5G Air Interface – Part II
LTE and NR
Physical layer

OFDMA

LTE and 5G NR are based on OFDM (or the related SC-FDM)

But what **M**ultiple **A**ccess and Duplexing mechanisms are used?

For **MA** an orthogonal version of FDMA is used

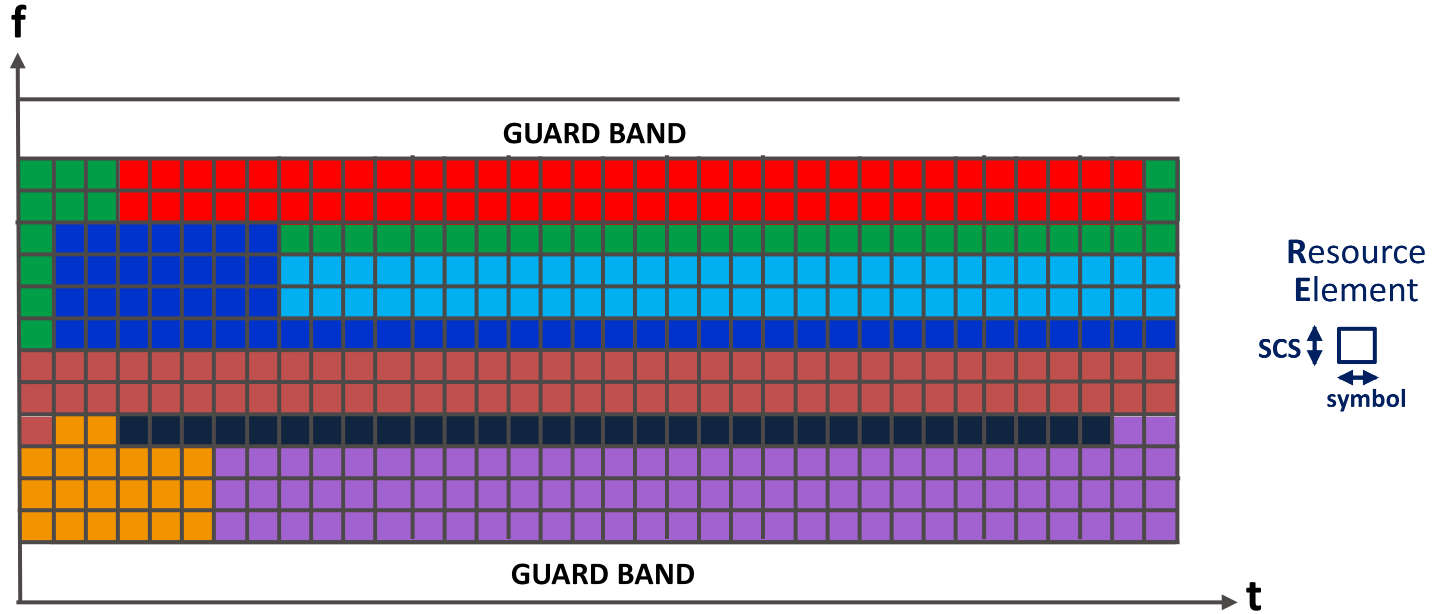
- signals from/to different users occupy different frequencies
- the **S**ub**C**arrier **S**pacing must be exactly the OFDM symbol rate

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

OFDMA

The basic OFDM paradigm can be readily extended to OFDMA
by allocating time-frequency **R**esource **E**lements 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

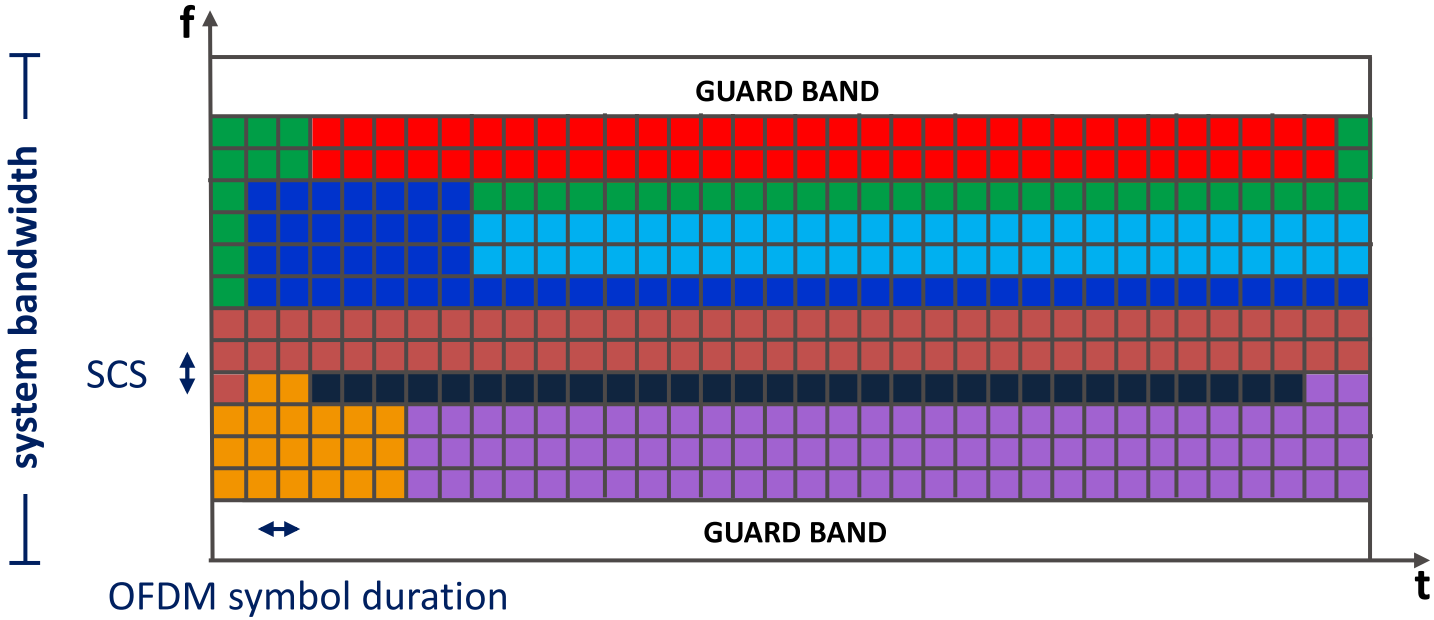
In order to maintain orthogonality, each UE must transmit at

- 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

OFDMA frequency macro-structure

The entire transmission occupies a frequency range of *system bandwidth*

- for LTE : 1.4, 3, 5, 10, 15, or 20 MHz — and guard bands occupy about 10 %
- 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 $\Delta f = 2^{\mu} * 15$ kHz

(i.e., SCS = 15, 30, 60, 120, 240, 480)

but not all SCS options are available for all RF bands

μ	SCS	RF	CP
0	15	< 6GHz	normal
1	30	< 6GHz	normal
2	60	both	normal/extended
3	120	> 6 GHz	normal
4	240	not in R15	normal
5	480	not in R15	normal

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)

For example:

SCS (slot)	20 MHz	50 MHz	100 MHz	200 MHz	400 MHz
15 kHz 1 ms	**1320** FFT 2048 OH = 1%	**3300** FFT 4096 OH = 1%			
30 kHz 500 μs	**660** FFT 1024 OH = 1%	**1644** FFT 2048 OH = 1.36%	**3300** FFT 4096 OH = 1%		
60 kHz 250 μs	**324** FFT 512 OH = 2.8%	**816** FFT 1024 OH = 2.08%	**1644** FFT 2048 OH = 1.36%	**3300** FFT 4096 OH = 1%	
120 kHz 125 μs		**408** FFT 512 OH = 2.08%	**816** FFT 1024 OH = 2.08%	**1644** FFT 2048 OH = 1.36%	**3300** FFT 4096 OH = 1%

subcarriers
FFT size
guard overhead

LTE
SCS=15kHz/BW=20MHz used only 1200 subcarriers (OH = 10%)

higher efficiency
But higher frequency sync requirements

Scalable SCS, bands, and bandwidths

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

NR band / SCS / UE Channel bandwidth

NR Band	SCS kHz	5 MHz	10[1,2] MHz	15[2] MHz	20[2] MHz	25[2] MHz	30 MHz	40 MHz	50 MHz	60 MHz	80 MHz	100 MHz
n1	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60		Yes	Yes	Yes							
n2	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60		Yes	Yes	Yes							
n3	15	Yes	Yes	Yes	Yes	Yes	Yes					
	30		Yes	Yes	Yes	Yes	Yes					
	60		Yes	Yes	Yes	Yes	Yes					
n5	15	Yes	Yes	Yes	Yes							
	30		Yes	Yes	Yes							
	60											

•••

NR Band	SCS kHz	5 MHz	10[1,2] MHz	15[2] MHz	20[2] MHz	25[2] MHz	30 MHz	40 MHz	50 MHz	60 MHz	80 MHz	100 MHz
n41	15		Yes	Yes	Yes			Yes	Yes			
	30		Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes
	60		Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes
n50	15	Yes	Yes	Yes	Yes			Yes	Yes			
	30		Yes	Yes	Yes			Yes	Yes	Yes	Yes[3]	
	60		Yes	Yes	Yes							
n51	15	Yes										
	30											
	60											

•••

Scalable symbol durations

The symbol duration in OFDM must be 1 / SCS

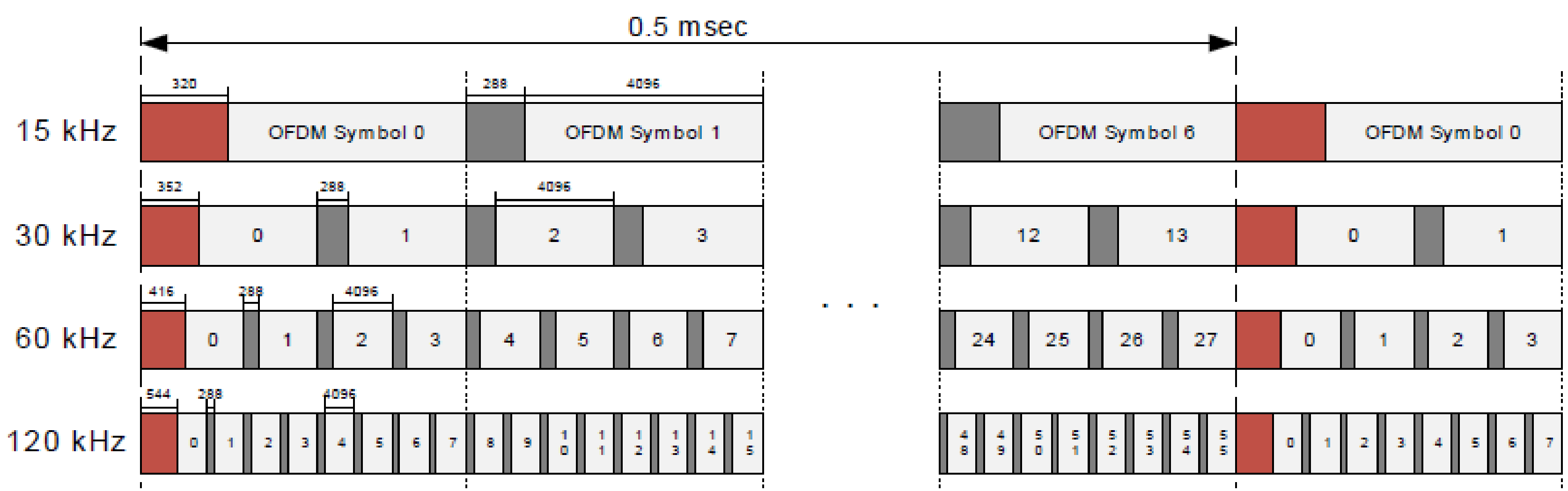
So, each 15 KHz OFDM symbol duration (including CP) precisely equals

- 2 symbol durations with SCS = 30 KHz
- 4 symbol durations with SCS = 60 KHz
- 2^{μ} symbol durations with SCS = 2^{μ} *15kHz

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 ½ 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*

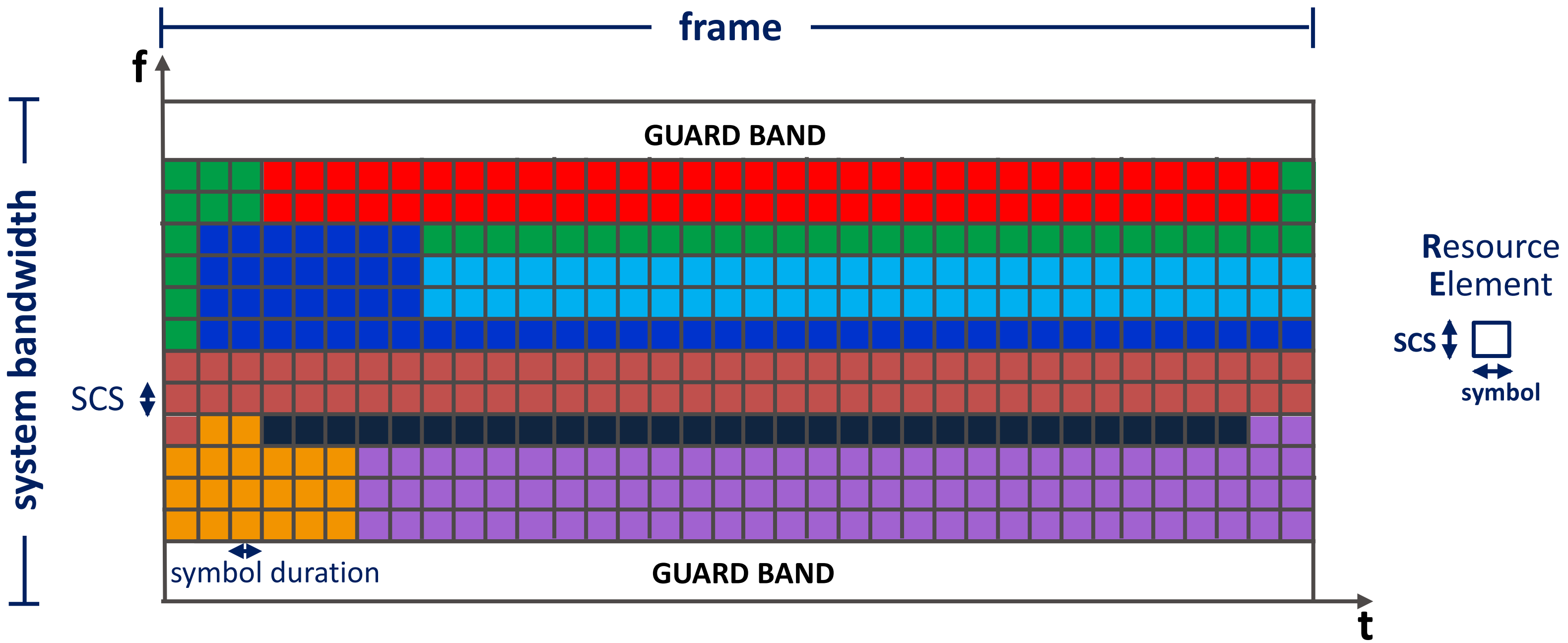
For both LTE and 5G the frame is always 10 ms. in duration

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) **C**yclic **P**refix 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 kHz = 66.7 μs.

For regular cases there are 7 OFDM symbols in a 500 μs. slot
the CP lasts 4.7 μs. so that 7(66.7+4.7)=500 μs.
which can absorb a path differential of 4.7*0.3=1.4 km time of flight!

The long (extended) CP lasts 16.7 μs. so that 6(66.7+16.7)=500 μs.
This CP can absorb 16.7*0.3=5 km of flight time
and is used only for very large cells

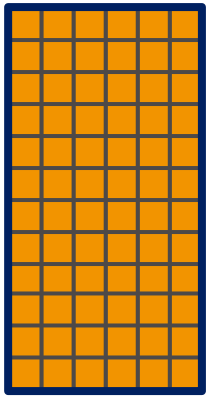
Resource Blocks

Each SCS * symbol-duration square is called a **R**esource **E**lement

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 **R**esource **B**lock
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



Resource **B**lock

LTE			
BW (MHz)	usable BW (MHz)	subchannels	RBs
1.4	1.08	72	6
3	2.7	180	15
5	4.5	300	25
10	9	600	50
15	13.5	900	75
20	18	1200	100

LTE Bottom up

6 or 7 symbols make up a *slot*

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

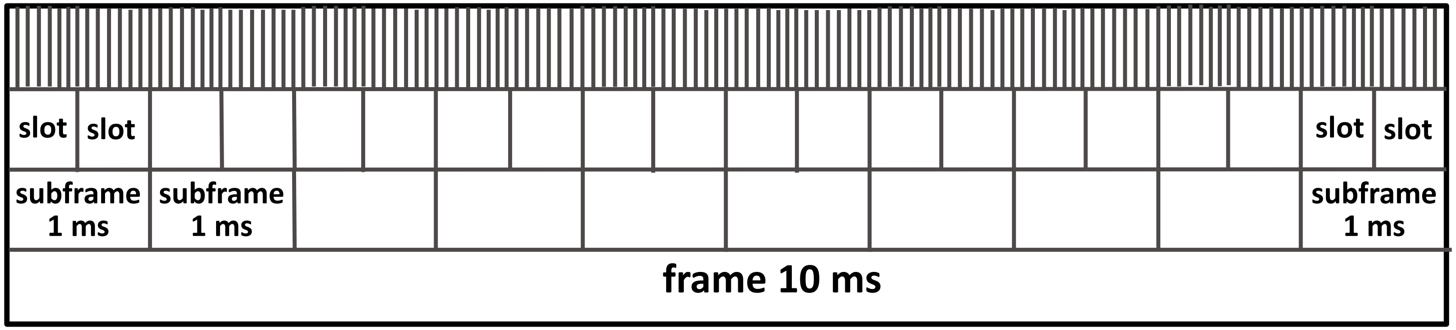
For FDD a frame is made up of 10 subframes (20 slots = 10 ms)

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 T_s = 0.067 ms. is the OFDM symbol duration
- T_{slot} = 7 T_{symbol} = 15360 T_s = 0.5 ms. is the slot duration
- $T_{subframe}$ = 2 T_{slot} = 14 T_{symbol} = 1 ms.
- T_{frame} = 10 $T_{subframe}$ = 10 ms. is the duration of a frame



Bit-rate calculation

A single RE with 64-QAM (max before R12) can contain 6 bits
with 256-QAM (R12 and above) 8 bits

An RB with 64-QAM holds 12*7*6= 504 bits
with 256-QAM 12*7*8= 672 bits

For 20 MHz there are 100 RBs
so 50,400 bits in ½ ms or 100.8 Mbps (the famous 100 Mbps)
or 67,200 bits in ½ ms or 134.4 Mbps

Code rate can be from 0.0762 with low SNR (CQI=1)
to 0.9258 with high SNR (CQI=15)

So, for high SNRs
pre-R12 can attain 93.32 Mbps
and R12+ 124.4 Mbps

5G nested RBs

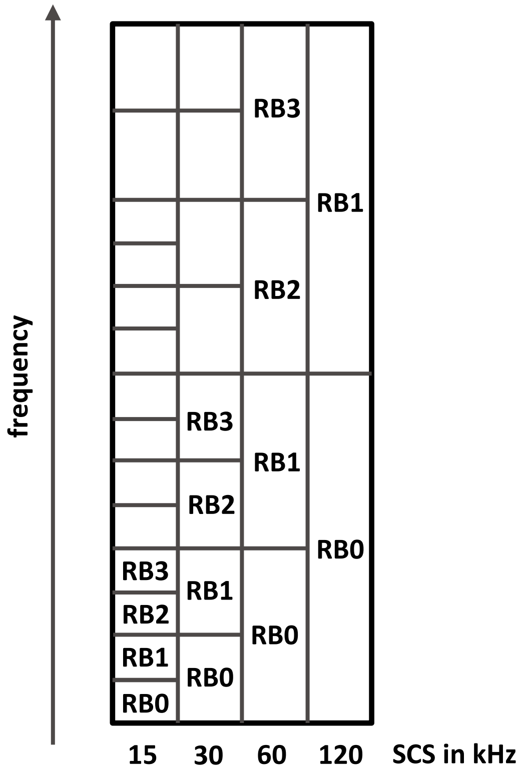
We previously stated
that different numerologies can coexist

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 = ½ ms like in LTE!)
(also called the **T**ransmission **T**ime **I**nterval)

So, the slot duration = 1 ms / 2^{μ}

- for SCS=15 kHz slot = 1 ms 1 slot per subframe
- for SCS=30 kHz slot = ½ ms 2 slots per subframe
- for SCS=60 kHz slot = ¼ 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

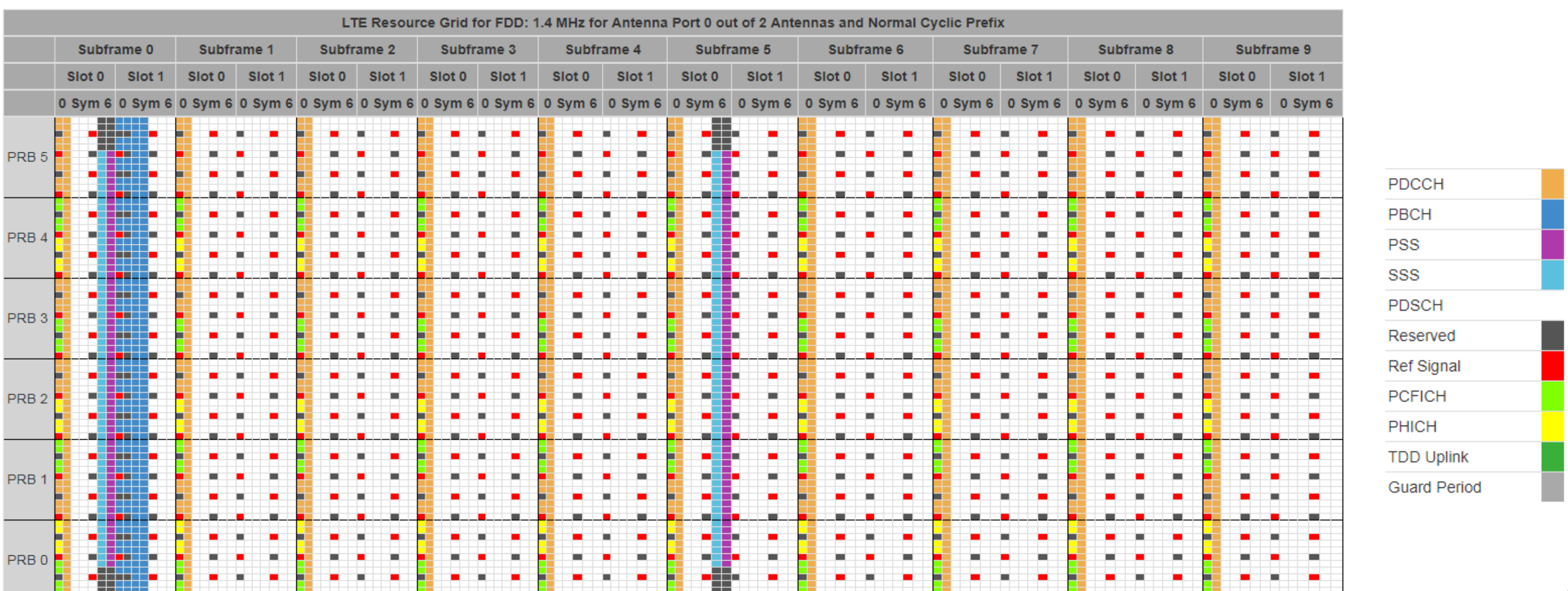
The OFDMA frame is divided into various *signals* and *physical channels*

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

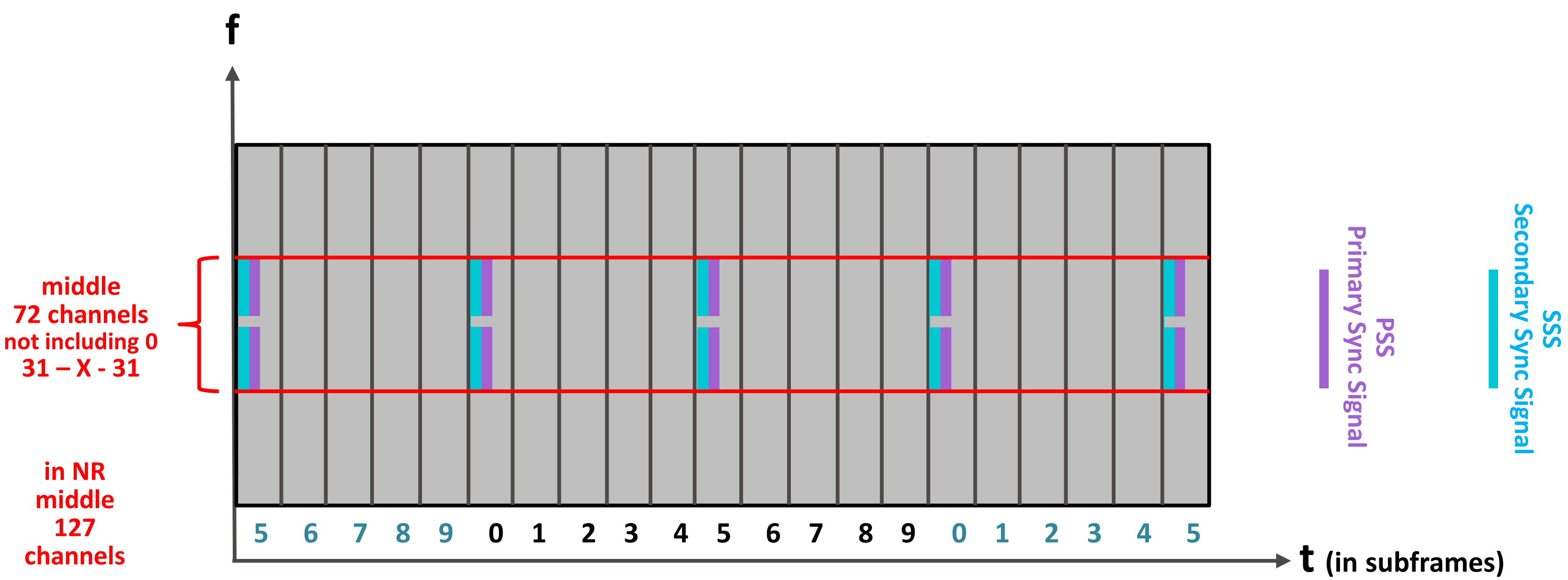
To understand how this all works, let's analyze a simple example

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



PSS and SSS

The UE uses 2 special DL signals

Primary **S**ynchronization **S**ignal and **S**econdary **S**ynchronization **S**ignal

to find

- frame timing
- cell ID (for LTE an integer 0 ... 503 for NR about twice as many)
  - ID = $3N_1 + N_2$ (LTE: N_1 = 0...167 is the group, N_2 = 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

PSS

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 $n=0 \ldots 30$

$\exp(-i \pi u (n+1) (n+2) / 63)$ for $n=31 \ldots 61$

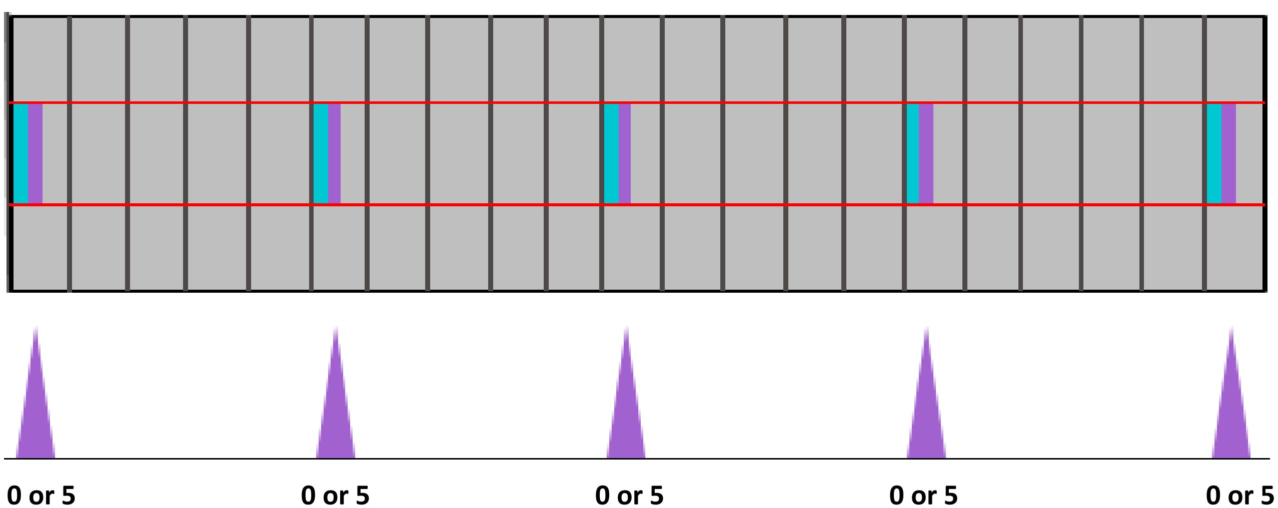
which have zero cyclic autocorrelation at all nonzero lags

N_2	u
0	25
1	29
2	34

in NR LFSR-127 sequence

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)



SSS

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 N_1

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 N_1 (values from table in standard)

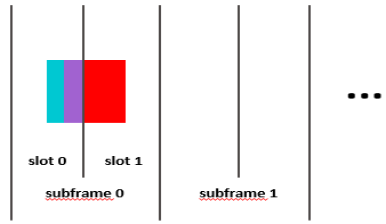
These sequences are further scrambled with shift-register scramblers

Once maximum cross-correlations are found, we know N_1

and can find the unique cell ID from ID = $3N_1 + N_2$

We now need to determine the channel bandwidth

using the PBCH



PBCH

The next step is to locate and decode the Physical Broadcast Channel

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 (2^{nd} 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 **M**aster **I**nformation **B**lock (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

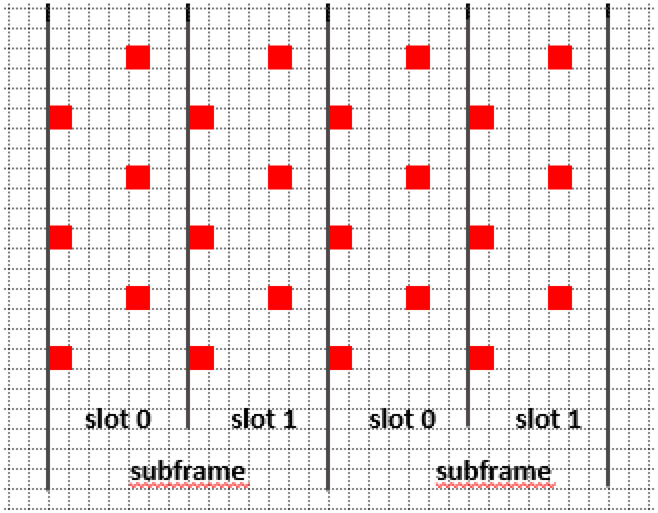
There are many different types of reference signals – for example

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 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

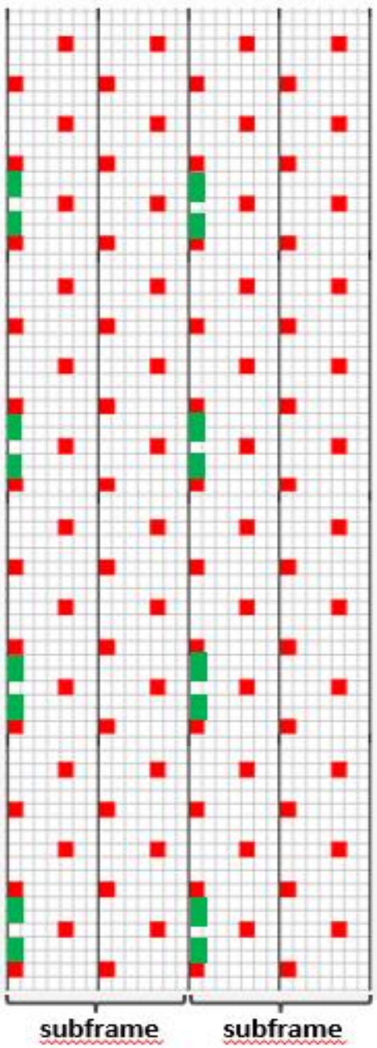
PCFICH

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 **C**ontrol **F**ormat **I**ndicator **CH**annel (PCFICH)
which contains the **C**ontrol **F**ormat **I**ndicator = 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)



HARQ

We saw that **H**ybrid **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

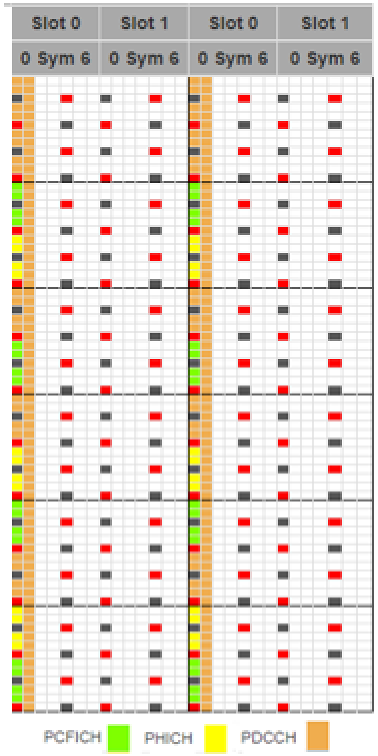
PHICH from different users are put into PHICH *groups*
  each PHICH group can carry HARQs for up to 8 users
    remember that the number of groups
    was specified in the MIB

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*2-6 or 3*4=12 OFDM subcarriers in symbol 0 of the subframe

PDCCH

The first 1-4 symbols of each subframe
are **P**hysical **D**ownlink **C**ontrol **CH**annel 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!

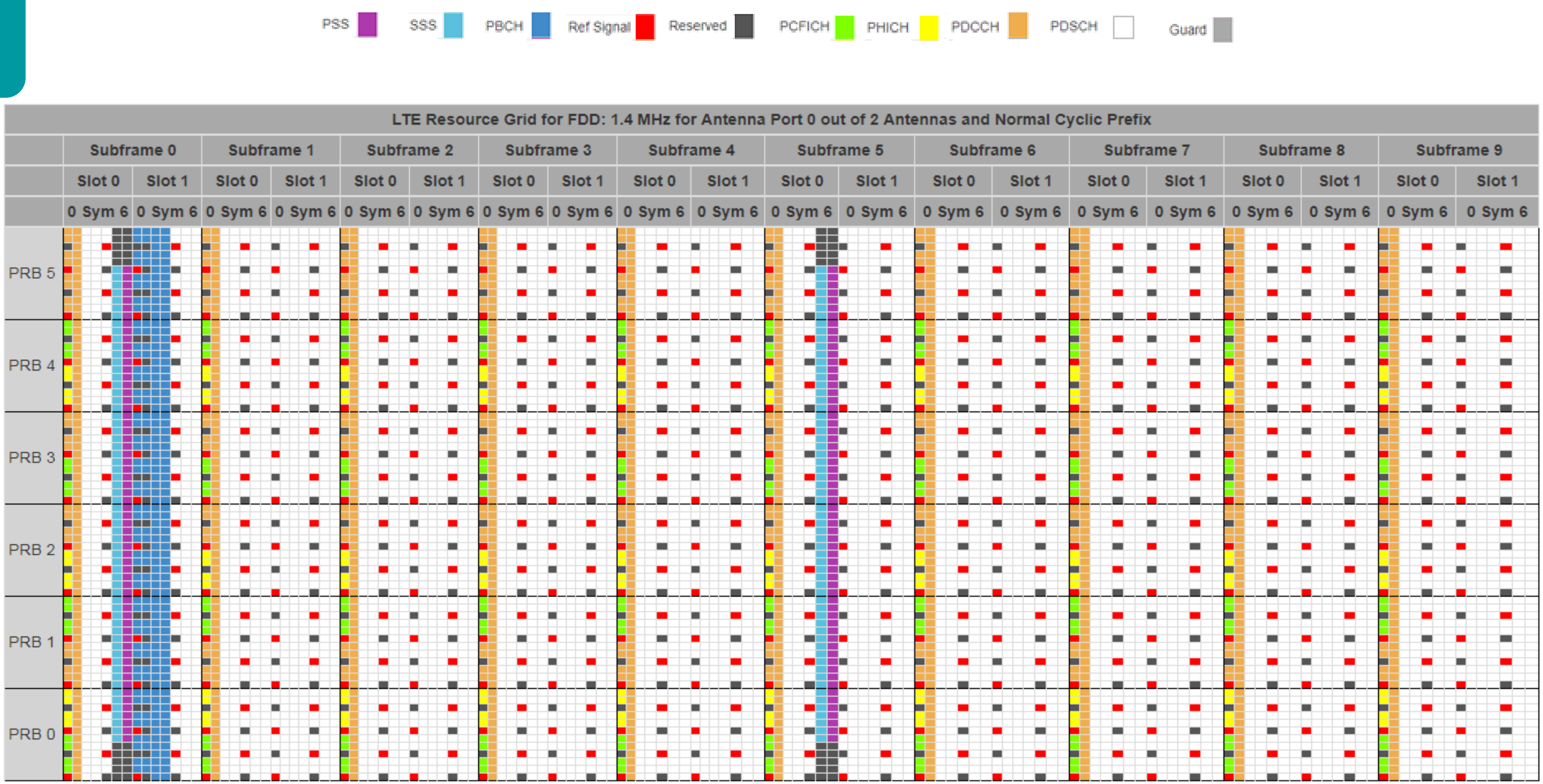
LTE PDSCH REs can be modulated using QPSK, 16QAM, 64QAM

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



key

Primary **S**ynchronization **S**ignal
Physical **B**roadcast **CH**annel
Physical **H**ARQ **I**ndicator **CH**annel
Physical **D**ownlink **S**hared **CH**annel

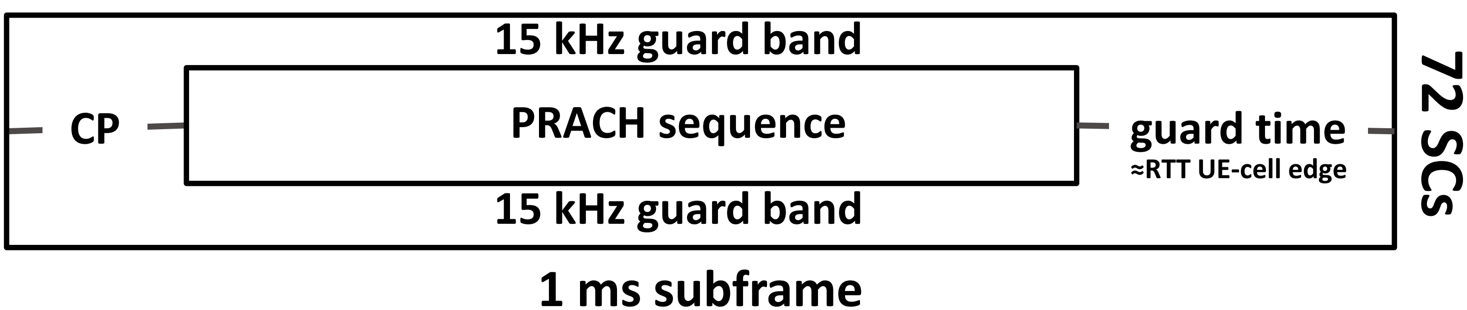
Secondary **S**ynchronization **S**ignal
Physical **C**ontrol **F**ormat **I**ndicator **CH**annel
Physical **D**ownlink **C**ontrol **CH**annel

UL physical channels

- PUSCH **P**hysical **U**plink **S**hared **CH**annel
  UL counterpart of PDSCH
- PUCCH **P**hysical **U**plink **C**ontrol **CH**annel
  UL control signaling (e.g., scheduling requests)
- PRACH **P**hysical **R**andom **A**ccess **CH**annel
  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



WiFi

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

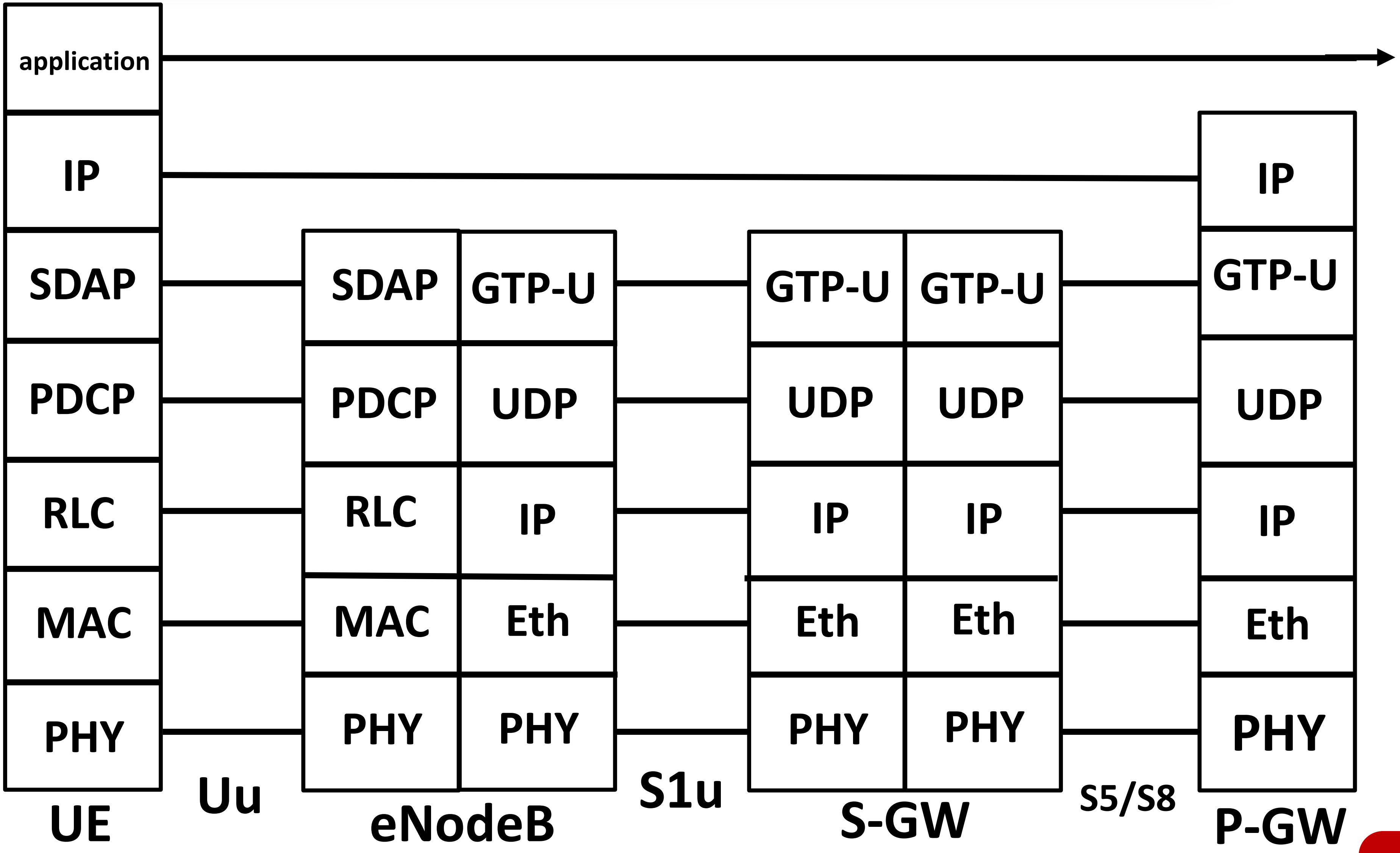
Higher layers

To finish our treatment of the air interface

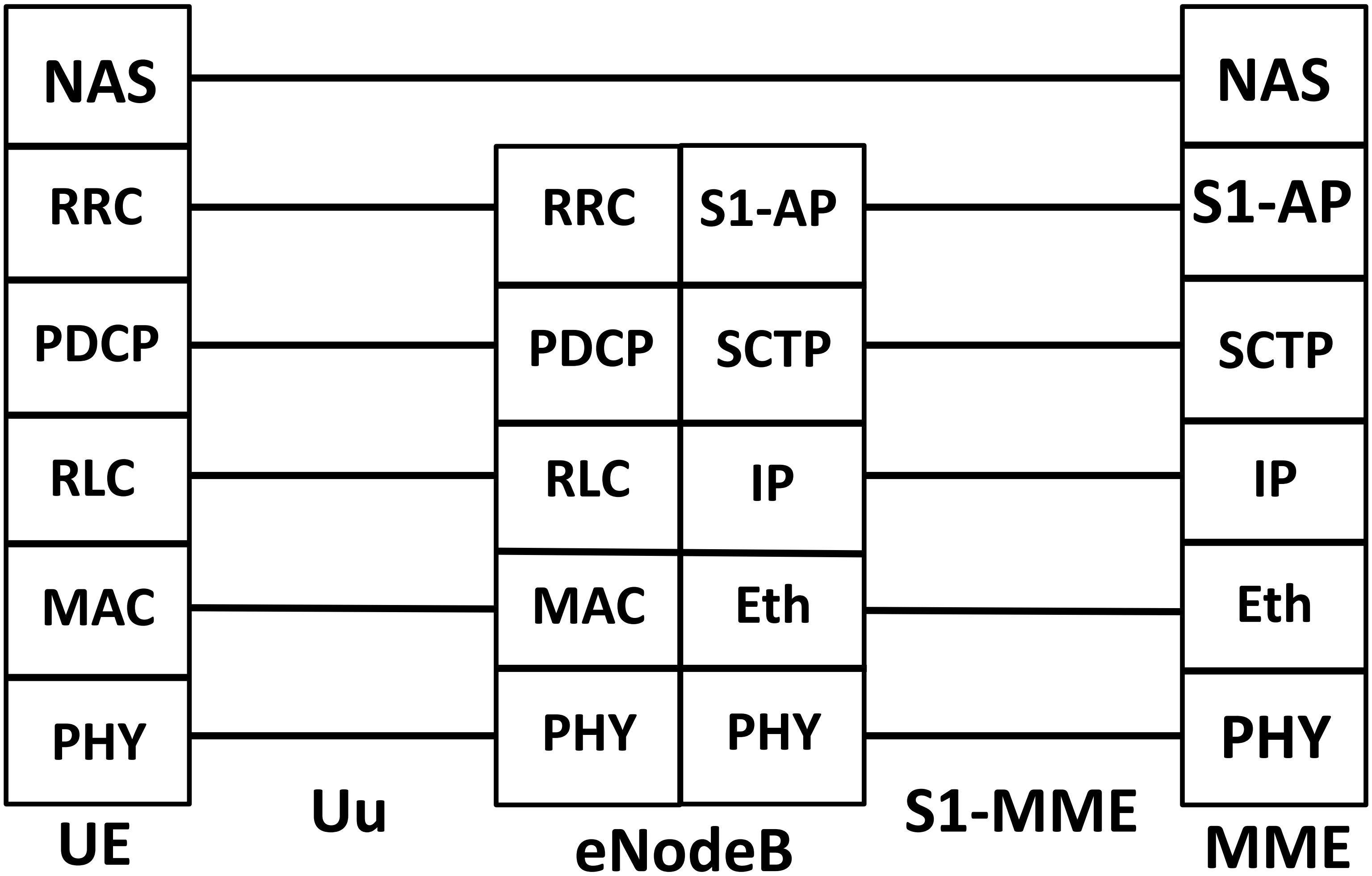
we need to briefly discuss some higher layers

SDAP	**RRC**	Radio Resource Control
PDCP		Packet Data Convergence Protocol
RLC		Radio Link Control
LOGICAL channels		
MAC		Media Access Control
TRANSPORT channels		
PHY		Physical layer
PHYSICAL channels		

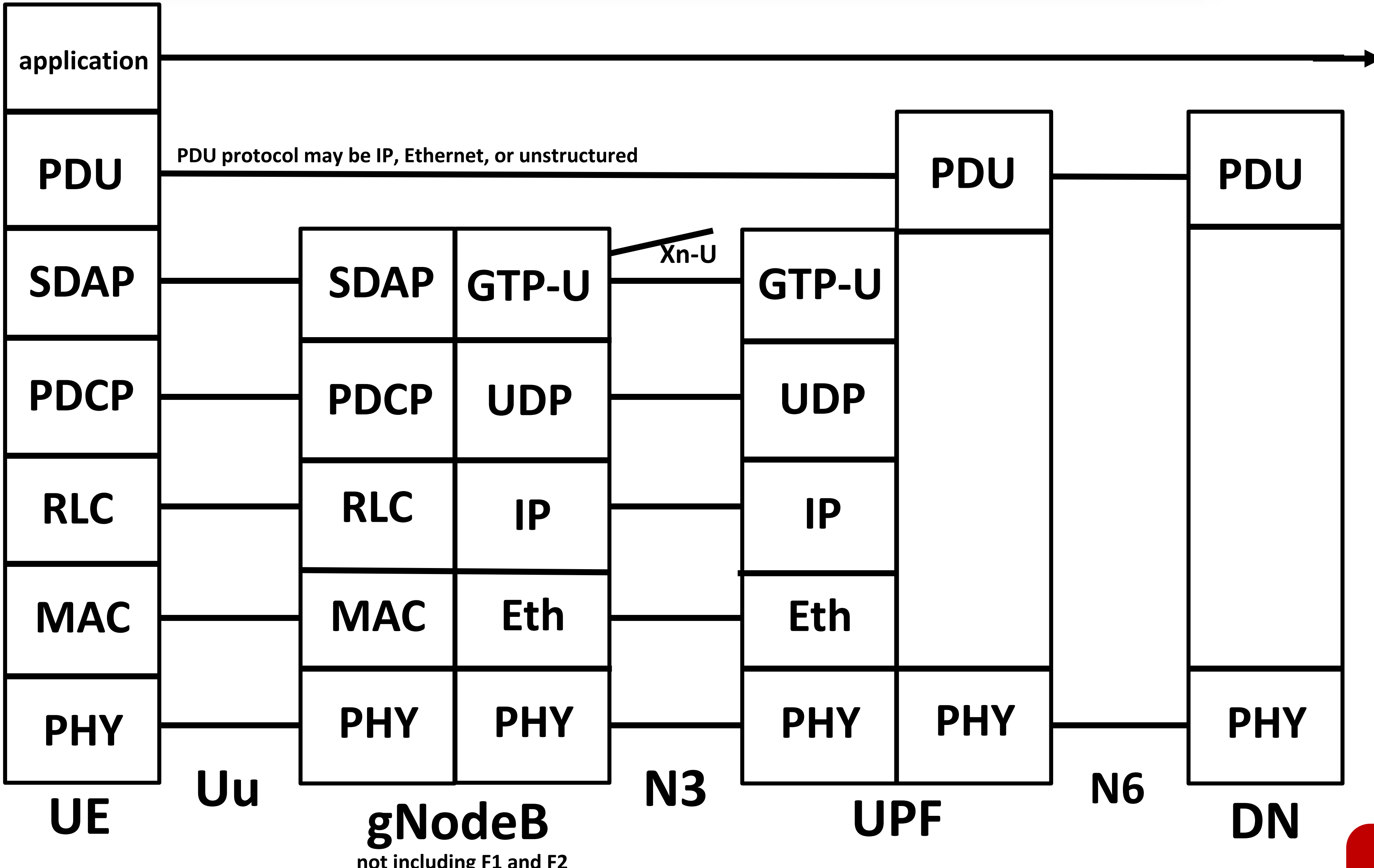
4G user plane stack



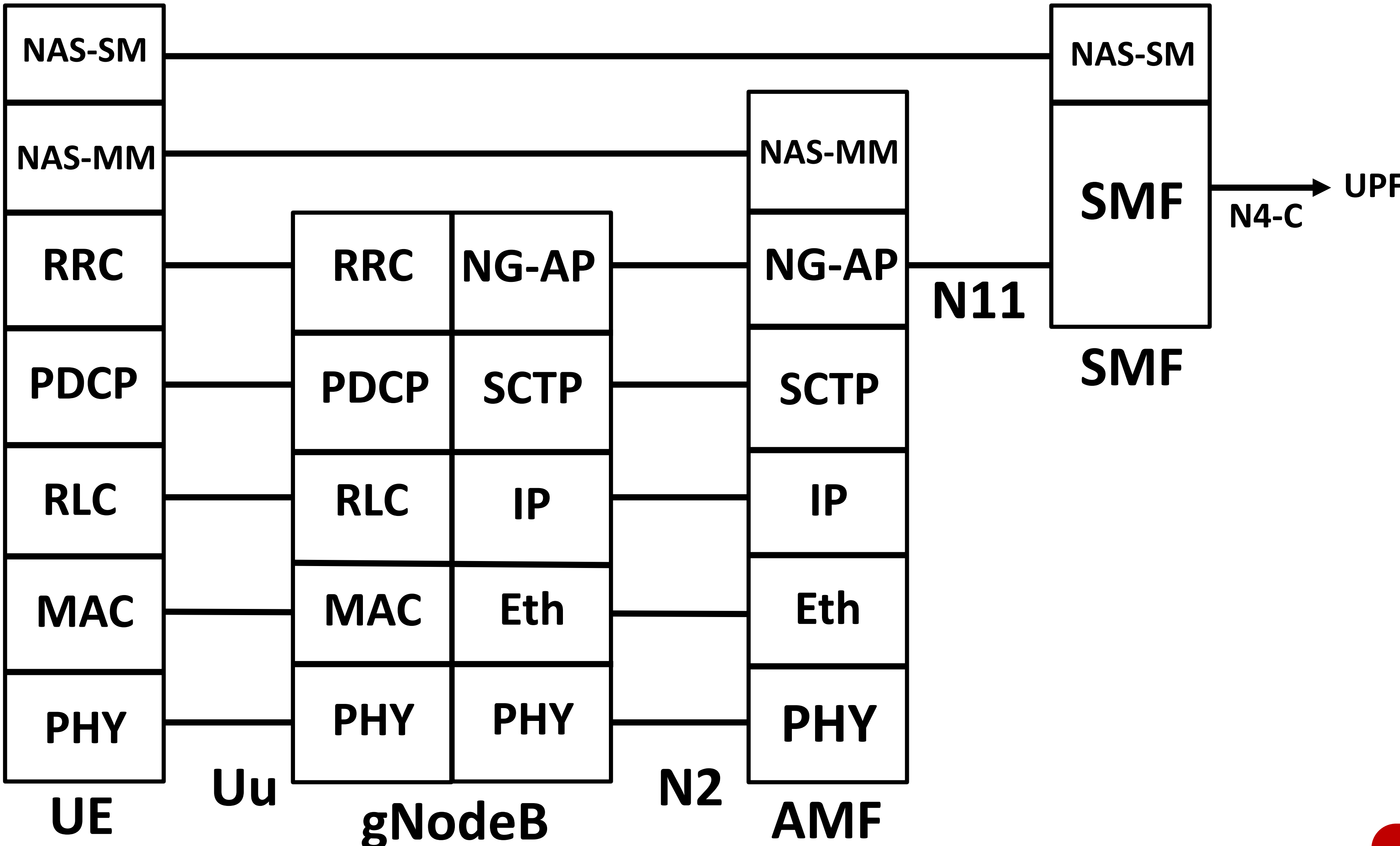
4G control plane stack



5G user plane stack



5G control plane stack



MAC

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 (in both UE and base-station)
  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

The UE RLC entity communicates with the base-station RLC entity

In the incoming direction 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:

- **A**cknowledged **M**ode
  - used for non-delay sensitive user or control data
  - most sophisticated mode
  - supports buffering, concatenation, reordering, ARQ
- **U**nacknowledged **M**ode
  - used for delay sensitive packets such as voice
  - supports concatenation and adds header
  - supports reordering
  - no retransmission
- **Tr**ansparent **M**ode
  - used for PCCH paging messages, BCCH/CCCH system info messages
  - RLC forwards transparently
    - no header is added/removed
    - no retransmission or reordering

PDCP

The PDCP converts between IP and mobile protocols

The major PDCP 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 **S**ervice **D**ata **A**daptation **P**rotocol
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