

We previously stated that different numerologies can coexist.

Now we see how in the frequency domain -

Each RB contains 12 consecutive subcarriers

- for SCS=15 kHz 1 RB = 180 kHz
- for SCS=30 kHz 1 RB = 360 kHz
- for SCS=60 kHz 1 RB = 720 kHz

So, the RBs nest across numerologies!

The nesting of slots and RBs enables muxing different numerologies for the same cell / same UE.
5G nested slots

In NR (like LTE) the frame is always 10 ms = 10 subframes of 1 ms
For normal CP there are 14 symbols per subframe (for SCS < 240 kHz)
   and this is defined as the basic slot (not 7 symbols = $\frac{1}{2}$ ms like in LTE!)
   (also called the Transmission Time Interval)

So, the slot duration = $1 \text{ ms} / 2^\mu$
- for SCS=15 kHz slot = 1 ms 1 slot per subframe
- for SCS=30 kHz slot = $\frac{1}{2}$ ms 2 slots per subframe
- for SCS=60 kHz slot = $\frac{1}{4}$ ms 4 slots per subframe   etc.

So the slots too *nest* across numerologies!

However, NR is even more flexible, allowing:
- slot aggregation
  transmission occupies 2 or more slots, in order to reduce overhead
- mini-slots (*non-slot-based scheduling*)
  transmission occupies less than a slot (2, 4, or 7 OFDM symbols)
  in order to reduce latency
- flexible (mixed DL/UL) slots for TDD operation
Flexible slots

A TDD slot can contain
• all DL symbols
• all UL symbols
• both DL and UL symbols, with 1 or 2 switching points per slot

The type is indicated by the Slot Format Indication (configured by PDCCH or RRC)

The *self-contained integrated* subframe (2 switching points)
  always starts with a DL control burst and end with a UL control burst
  − DL-centric subframe
    DL control, DL data (single user), guard, UL control
  − UL-centric subframe
    DL control, guard, UL data (to multiple users), UL control

This enables (e.g., for DL-centric subframes)
• lower latency, since the UL HARQ ACK is in the same subframe (self-contained)
  note: LTE assumes HARQ processing time of 3 ms, NR requires DL < 1 ms and UL < 0.3-0.8 ms
• massive MIMO tracking, since the UL link quality is in the same subframe
• use of shared spectrum, via Listen-Before-Talk indications from network
Signals and physical channels

The OFDMA frame is divided into various *signals* and *physical channels*

A signal is a special position in the frame needed for specific purposes such as synchronization or channel estimation

A channel is a position in the frame that carries information

Warning: don’t be confused, there are

- *physical channels* in the OFDMA frame carry user data and control messages
- *transport* channels are transported by the physical channels
- *logical channels* provide services to the MAC layer (L2)
LTE walk-through

To understand how this all works, let’s analyze a simple example. What happens when you turn on your 4G phone? (It’s similar in 5G)

The first steps are:
- to lock onto the DL signal
- find its cell ID
- find the system bandwidth

We use special signals in the middle 72 subcarriers for these tasks.

![Diagram](image)
PSS and SSS

The UE uses 2 special DL signals
- Primary Synchronization Signal and Secondary Synchronization Signal to find
  - frame timing
  - cell ID (for LTE an integer 0 ... 503 for NR about twice as many)
    - ID = 3N₁ +N₂ (LTE: N₁ = 0...167 is the group, N₂ = 0,1,2 is the sector)

Dividing into 2 signals simplifies the processing

Locking onto the frame frequency and finding the frame beginning allows us to continue decoding the frame

The cell ID is used to reduce intercell interference
- cell ID determines the scrambler used
- cell ID determines placement of reference signals (pilots)

Both PSS and SSS must be in the 72 middle subcarriers since we don’t yet know what the channel bandwidth is!

Assuming FDD, both appear in subframes 0 and 5
- PSS in the last OFDM symbol and SSS in the preceding one
First we need to find the PSS
which consists of 62 complex symbols (5 symbols on each side are unused)
The LTE PSS is based is a *(modified)* Zadoff-Chu sequence
\[ \exp(-i \pi u n (n+1) / 63) \] for \( n=0...30 \)
\[ \exp(-i \pi u (n+1) (n+2) / 63) \] for \( n=31...61 \)
which have zero cyclic autocorrelation at all nonzero lags
By cross-correlating with the 3 possible sequences, we find
- the positions of subframes 0 and 5 (the SSS will disambiguate this)
- \( N_2 \) (only 1 of the 3 \( u \) values gives cross-correlation peaks)
After finding the PSS we search for the SSS
The SSS is different in subframe 0 and 5
removing the ambiguity and uniquely identifying subframe 0
168 different SSS sequences used, depending on cell group ID N₁
These sequences are BPSK modulated maximum length LFSR sequences
with generating polynomial \( x^5 + x^2 + 1 \)
Subframe 0 and subframe 5 are different shifts of the same sequence
the shifts depend on N₁ (values from table in standard)
These sequences are further scrambled with shift-register scramblers
Once maximum cross-correlations are found, we know N₁
and can find the unique cell ID from ID = 3N₁ + N₂
We now need to determine the channel bandwidth
using the PBCH
The next step is to locate and decode the Physical Broadcast Channel (PBCH). PBCH is only in the DL, and is broadcast from the eNB to all UEs:

- It occupies the middle 72 subcarriers (we still don’t know the bandwidth!)
- Located in OFDM symbols 0,1,2,3 of slot 1 (2nd slot) of every frame
- Spread over four times (4 frames = 40 ms) for robustness

So there are 72*4 REs, but 48 of these are reference signals and NOT PBCH, meaning that PBCH occupies 240 REs.

Since PBCH always utilizes QPSK modulation, this means 480 bits per frame, 1920 bits in 4 frames:

- The 1920 bits are scrambled form of 16 repetitions of 120 bits
- The 120 bits are a 3* tail-biting convolutional coding of 40 bits
- The 40 bits are 14 bits of MIB + 10 reserved bits + 16 bit CRC

There is a tremendous amount of redundancy (14 bits → 1920 bits) because the MIB is critical for decoding the rest of the frame.

However, the PBCH in each frame is self-decodable, so if the signal is strong then delay and UE battery consumption are minimized.
MIB

The Master Information Block (MIB) contains

- downlink system bandwidth (3 bits) 1.4/3/5/10/15/20 (for LTE)
- the PHICH Physical Hybrid-ARQ Indicator Channel structure
  - PHICH duration - normal or extended (1 bit)
  - Ng (2 bits) (number of PHICH groups – we’ll see this later ...)
    PHICH specifies the location of HARQ (N)ACKs for previously sent UL data
    and implicitly tells us where we can find our data
- the most significant eight-bits of the System Frame Number
  - the last 2 bits can be derived from the MIB 4-frame spread structure

And furthermore

- the MIB’s CRC is XORed with a mask
  that tells us the number of transmit antennas used by the eNB

So, now we know the full bandwidth
  and can start looking at more spectrum
Reference signals

Reference signals are known signals transmitted across the entire bandwidth and are used for channel estimation and equalization.

There are many different types of reference signals – for example:

**Cell specific Reference Signal (C-RS)** is a DL reference signal used to
- estimate the DL receive power
- to estimate the channel frequency response in order to FEQ equalize

C-RS appears only in symbols 0 and 4 of a slot and at subcarriers separated by 6 (the exact position determined by the Cell ID).

There are also:
- DL UE specific reference signal
- DL Positioning Reference Signal (P-RS)
- UL Demodulation Reference Signal (DMRS)
- UL sounding reference signal (SRS)
- ...
Not yet!

Unfortunately, we are not yet ready to read our data 😞

In order to be as efficient as possible, the remaining resource elements are distributed among several channels.

Altogether there are 5 physical DL channels:

- **PBCH** Physical Broadcast channel (carries the MIB) that we have already seen.
- **PCFICH** Physical Control Format Indicator Channel
  - tells us how much control data there is.
- **PHICH** Physical Hybrid ARQ Indicator Channel
  - carries HARQ ACK/NACK indications.
- **PDCCH** Physical Downlink Control Channel.
- **PDSCH** Physical Downlink Shared Channel (this is what we want to read!)
  - allocated to users on a dynamic and opportunistic basis.
  - carries both user data traffic and misc. signaling:
    - **SIBs** (System Information Blocks) carrying cell related information.
    - paging broadcast messages.
    - **RRC** (Radio Resource Control) messages.
The first 1-4 symbols of each subframe are PDCCH symbols. To know how many control symbols there are in a subframe, we need to read the Physical Control Format Indicator CHannel (PCFICH), which contains the Control Format Indicator = 1...4. PCFICH appears in the first symbol of each subframe. PCFICH is critical for proper decoding, so it is:

- always in OFDM symbol 0 of the subframe
- block coded
- scrambled
- QPSK modulated (only)
- repeated 4 times separated by 1/4 of the bandwidth (to maximize diversity)
We saw that **Hybrid ARQ (HARQ)** is a hybrid (combination) of FEC and ARQ
if the FEC can correct the errors, then it does so
if there are more errors than can be corrected, ARQ is used

There are many variations of HARQ in LTE/5G
(depending on UL/DL, FDD/TDD, etc.)

The DL PHICH channel contains the HARQ (N)ACK indications
for the UL PUSCH channel (which is the UL counterpart of PDSCH)

We need to locate the PHICH (N)ACKs in order to
• read them (to know if previous UL transmissions were correctly received)
• remove them and continue decoding
PHICH decoding

Like PCFICH, PHICH is carried by the first symbol of each subframe.

PHICH from different users are put into PHICH *groups*. Each PHICH group can carry HARQs for up to 8 users. Remember that the number of groups was specified in the MIB.

Each ACK/NACK is one bit: ACK=0, NACK=1.

Once again, extensive redundancy is employed to ensure correct PHICH decoding.

The ACK/NACKs first undergo simple repetition coding: 1 → 111 and 0 → 000.

Next, these indications are spread by a factor of 2 or 4 times for extended/normal CP type respectively by choosing one of 8 orthogonal Walsh sequences.

This results in $3 \times 2 - 6$ or $3 \times 4 = 12$ OFDM subcarriers in symbol 0 of the subframe.
The first 1-4 symbols of each subframe are Physical Downlink Control CHannel symbols (we already know how many from the PCI in PCFICH)

But these symbols are muxed with:

- PBCH (in first 4 symbols of slot 1 of middle 72 subcarriers)
- PCFICH (in first symbol of each subframe in 4 different frequency regions)
- PHICH (also in the first symbol)
- reference signals (in first and fifth symbols of each slot)

and we already know exactly where these are!

The remaining REs contain the PDCCH which gives the UE DL resource allocation information:

- number of Resource Blocks (RBs)
- Modulation and Coding Schemes (MCS)
- MIMO schemes
- UL power control command with Channel Quality Index (CQI) reporting

The PDCCH is separated from the PDSCH for decoding efficiency
PDSCH at last!

LTE PDSCH REs can be modulated using QPSK, 16QAM, 64QAM
the modulation adaptively chosen based on quality and buffer capacity

PDSCH is a shared channel – it carries

- user data for all the UEs receiving data
- paging broadcast messages to all UEs in idle mode
- RRC signaling
- System Information Blocks (SIBs) (more information not in the PBCH)
  - PLMN Identity, cell identity, cell status
  - cell selection information (e.g., Minimum Receiver Level)
  - scheduling information
  - access barring information
  - PRACH Configuration
  - UL frequency Information
  - information relating to intra-frequency cell reselections
  - ...
**Summary example**

<table>
<thead>
<tr>
<th>Key</th>
<th>Description</th>
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<tbody>
<tr>
<td>Primary Synchronization Signal</td>
<td>Physical Broadcast Channel</td>
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<tr>
<td>Secondary Synchronization Signal</td>
<td>Physical Control Format Indicator Channel</td>
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<tr>
<td>Physical HARQ Indicator Channel</td>
<td>Physical Downlink Control Channel</td>
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<tr>
<td>Physical Downlink Shared Channel</td>
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</tbody>
</table>

**LTE Resource Grid for FDD: 1.4 MHz for Antenna Port 0 out of 2 Antennas and Normal Cyclic Prefix**

<table>
<thead>
<tr>
<th>Subframe 0</th>
<th>Subframe 1</th>
<th>Subframe 2</th>
<th>Subframe 3</th>
<th>Subframe 4</th>
<th>Subframe 5</th>
<th>Subframe 6</th>
<th>Subframe 7</th>
<th>Subframe 8</th>
<th>Subframe 9</th>
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</table>
UL physical channels

- **PUSCH** Physical **U**plink **S**hared **C**hannel
  UL counterpart of PDSCH
- **PUCCH** Physical **U**plink **C**ontrol **C**hannel
  UL control signaling (e.g., scheduling requests)
- **PRACH** Physical **R**andom **A**ccess **C**hannel
  used by UEs just waking, to provide BS with UL time synchronization
  PRACH is different from all other channels
  - PRACH position and format are defined in SIB
  - UE transmits a ZC code (1/64), enabling BS to estimate UL offset
  - UE initiates PRACH procedure after it has acquired DL freq/time sync
  - PRACH uses a SCS of 1.25 (7.5) kHz and symbol duration of 800 (133) ms
The 3GPP documents mention *non-3GPP access* – i.e., IEEE 802.11 (WiFi)

WiFi is different from 4G/5G in many ways

- some variants are not OFDM (original, b) although the newer ones are
- 802.11 is nomadic - not true mobile
  - access radius is < 300 m (150 indoors)
  - there is no handoff
  - there is no RF coordination between neighbors (*channels* strongly overlap)
- 802.11 is less efficient (but requires less synchronization)
  - beacon (typically every 100 ms) overhead (frequently up to 20%)
  - every frame is acknowledged
  - 1-way delay is about 30 ms
  - burst transmission
    - preamble for synchronization
    - Clear To Send messages with hold-off timer
- WiFi is actually more power efficient when transmitting
  but doesn’t have *RRC* idle states
To finish our treatment of the air interface we need to briefly discuss some higher layers.

<table>
<thead>
<tr>
<th></th>
<th>SDAP</th>
<th>RRC</th>
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<tr>
<td></td>
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<td>Radio Resource Control</td>
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<td>Packet Data Convergence Protocol</td>
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<td>Radio Link Control</td>
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<td>Media Access Control</td>
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<td>Physical layer</td>
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<td>LOGICAL channels</td>
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<td>RLC</td>
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<td>TRANSPORT channels</td>
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<td>MAC</td>
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<td>PHYSICAL channels</td>
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</table>
In the incoming direction (DL for the UE, UL for base-station)
- the RLC layer passes RLC PDUs in logical channels to the MAC layer
- the MAC layer processes these into transport channels
- the MAC layer sends transport channels to the PHY layer
  which converts them into physical channels and transmits them

The MAC’s main functions are:
- mapping between logical channels and transport channels
  including mux/demux from logical channels to transport blocks (TB)
- HARQ
  including ACK/NACK signaling and retransmission of TBs
- dynamic scheduling (UE priority handling)
- various control functions, such as
  - resource requests
  - power reporting
  - discontinuous reception (DRX) – UE sleep/wake modes
RLC

The RLC is similar to TCP in that it
- segments(concatenates) packets
- performs ARQ of lost packets
- reorders packets
- flow control by adjusting sender data rate
- maintains timers

In the incoming direction
- IP packets arrive at the PDCP layer that
  - compresses(encrypts) them
  - adds a PDCP header creating PDCP PDU
  - sends PDCP PDU to the RLC
- the RLC layer
  - fragments(concatenates) multiple PDCP PDUs
  - adds a RLC header with additional information (e.g., Length Indicator) creating RLC PDUs
  - sends RLC PDUs to the MAC layer over logical channels
RLC modes

The RLC operates in one of 3 modes:

• **Acknowledged Mode**
  – used for non-delay sensitive user or control data
  – most sophisticated mode
  – supports buffering, concatenation, reordering, ARQ

• **Unacknowledged Mode**
  – used for delay sensitive packets such as voice
  – supports concatenation and adds header
  – supports reordering
  – no retransmission

• **Transparent Mode**
  – used for PCCH paging messages, BCCH/CCCH system info messages
  – RLC forwards transparently
    • no header is added/removed
    • no retransmission or reordering
The PDCP converts between IP and mobile protocols

The major RRC functions are:
- transfer of user plane data
- transfer of control plane data
- insertion/processing sequence numbers
- optional header compression (using RFC 3095 ROHC)
- encryption (or null cipher)
- integrity protection of control data
- reordering and duplicate discard of control data
RRC (L3 control plane)

The RRC is responsible for configuring and tracking the UE state in order to manage radio resources and conserve UE battery.

The RRC maintains the UE state machine including inactivity timers.

The major RRC functions are:
- connection establishment and release
- broadcast of system information
- radio bearer establishment
- reconfiguration and release
- RRC connection mobility procedures
- paging notification and release
- outer loop power control
SDAP (L3 user plane)

The **Service Data Adaptation Protocol** forwards user packets from the RAN towards the user plane of the core.

The SDAP is the user plane protocol responsible for QoS Flow handling.

The SDAP maps a session to a corresponding Radio Bearer (which has been previously set-up for this QoS).

The SDAP also marks core-bound packets with the correct QFI (QoS Flow ID) for the packet to be handled with the correct QoS afterwards.
The gNB block diagram

We have already seen this, but now can understand it better.