5G Air Interface – Part II
OFDMA and LTE

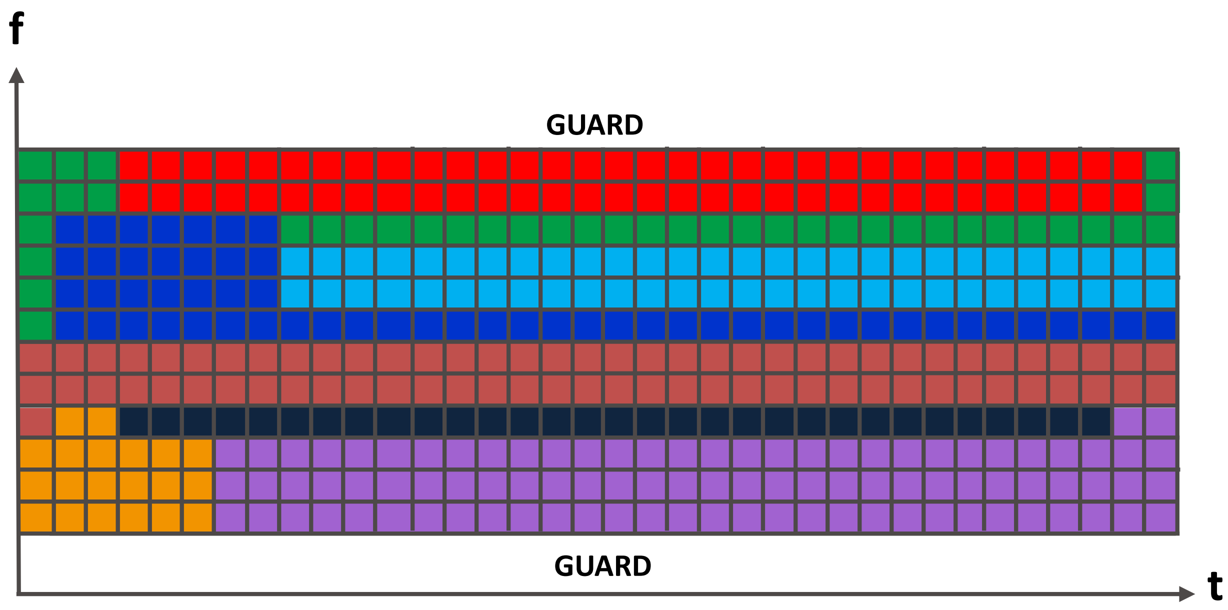
OFDMA

The basic OFDM paradigm can be readily extended to OFDMA

Each UE must transmit at

- precisely the correct symbol rate
- precisely the correct symbol timing (*as seen at the BS*)
- sub-carrier frequencies allocated to it
- time(s) allocated to it

All of this necessitates very accurate synchronization!



Resource Blocks

It is not practical or necessary
 to allocate at the granularity of individual channels/symbol-times

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 72/84 Resource Elements (1 channel * 1 symbol duration)

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

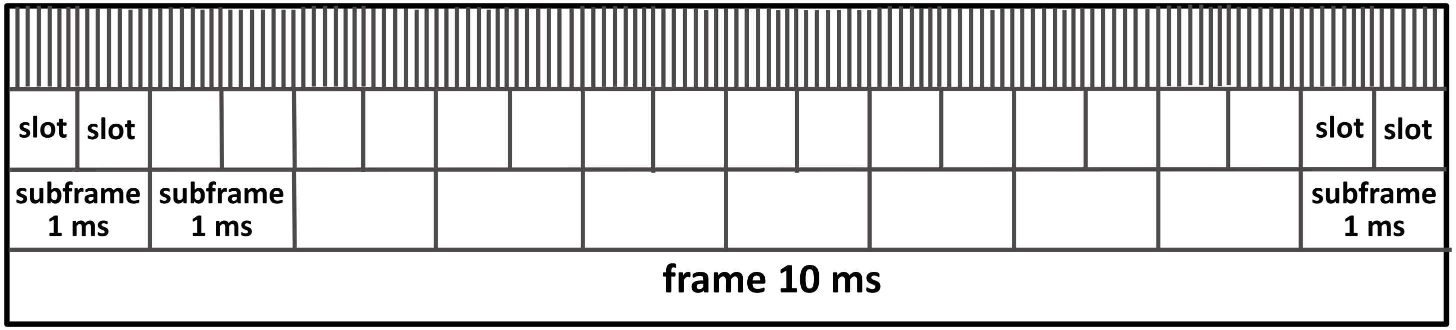
Frames, subframes, slots

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

For FDD 10 subframes (20 slots = 10 ms) make up a *frame*
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

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



Signals and physical channels

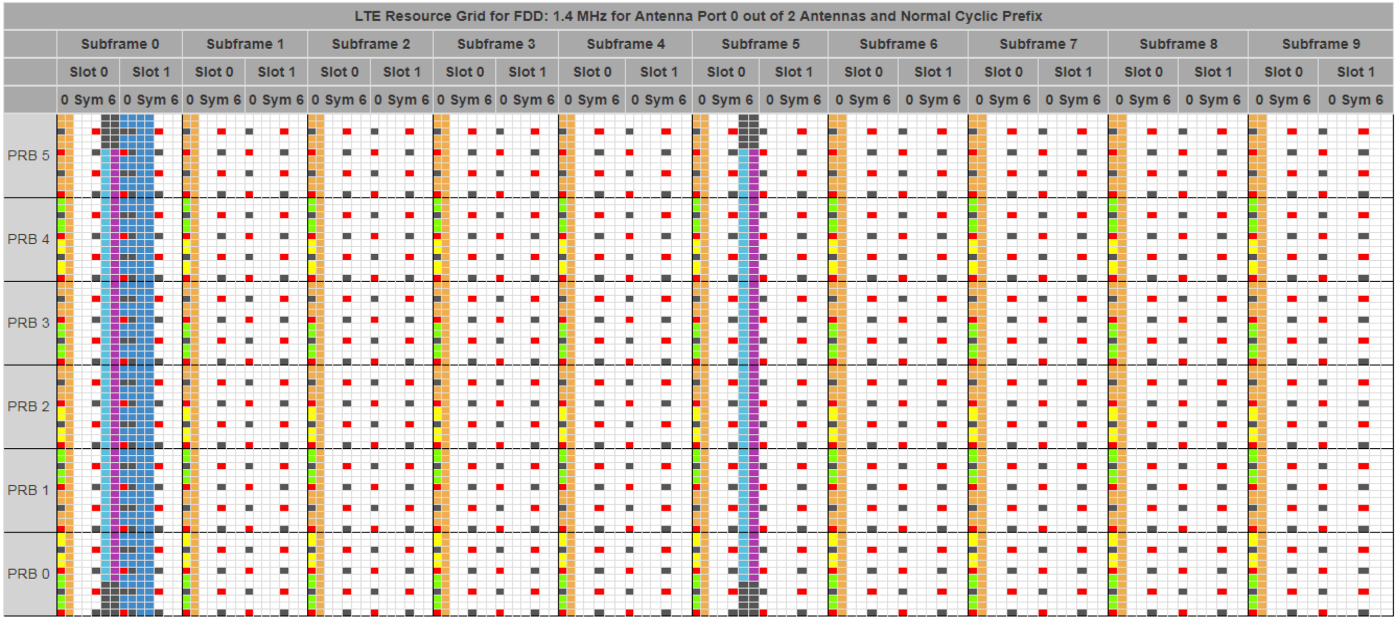
The OFDMA frame is divided into various *signals* and *physical channels*

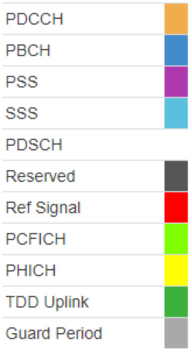
A signal is a special position in the frame needed for specific purposes such as synchronization or channel estimation

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)





Some of the signals and channels

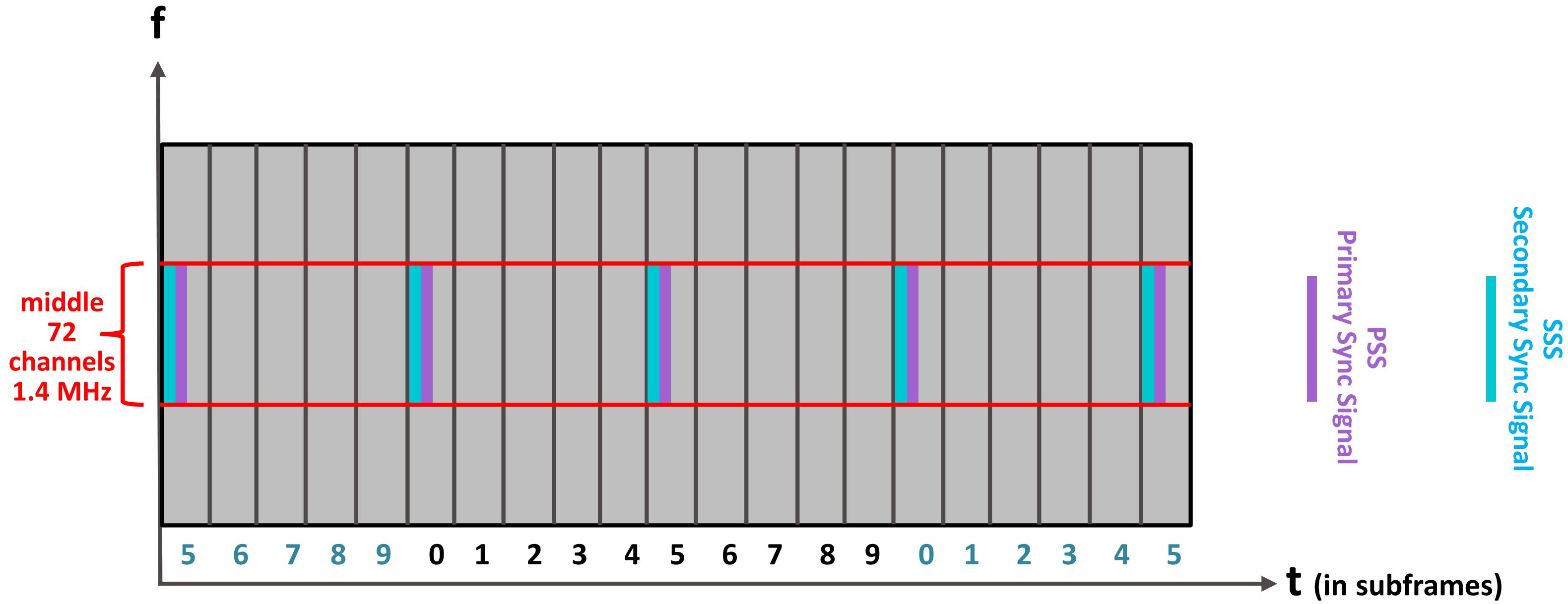
To understand how this all works, let’s analyze an example

What happens when you turn on your LTE phone ?

The first steps are

- to lock onto the signal
- find the cell ID
- find the channel bandwidth

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



PSS and SSS

The UE uses 2 special DL signals

Primary Synchronization Signal and Secondary Synchronization Signal

to find

- frame timing
- cell ID (an integer 0 ... 503)
  - ID = $3N_1 + N_2$ (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)

N_2	u
0	25
1	29
2	34

The PSS is based is a Zadoff-Chu sequence

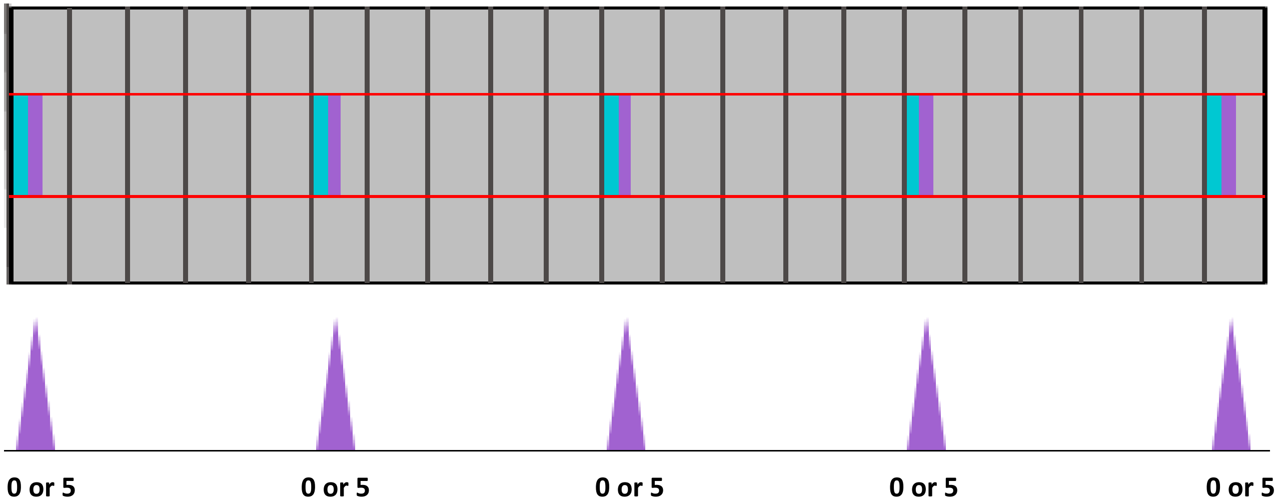
$\exp(-i \pi u n (n+1) / 63)$ for n=0...30

$\exp(-i \pi u (n+1) (n+2) / 63)$ 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)



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 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 dependent on N_1 (values from table in standard)

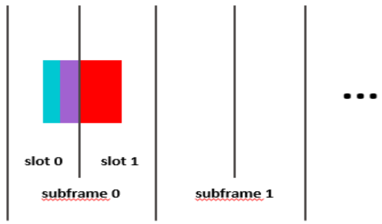
These sequences are further scrambled with shift-register scramblers

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, 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
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
- 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

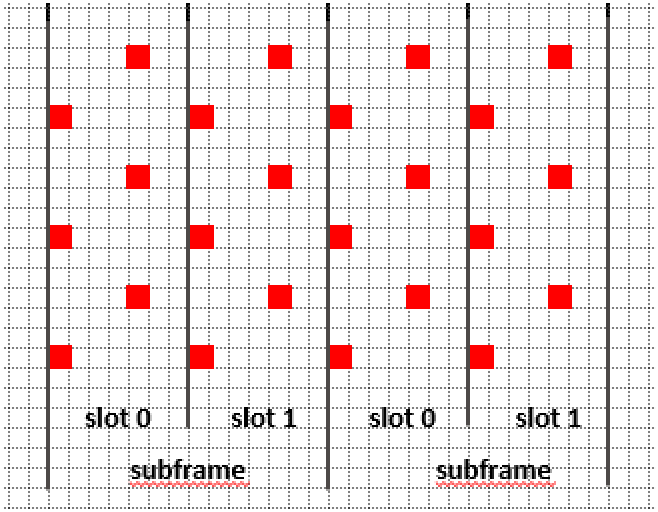
Reference signals are known signals transmitted across the entire bandwidth and are used for channel estimation and equalization

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 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

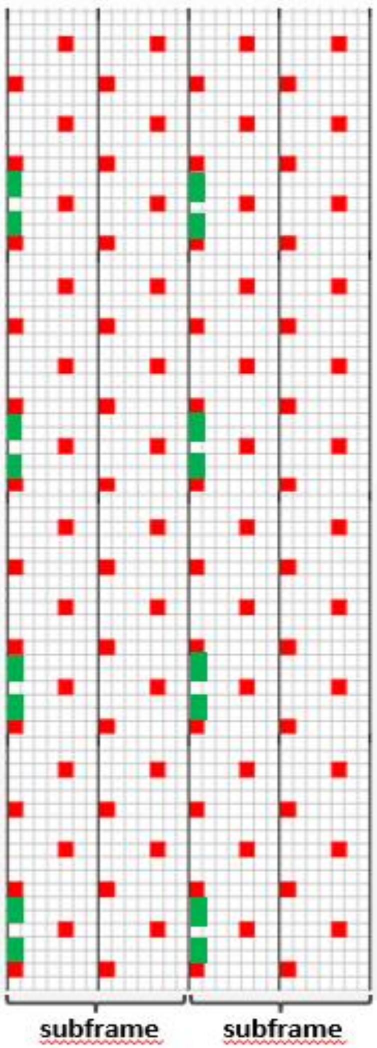
PCFICH

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 symbol 0 of subframe
- block coded
- scrambled
- QPSK modulated
- repeated 4 times separated by 1/4 of the bandwidth
  (to maximize diversity)



HARQ

In **F**orward **E**rror **C**orrection (FEC)

an error *correction* code corrects incorrectly received data

but FECs can only correct when there are a limited number of errors

In **A**utomatic **R**epeat re**Q**uest (ARQ)

an error *detection* code triggers a repeat request (NACK)

(it is easier to detect bit errors than to correct them)

Hybrid **ARQ** (HARQ) is a hybrid (combination) of FEC and ARQ

if the FEC can correct the errors, then it does so

if more errors are detected than can be corrected, ARQ is used

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

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

the number of groups was specified in the MIB (remember?)

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

Once again, much 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 PDCCH 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 form the PDSCH for decoding efficiency

PDSCH at last!

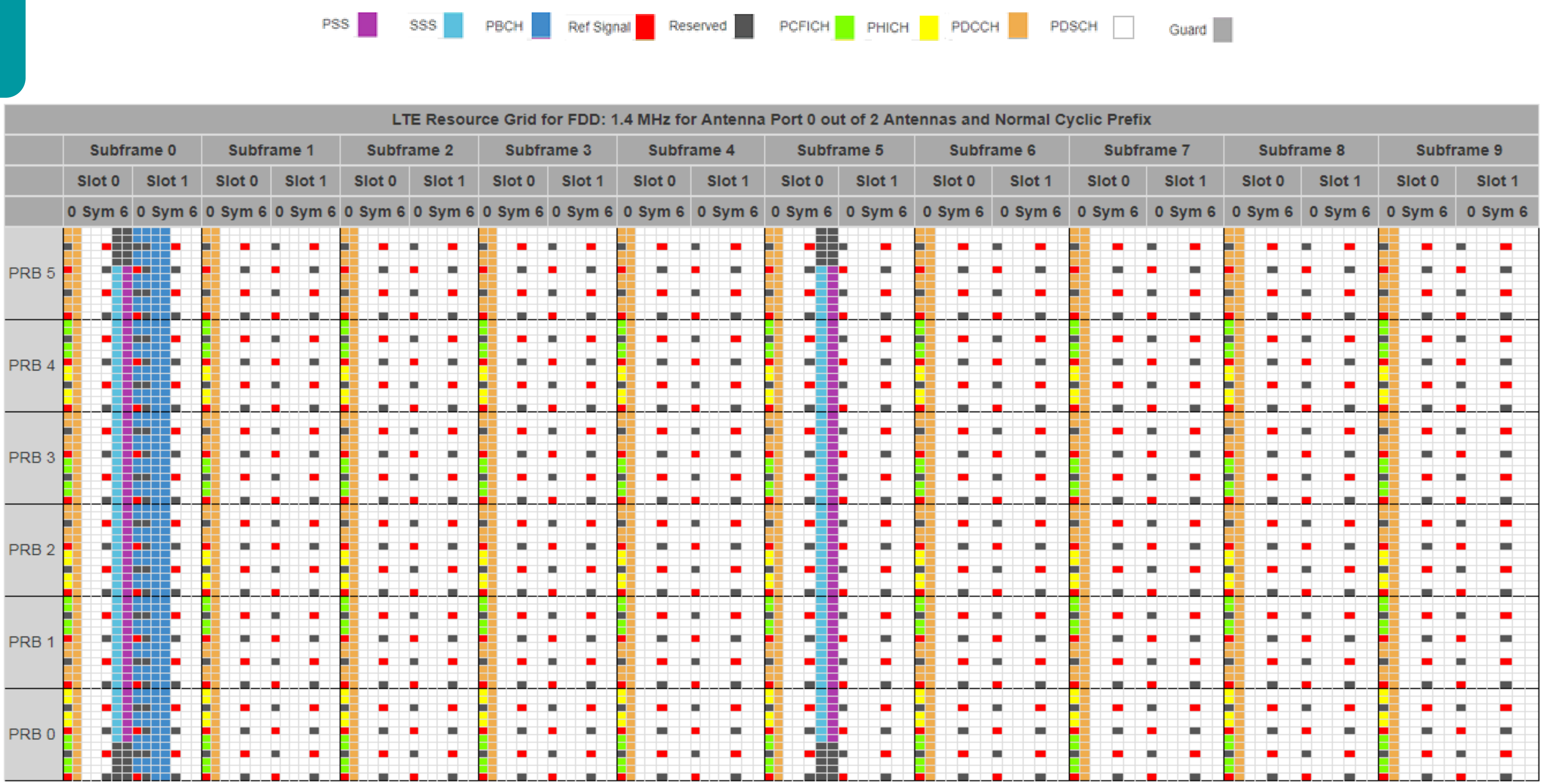
LTE PDSCH REs can be modulated using QPSK, 16QAM, 64QAM

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
  - ...

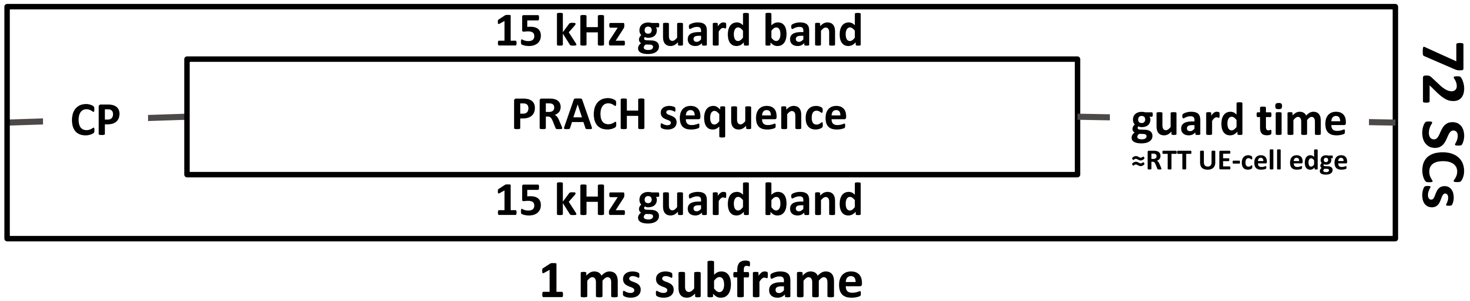
Summary example



UL physical channels

- PUSCH Physical Uplink Shared Channel
  UL counterpart of PDSCH
- PUCCH Physical Uplink Control Channel
  UL control signaling (e.g., scheduling requests)
- PRACH Physical Random Access Channel
  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