UMTS Long Term Evolution (LTE)

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3GPP UMTS Evolution
What are the major technical „road works“?

As usual: Bandwidth

-Wider frequency bandwidth
-MIMO systems
-Additional frequency bands
-Higher value modulation schemes

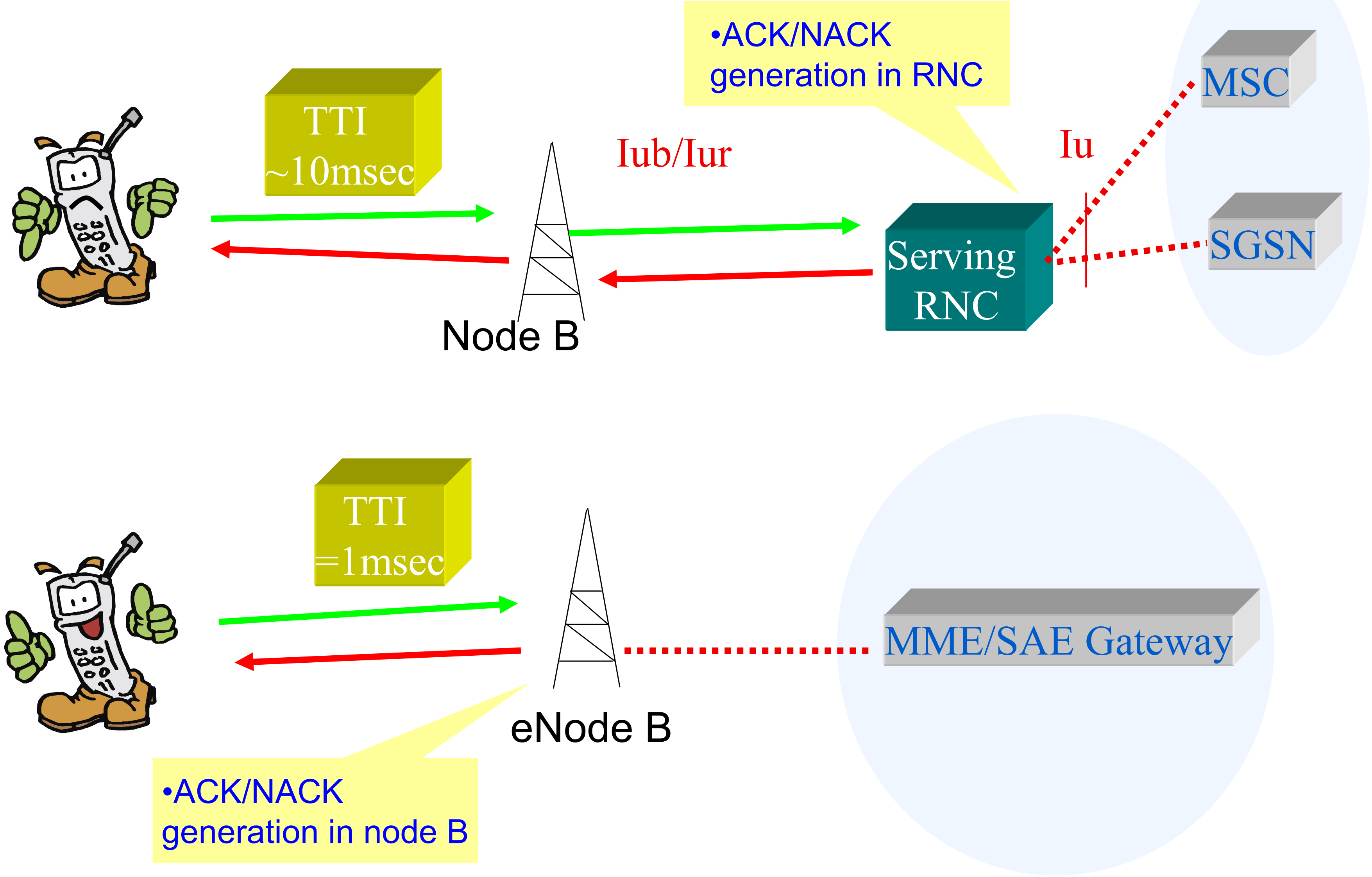
Reduce Round Trip Time, RTT

-Node-B upgrade
-Fast scheduling methods

All over Packet Switched Connection

-Deployment of IMS (IP Multimedia Subsystem) in core networks
-solely Shared Channel setups

Round Trip Time, RTT



Numbers to remember …

$$T_f = 10ms = 20\,slots = 20\cdot 7\ OFDM\,symbols = 140\cdot T_{symbol}^{air}$$

$$T_{symbol} = \frac{1}{\Delta f} = \frac{1}{15000} = 66\frac{2}{3}\,\mu s$$

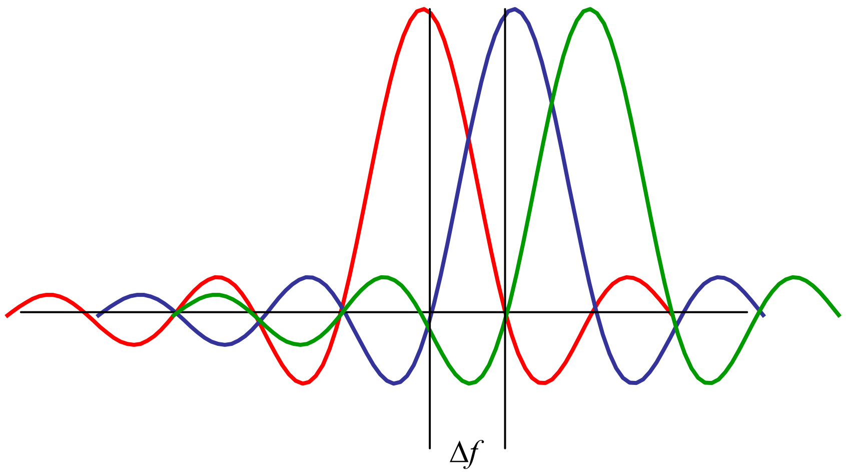
$$T_{symbol}^{air} = (1+CP)\cdot T_{symbol} = \left(1+\begin{Bmatrix} CP_{normal} = \frac{1}{14} \\ CP_{extended} = \frac{1}{4} \end{Bmatrix}\right)\cdot T_{symbol} = \begin{Bmatrix} \frac{15}{14}\cdot T_{symbol} \\ \frac{5}{4}\cdot T_{symbol} \end{Bmatrix} = \begin{Bmatrix} \frac{500}{7}\mu s \\ \frac{250}{3}\mu s \end{Bmatrix}$$

$$1\,slot = 7\cdot T_{symbol}^{air} = 7\cdot\frac{15}{14}\cdot T_{symbol} = \frac{15}{2}\cdot T_{symbol} = \frac{15}{2}\cdot\frac{1}{15000} = \frac{1}{2000} = 0.5\,ms$$

$$T_S = \frac{T_{symbol}}{2048} = \frac{1}{2048\cdot\Delta f} = \frac{1}{2048\cdot 15000} \approx 32.55\,ns \quad (\approx 10\,m\ resolution)$$

$$T_{symbol} = 2048\cdot T_S$$

Basic OFDM parameter



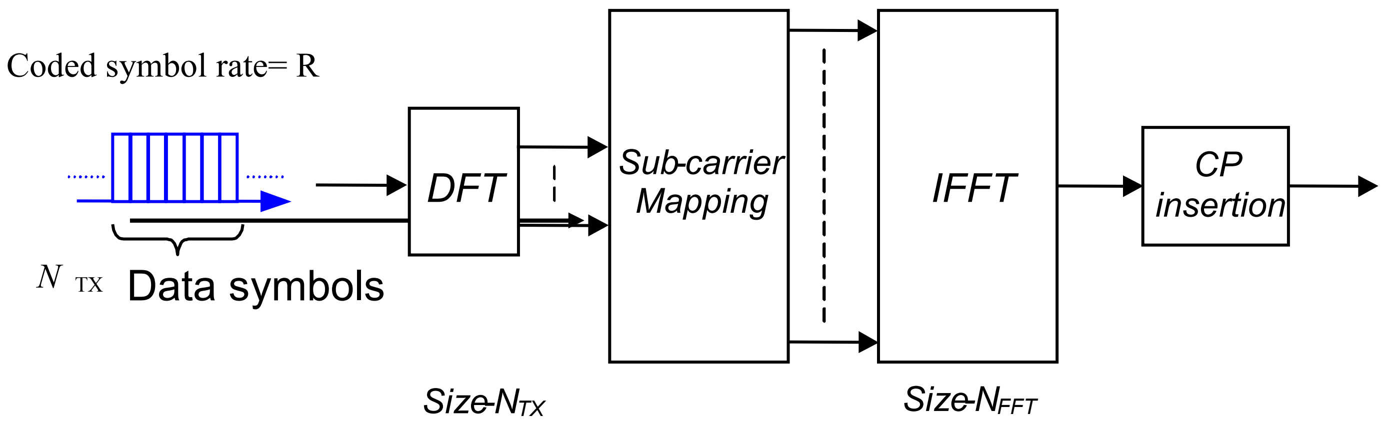
LTE

$$\Delta f = 15\ kHz = \frac{1}{T}$$

$$F_s = N_{FFT} \cdot \Delta f$$

$$F_s = \frac{N_{FFT}}{256} \cdot 3.84 Mcps$$

$$N_{FFT} = 2048$$



Basic time unit definitions

$$t_{sample} = \frac{1}{f_{sample}} \xrightarrow{OFDM} t_{sample} = \frac{1}{\Delta f \cdot N_{FFT}}$$

WiMAX

$$PS = \frac{4}{F_s} = \frac{4}{n \cdot BW}$$

-Physical slot, PS
-Depends of sampling frequency F_s
-n oversampling factor
-Nominal bandwidth BW

LTE

$$T_s = \frac{1}{15kHz \cdot 2048} = \frac{1}{8 \cdot 3.84Mcps}$$

-Constant value Δf=15 kHz
-$N_{FFT,max}$ = 2048
-Integer multiple of WCDMA/HSPA chiprate

T_s ~ 32,55 nano seconds

The LTE basic time unit T_s

This time unit is used to specify all timing aspects in LTE, e.g. the length of the cyclic prefix is defined as 144 * T_s

$$T_s = \frac{1}{15kHz \cdot 2048} \approx 32.55 nano \sec$$

LTE time unit T_s is a multiple of the legacy chiprate to alleviate multimode chipsets design

But also the legacy:

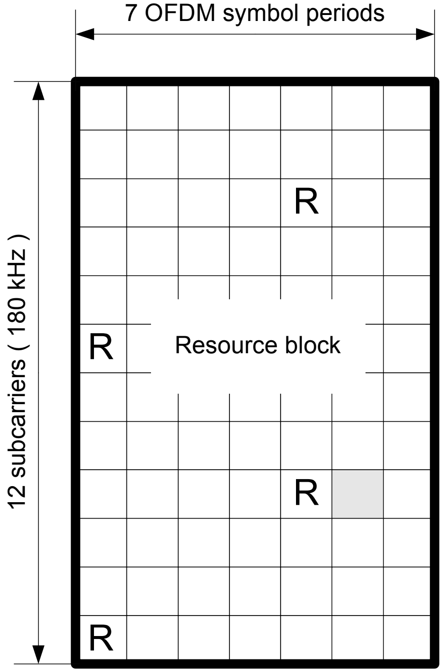
WCDMA chiprate = 3.84 MCps

$$T_s = \frac{1}{15kHz \cdot 2048} = \frac{1}{8 * 3.84}$$

CDMA2000 chiprate = 1.2288 MCps

$$T_s = \frac{1}{15kHz \cdot 2048} = \frac{1}{25 * 1.2288}$$

Downlink basic resources: Data rate aspects



Resource block incl. 80 modulation symbols
and 4 reference symbols (R)

$$R_{RB} = \frac{80 \cdot M}{0.5\ ms}$$

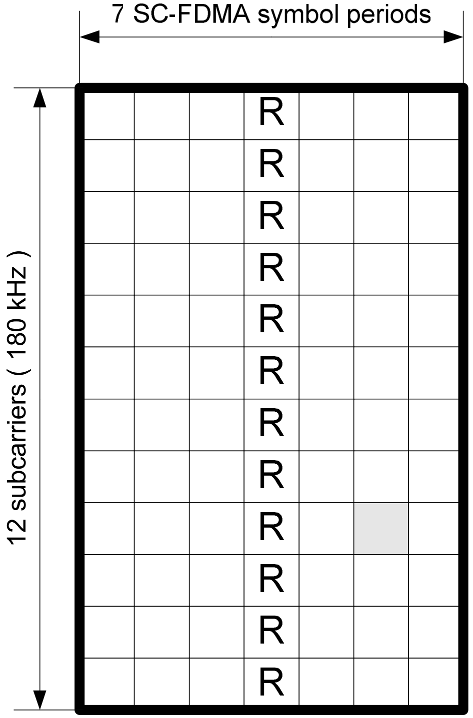
$$R_{RB} = 160 \cdot 6 \cdot 10^3 = 0.96 Mbps$$

$$R_{50RB} = 48 Mbps @ 10 MHz$$

$$R_{110RB} = 105.6 Mbps @ 20 MHz$$

Best case scenario: 64QAM modulation scheme (6bits = 1 symbol)
and no error correction at all!

Uplink basic resources



Resource block
incl. 72 modulation symbols
and 12 reference symbols (R)

$$R_{RB} = \frac{72 \cdot M}{0.5\ ms}$$

$$R_{RB} = 144 \cdot 6 \cdot 10^3 = 0.864 Mbps$$

$$R_{50\,RB} = 86.4 Mbps @ 20 MHz$$

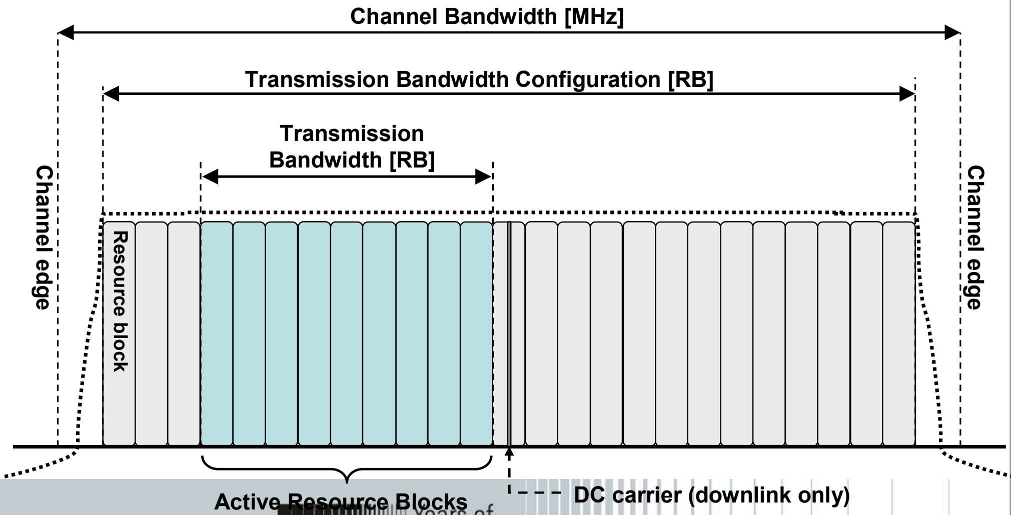
Best case scenario: 64QAM modulation scheme (6bits = 1 symbol)
and no error correction at all!

LTE – spectrum flexibility

- LTE physical layer supports any bandwidth from 1.4 MHz to 20 MHz in steps of 180 kHz (resource block)
- Current LTE specification supports only a subset of 8 different system bandwidths
- All UEs must support the maximum bandwidth of 20 MHz

Channel bandwidth $BW_{Channel}$ [MHz]	1.4	3	5	10	15	20
FDD and TDD mode	6	15	25	50	75	100

number of resource blocks



Channel bandwidth parameters

Bandwidth $BW_{Channel}$	FFT size	N_{BW}^{DL} Number of sub carriers excl. DC carrier	N_{BW} Transmission Bandwidth Configuration	Occupied Bandwidth	Max Data rate
1.4 MHz	128	72	6	1.095 MHz	5.76 Mbps
3 MHz	256	180	15	2.715 MHz	14.4 Mbps
5 MHz	512	300	25	4.515 MHz	24.0 Mbps
10 MHz	1024	600	50	9.015 MHz	48.0 Mbps
15 MHz	1536	900	75	13.515 MHz	72.0 Mbps
20 MHz	2048	1200	100	18.015 MHz	96.0 Mbps

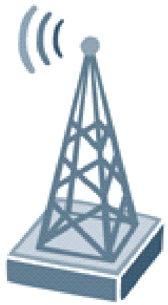
Channel bandwidth = eNodeB system bandwidth ≠ the allocated bandwidth to 1 UE!

Baseline parameters:
- 12 subcarriers per resource block (default)
- 7 symbols per resource block (default)
- Δf = 15 kHz
- Generic FDD radio framing type 1 (i.e. 20 slots @ 10 ms)
- Normal cyclic prefix

LTE: new physical channels for data and control

Physical Control Format Indicator Channel PCFICH:
Indicates Format of PDCCH

Physical Downlink Control Channel PDCCH:
Downlink and uplink scheduling decisions



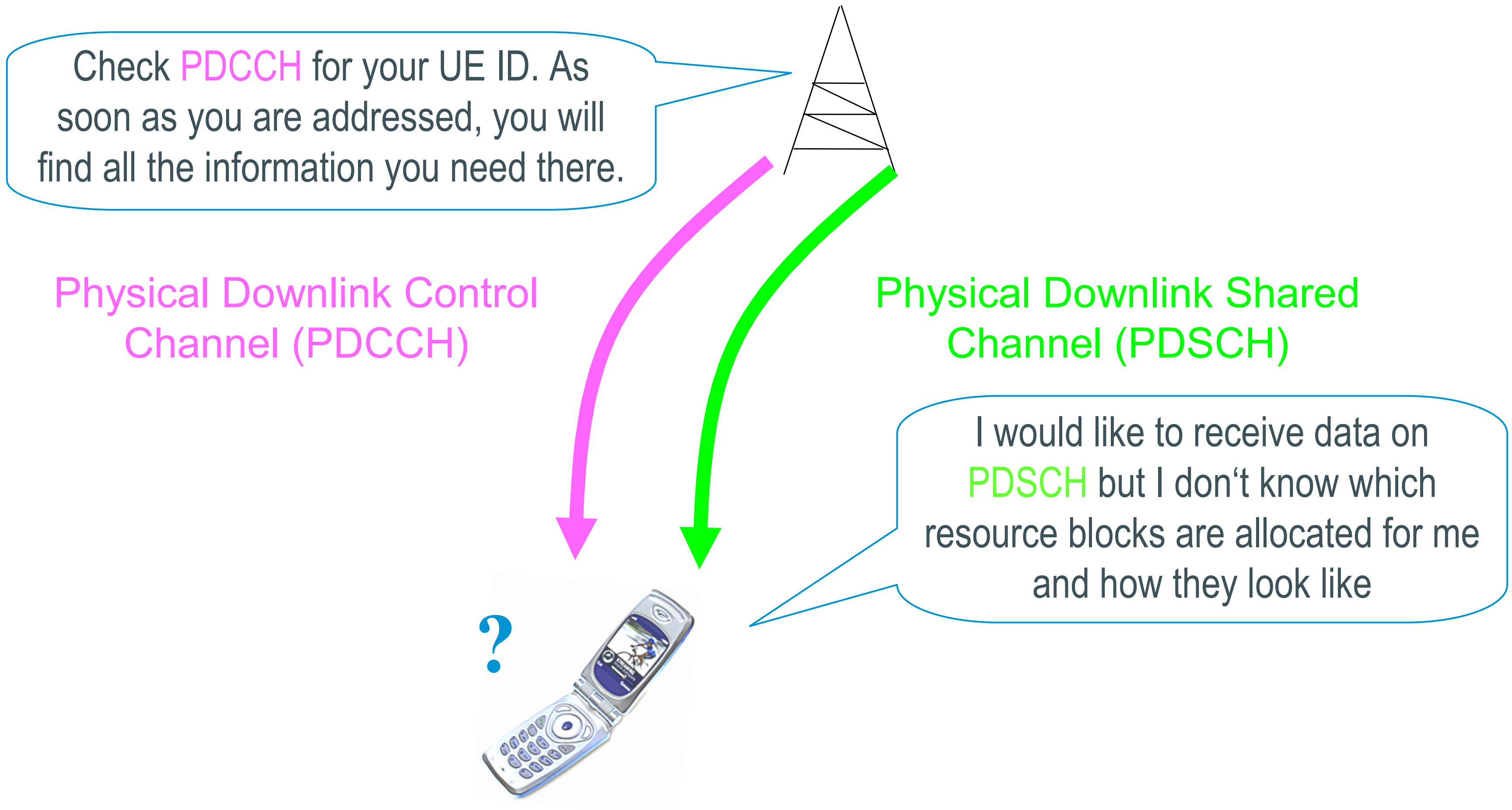
Physical Downlink Shared Channel PDSCH: Downlink data

Physical Hybrid ARQ Indicator Channel PHICH:
ACK/NACK for uplink packets

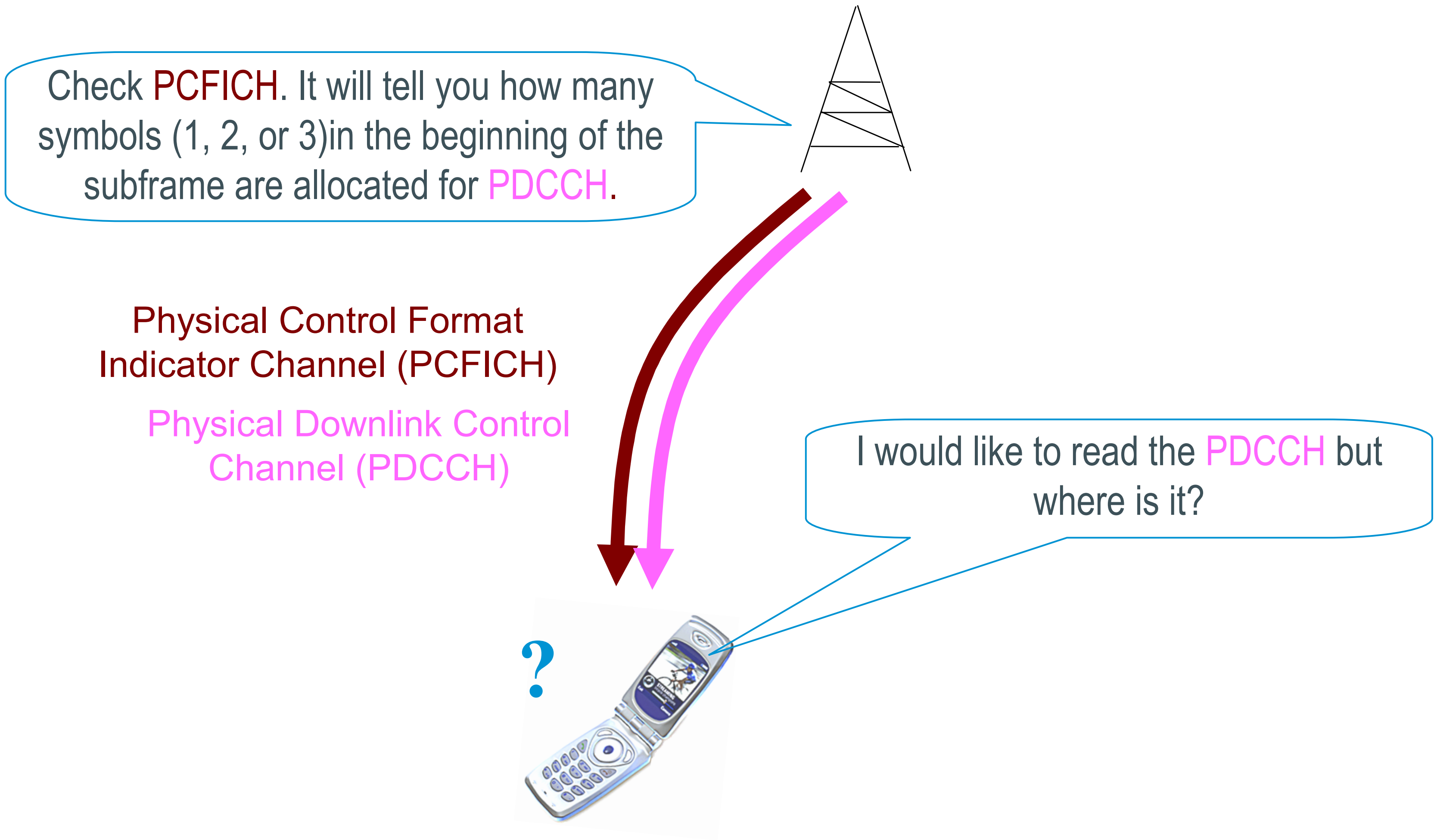
Physical Uplink Shared Channel PUSCH: Uplink data

Physical Uplink Control Channel PUCCH:
ACK/NACK for downlink packets, scheduling requests, channel quality info

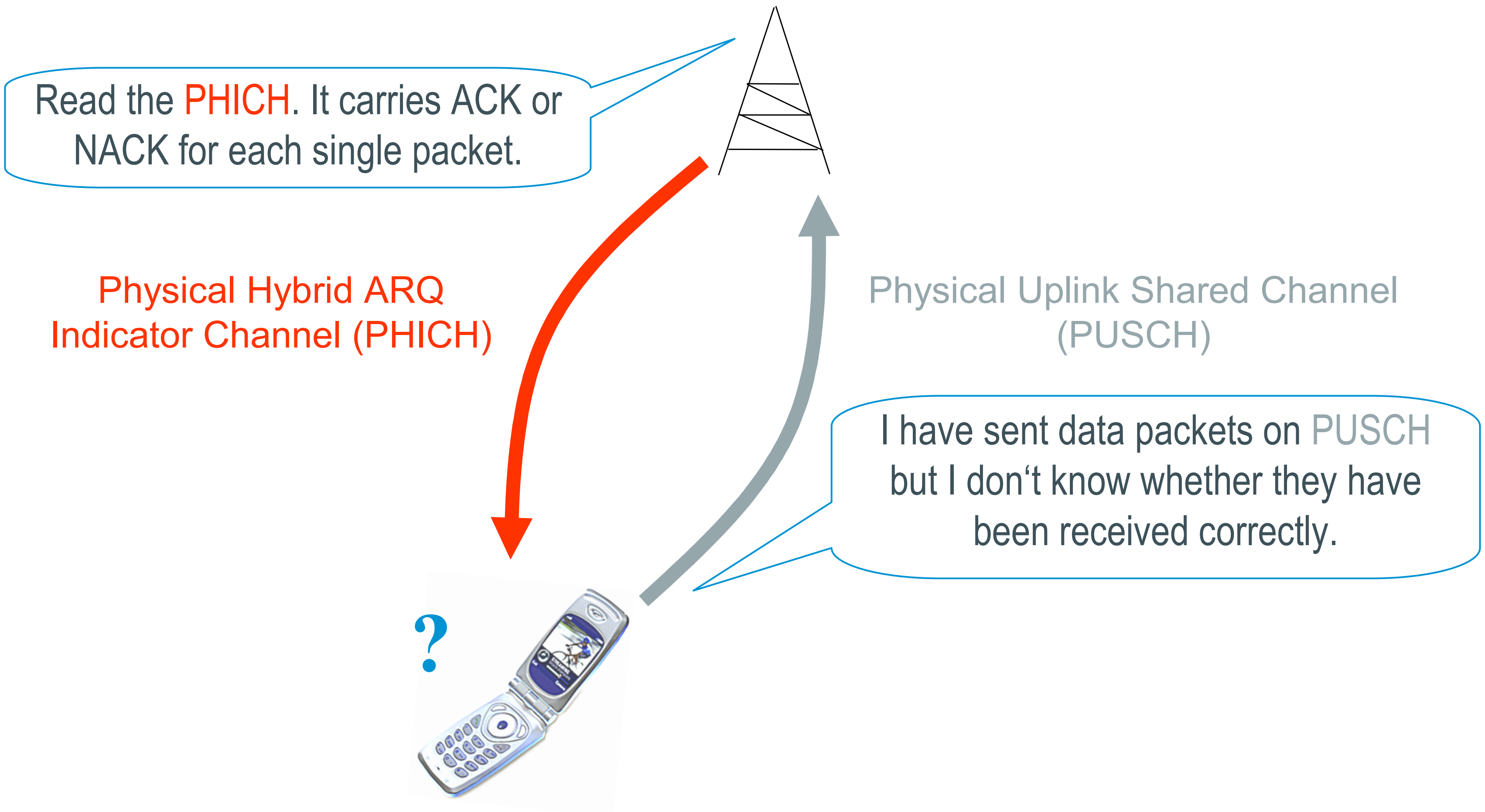
LTE downlink
Scheduling of downlink data



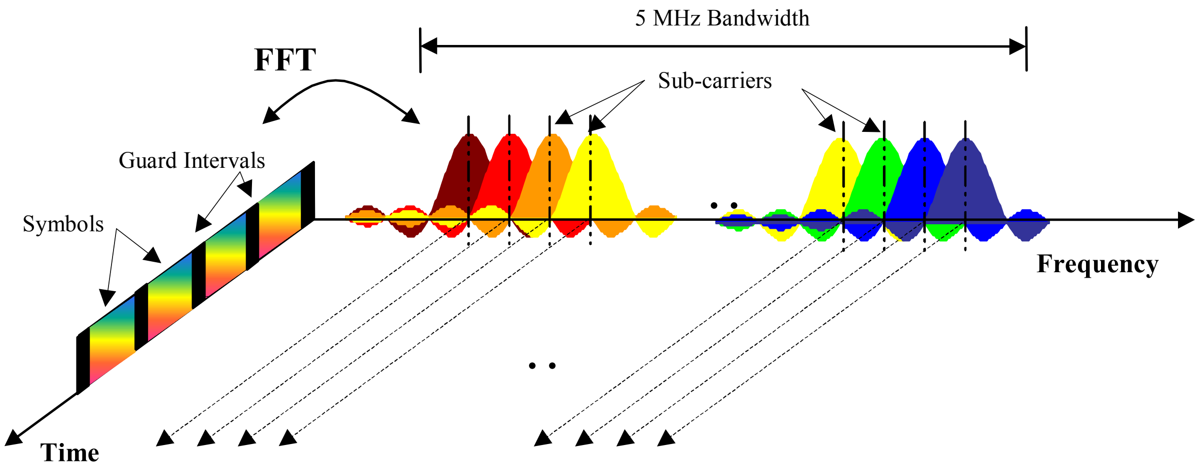
Physical Control Format Indicator Channel (PCFICH) Indicating PDCCH format



Physical Hybrid ARQ Indicator Channel (PHICH) Acknowledging uplink data packets

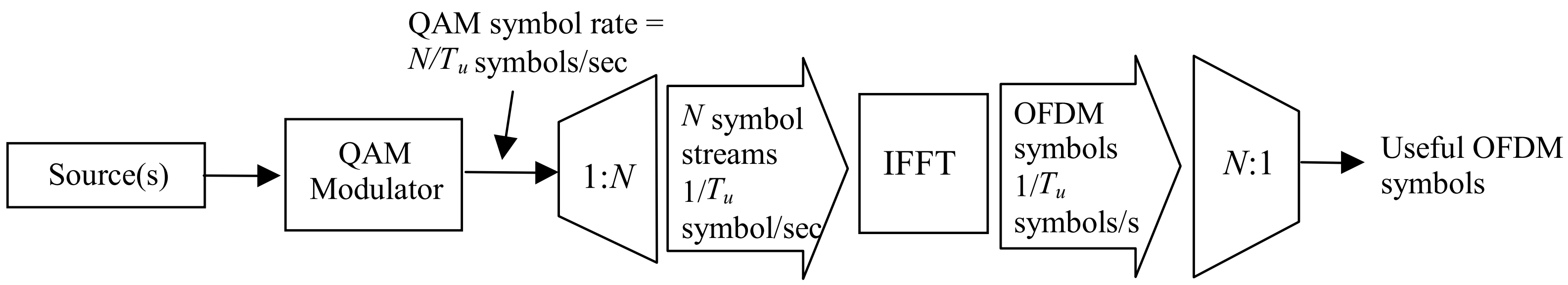


LTE Downlink:
How does the OFDMA signal look like?



- Each sub-carrier (frequency channel) carries a separate low-rate stream of data
- Frequencies are chosen so that the modulated data streams are orthogonal to each other
- Each sub-carrier is independently modulated
- A guard time is added to each symbol (cyclic prefix in LTE)
- Symbol duration is relatively long compared to channel delay spread -> less intersymbol interference

LTE Downlink:
How to generate an OFDMA signal in theory?



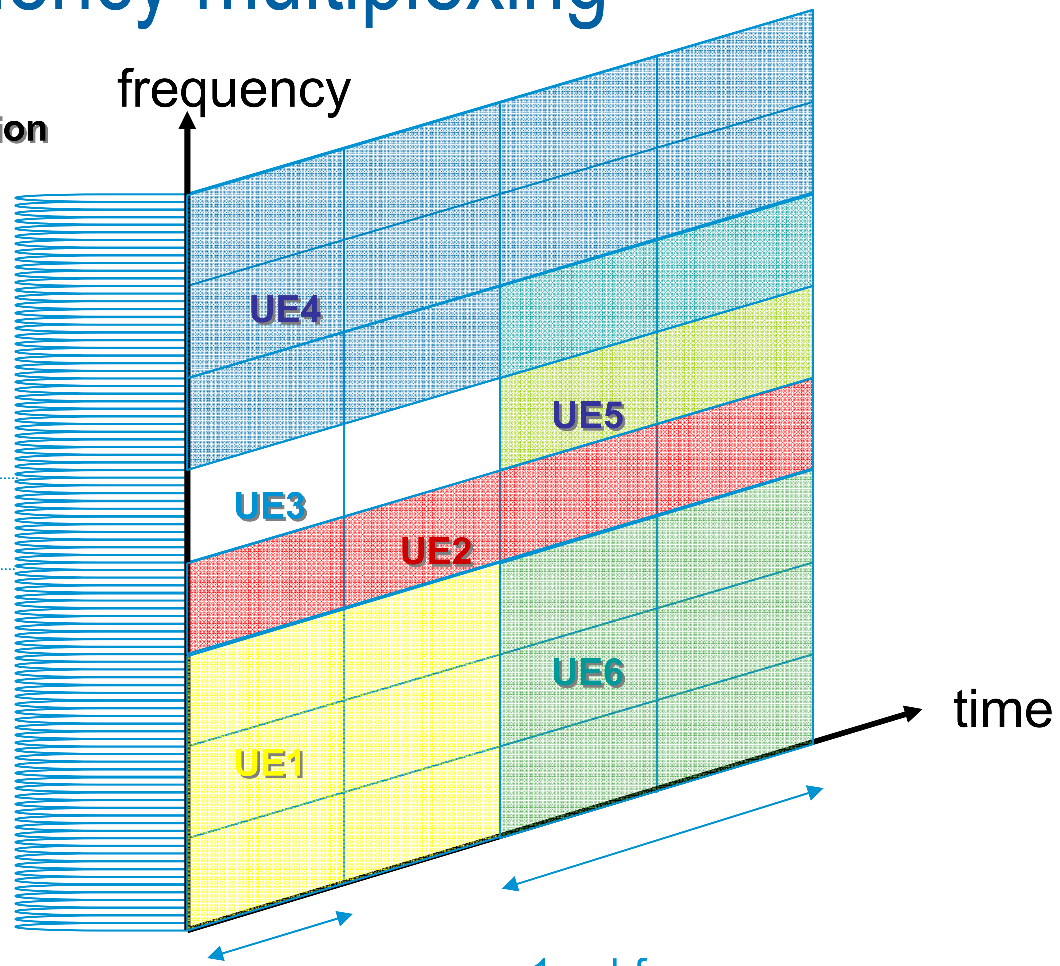
- Mapping of serial stream of modulated symbols to N parallel streams
- LTE provides **QPSK, 16QAM, 64QAM** as downlink modulation schemes
- Symbols on N streams are used as frequency domain bins for the IFFT (Inverse FFT)
- IFFT provides N-point set of complex time-domain samples
- Useful OFDM symbol is the time superposition of N orthogonal subcarriers

LTE Downlink
OFDMA time-frequency multiplexing

QPSK, 16QAM or 64QAM modulation

1 resource block =
180 kHz = 12 subcarriers

Subcarrier spacing = 15 kHz



1 slot = 0.5 ms =
7 OFDM symbols**

1 subframe =
1 ms= 1 TTI*=
1 resource block pair

*TTI = transmission time interval

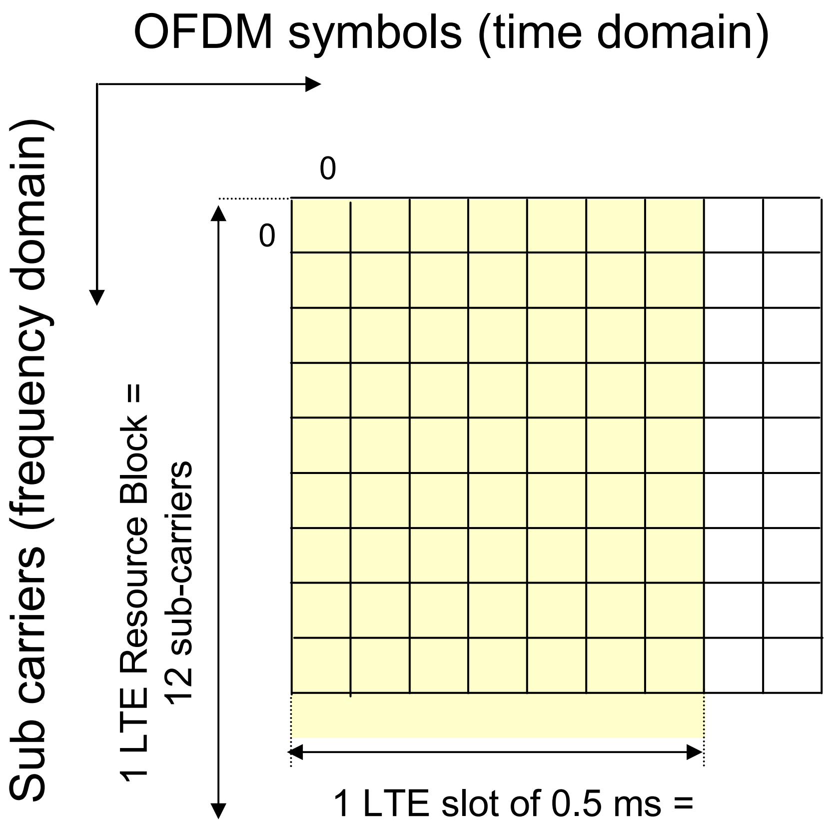
** For normal cyclic prefix duration

LTE Downlink:
OFDMA Time/Frequency Representation

Resource block

- Sub-carrier spacing in **LTE = 15 kHz** (7.5 kHz for MBMS scenarios)
- Data is allocated in multiples of resource blocks
- 1 resource block spans 12 sub-carriers in the frequency domain and 1 slot in the time domain
- Resource block size is identical for all bandwidths

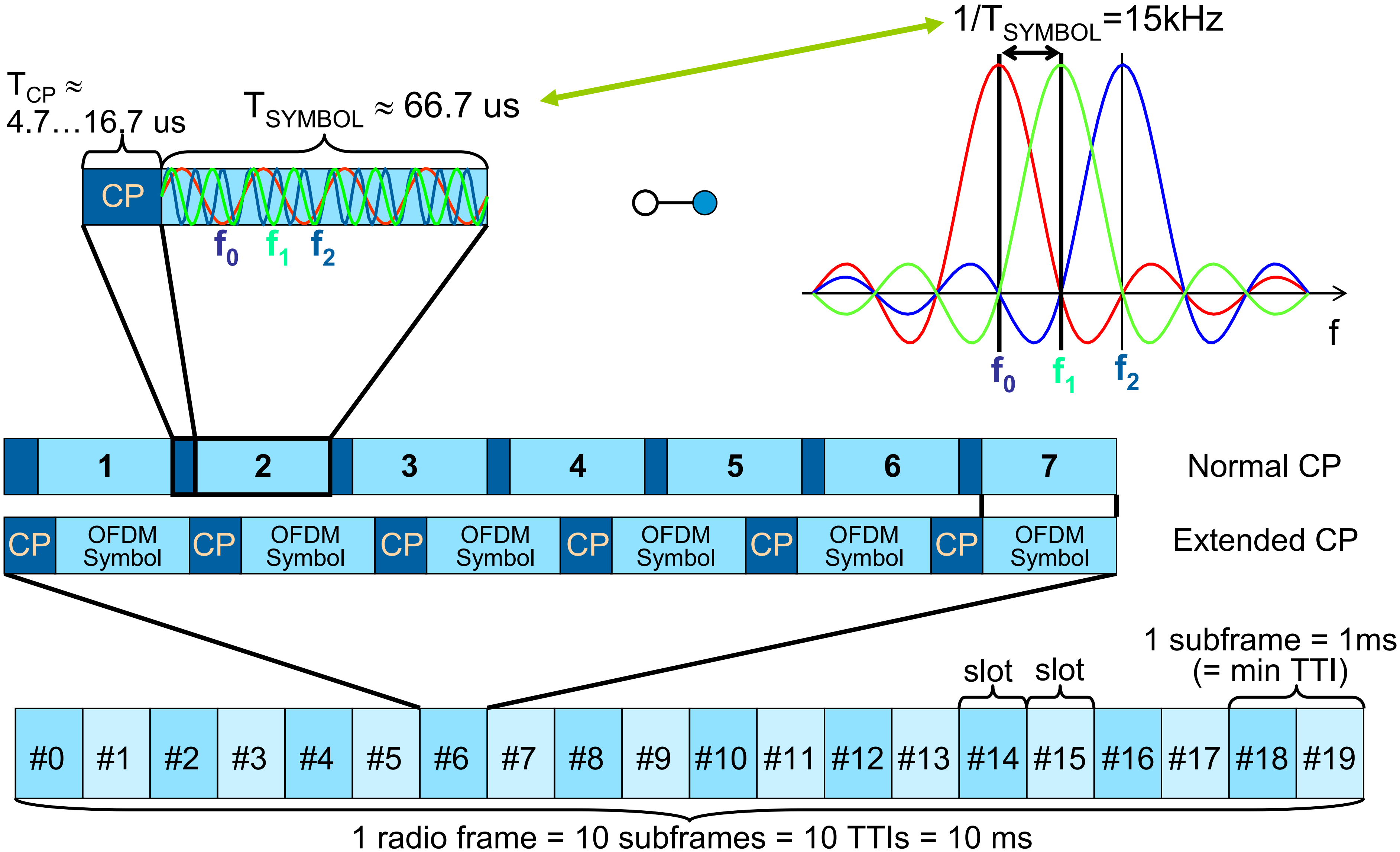
Normal scenario: carrier spacing of 15 kHz
Big cell scenario: 7,5 kHz + extended guard time



6 / 7 OFDM symbols dep. on cyclic prefix length

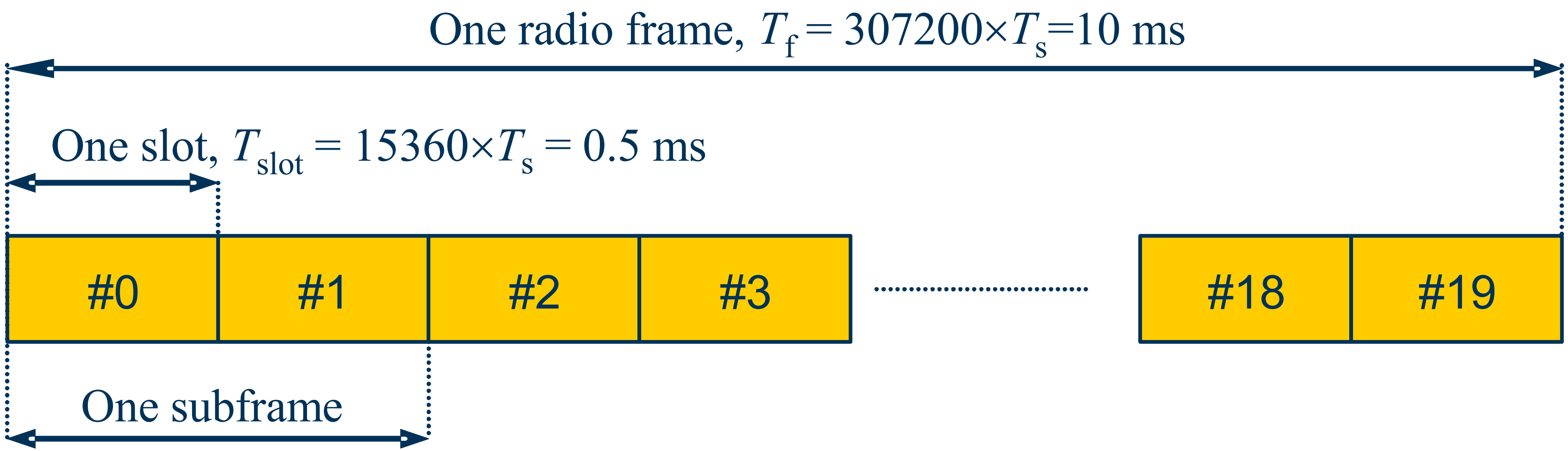
(3 symbols for 7.5 kHz spacing / MBMS scenarios)

Basic Frame Structure – E-UTRA FDD and TDD



LTE Downlink:
Downlink slot and (sub)frame structure

Symbol time, or number of symbols per time slot is not fixed

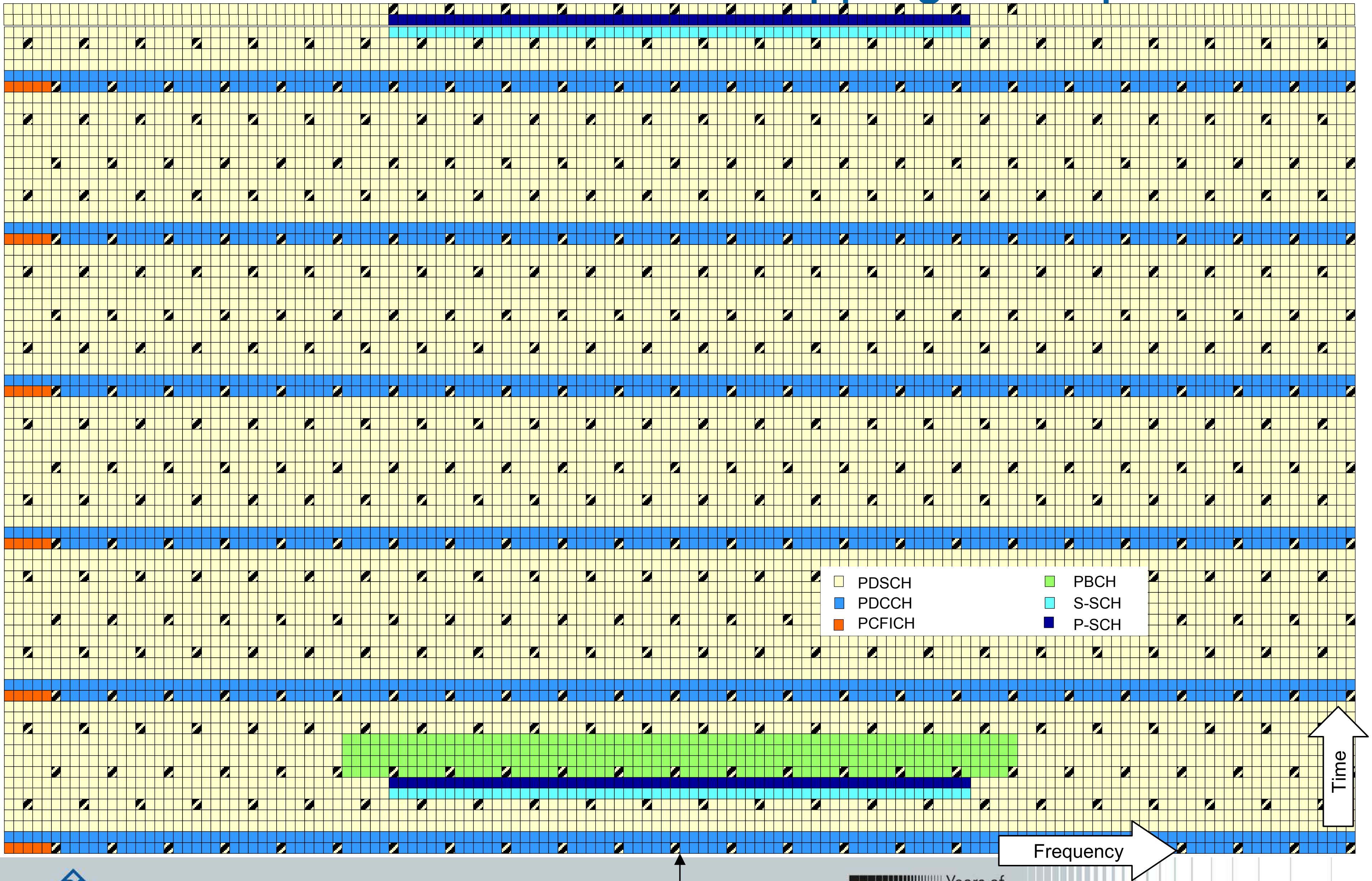


We talk about 1 slot, but the minimum resource is 1 subframe = 2 slots !!!!!

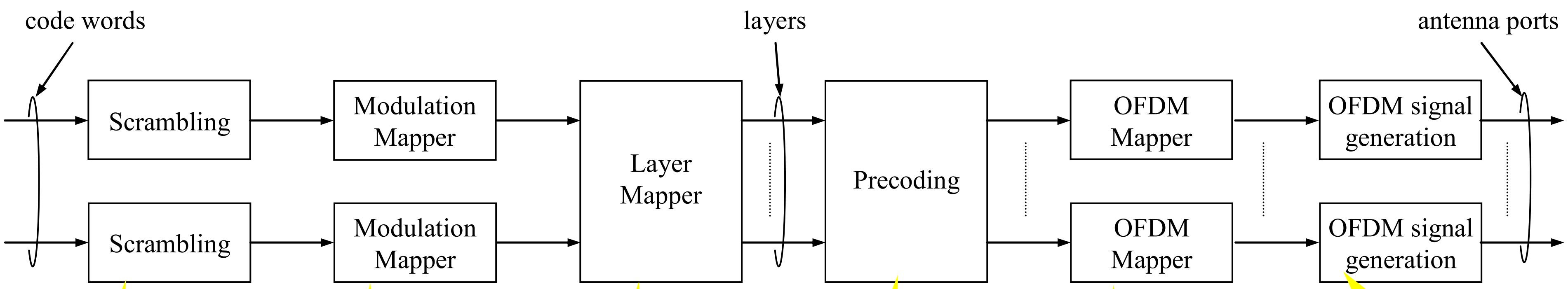
Ts = 32.522 ns

$$T_s = 1/(15000 \times 2048)$$

LTE Downlink: FDD channel mapping example



LTE Downlink: baseband signal generation



Avoid constant sequences

QPSK
16 QAM
64 QAM

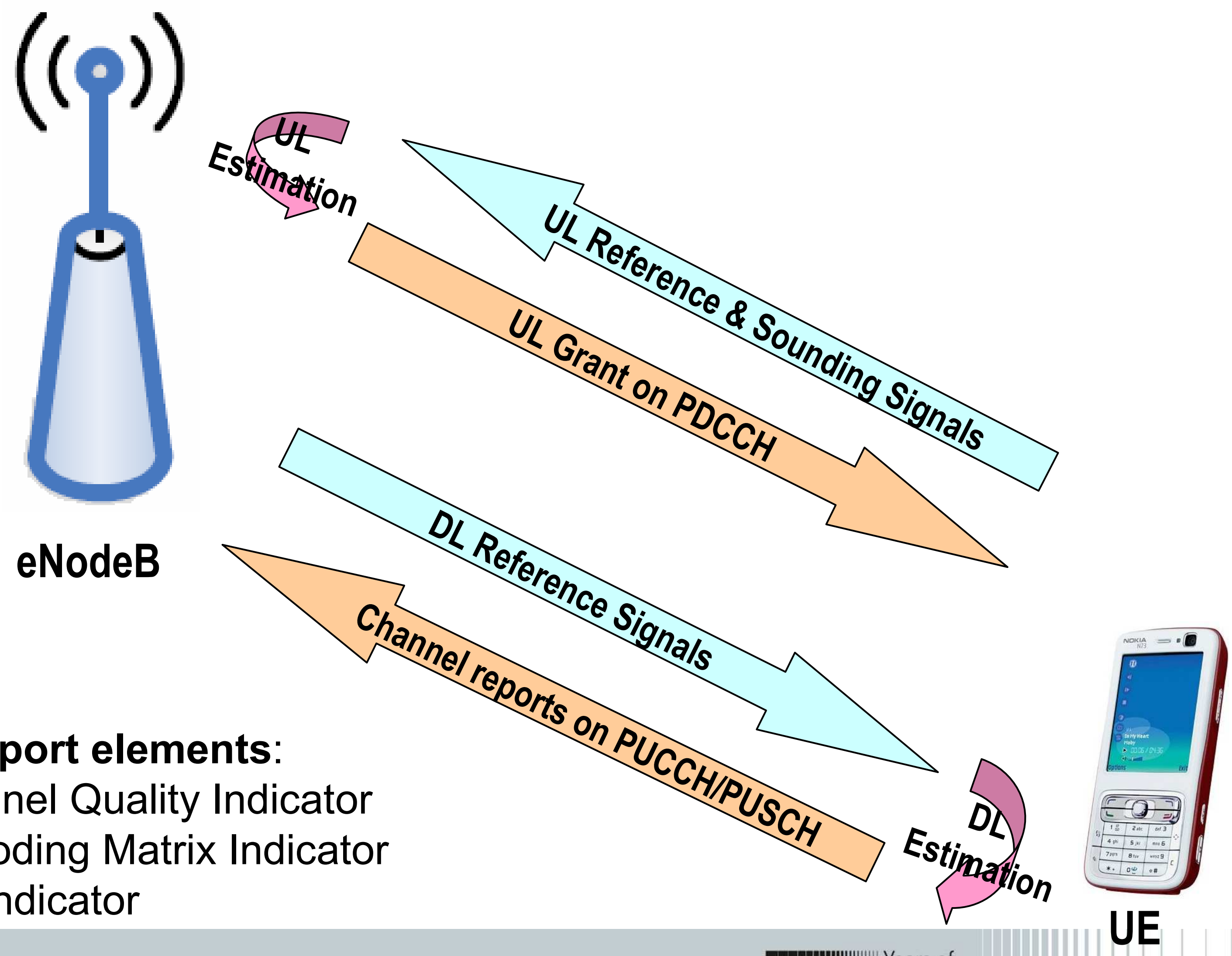
For MIMO Split into Several streams if needed

Weighting data streams for MIMO

1 OFDM symbol per stream

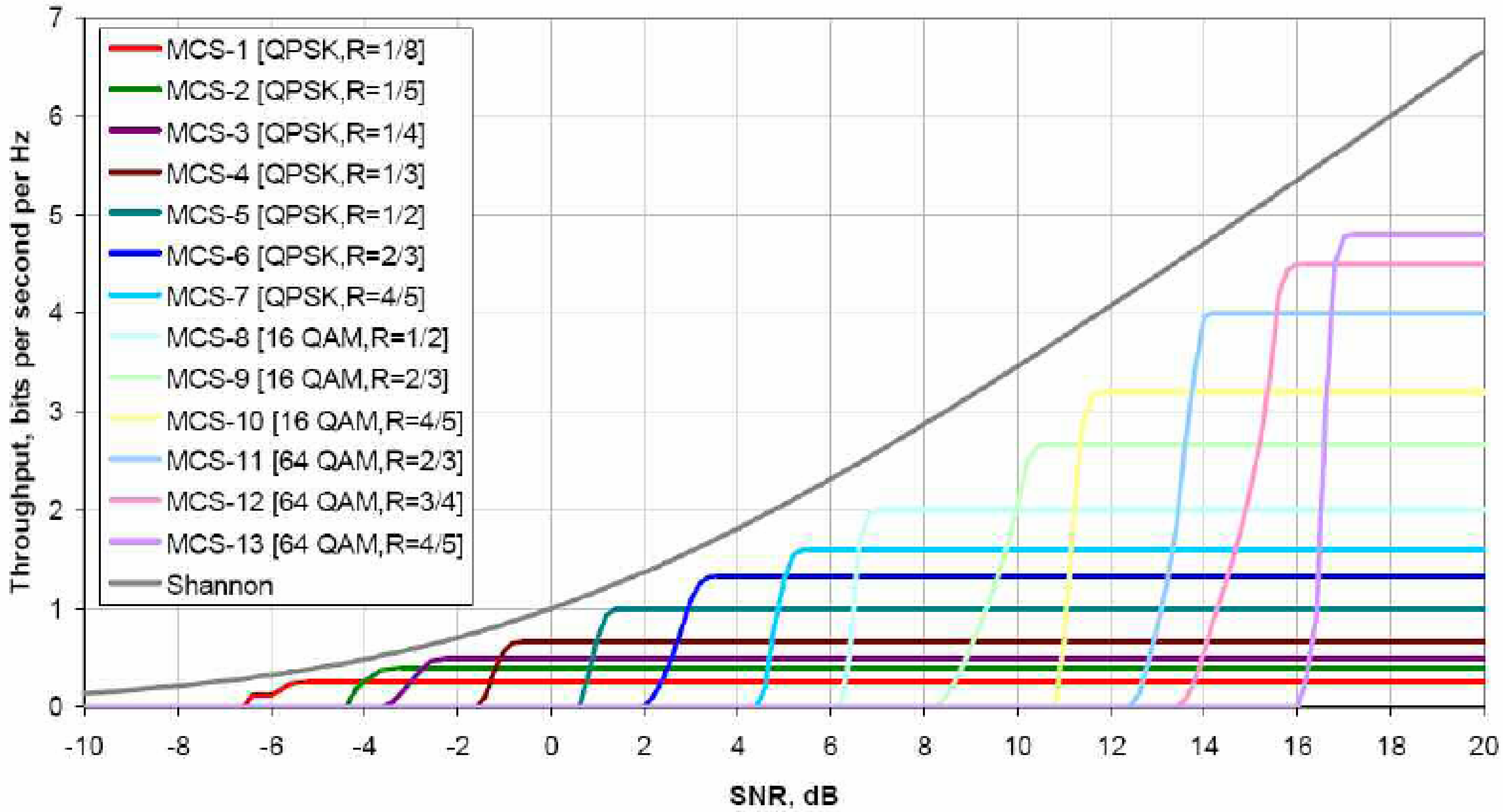
1 stream = several subcarriers, based on Physical ressource blocks

LTE Link Adaptation



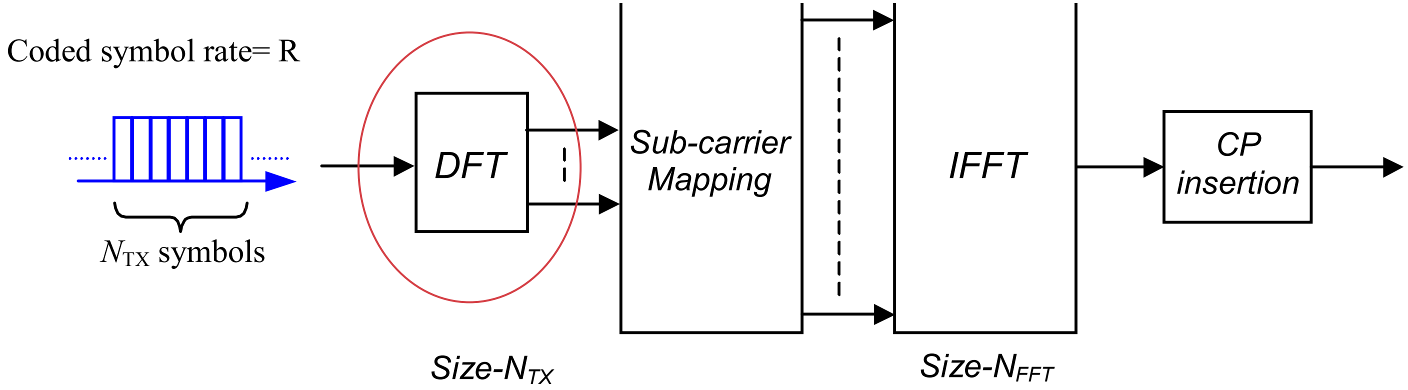
Channel report elements:
CQI – Channel Quality Indicator
PMI – Precoding Matrix Indicator
RI – Rank Indicator

Channel Coding Performance



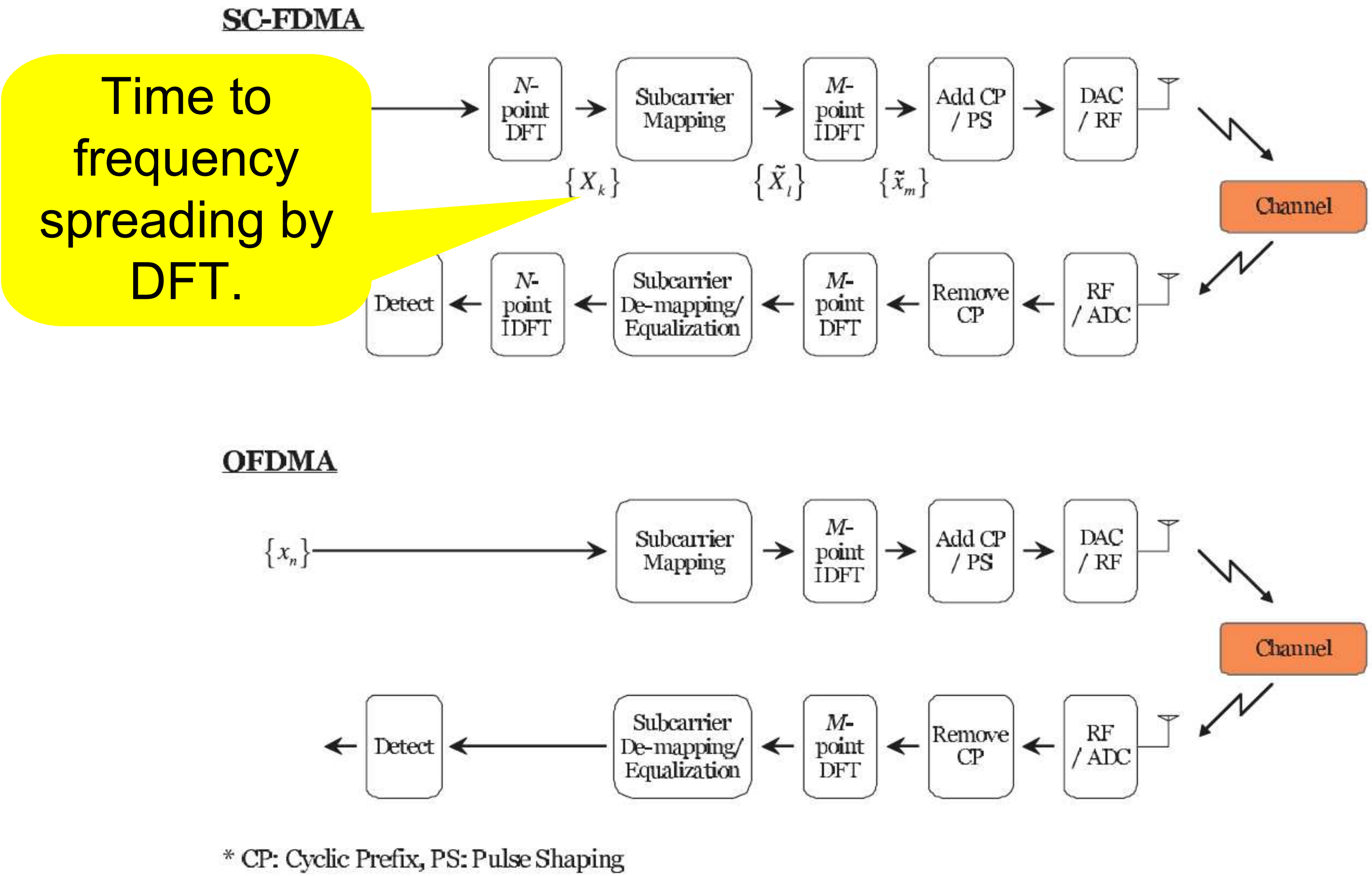
LTE Physical Layer:
SC-FDMA in uplink

LTE Uplink:
How to generate an SC-FDMA signal in theory?



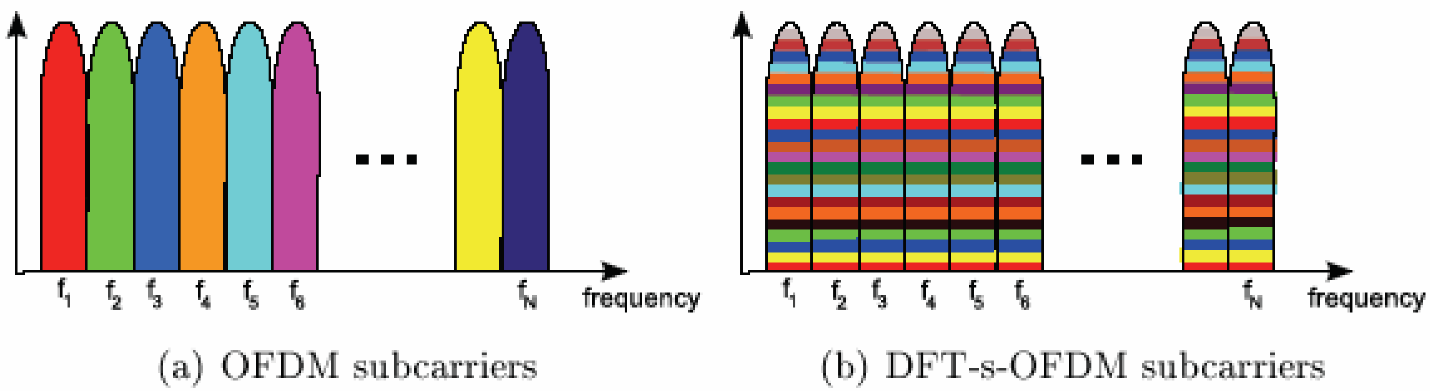
- LTE provides QPSK,16QAM, and 64QAM as uplink modulation schemes
- DFT is first applied to block of N_{TX} modulated data symbols to transform them into frequency domain
- Sub-carrier mapping allows flexible allocation of signal to available sub-carriers
- IFFT and cyclic prefix (CP) insertion as in OFDM
- Each subcarrier carries a portion of superposed DFT spread data symbols
- Can also be seen as "**pre-coded OFDM**" or "**DFT-spread OFDM**"

SC-FDMA and OFDMA - differences



LTE Uplink:
How does the SC-FDMA signal look like?

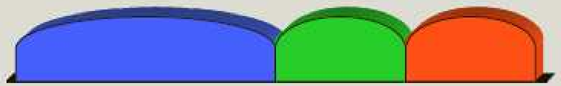
- In principle similar to OFDMA, **BUT**:
  - In OFDMA, each sub-carrier only carries information related to **one specific symbol**
  - In SC-FDMA, each sub-carrier contains information of **ALL** transmitted symbols



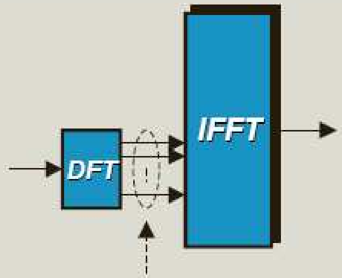
Localized versus Distributed FDMA

We have seen that DFT will distribute the time signal over the frequency. Next question that arises is: how is that distribution done: localized or distributed?

Localized FDMA



- Each user transmission localized in the frequency domain
- Low-PAPR by single-carrier transmisssion
- Flexible transmission bandwidth
- Channel-dependent scheduling in frequency domain

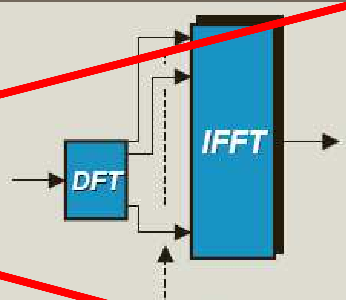


Consecutive spectrum

Not used in LTE

Distributed FDMA

- Each user distributed in the frequency domain
- Low PAPR by means of IFDMA ("single carrier")
- Flexible number of "sub-carriers" (different IFDMA repetition factors)
- Frequency diversity
- Sensitive to frequency errors, user synchronization required



Distributed spectrum

SC-FDMA Peak to average

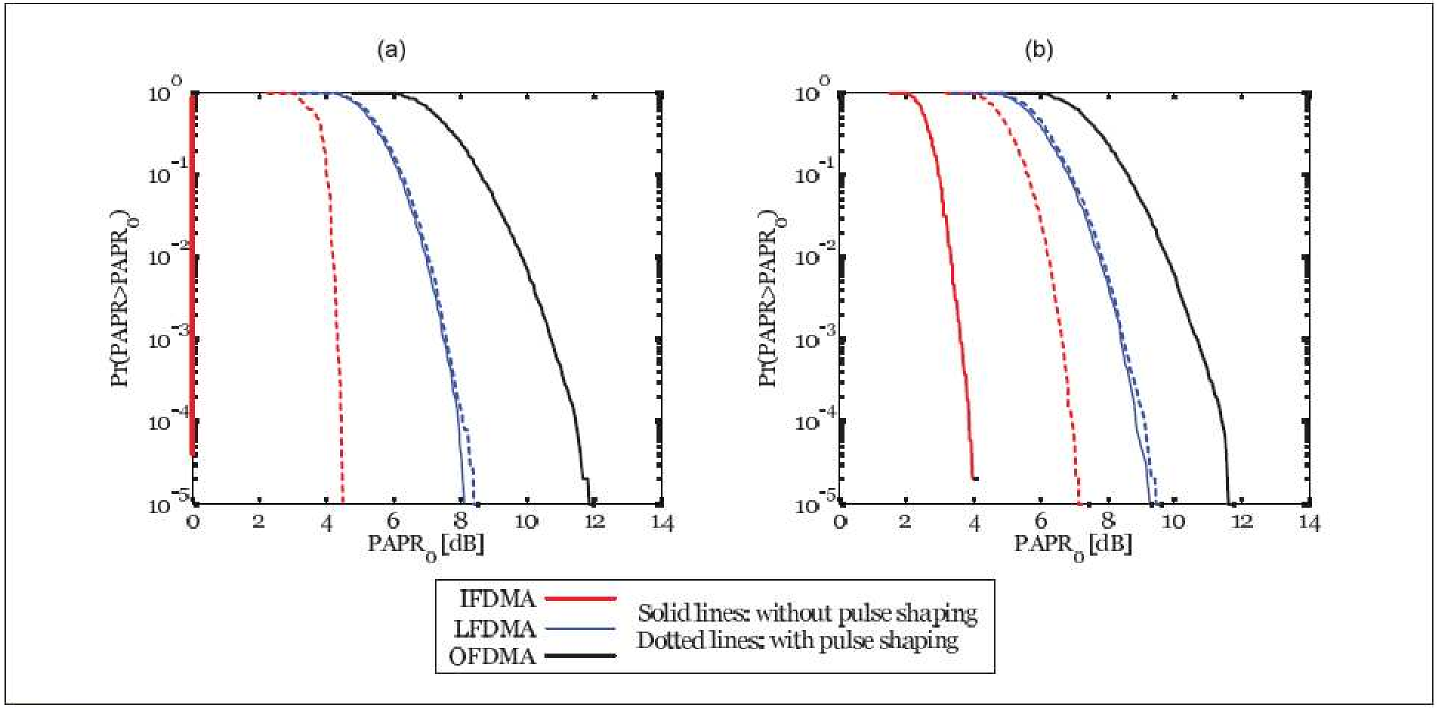
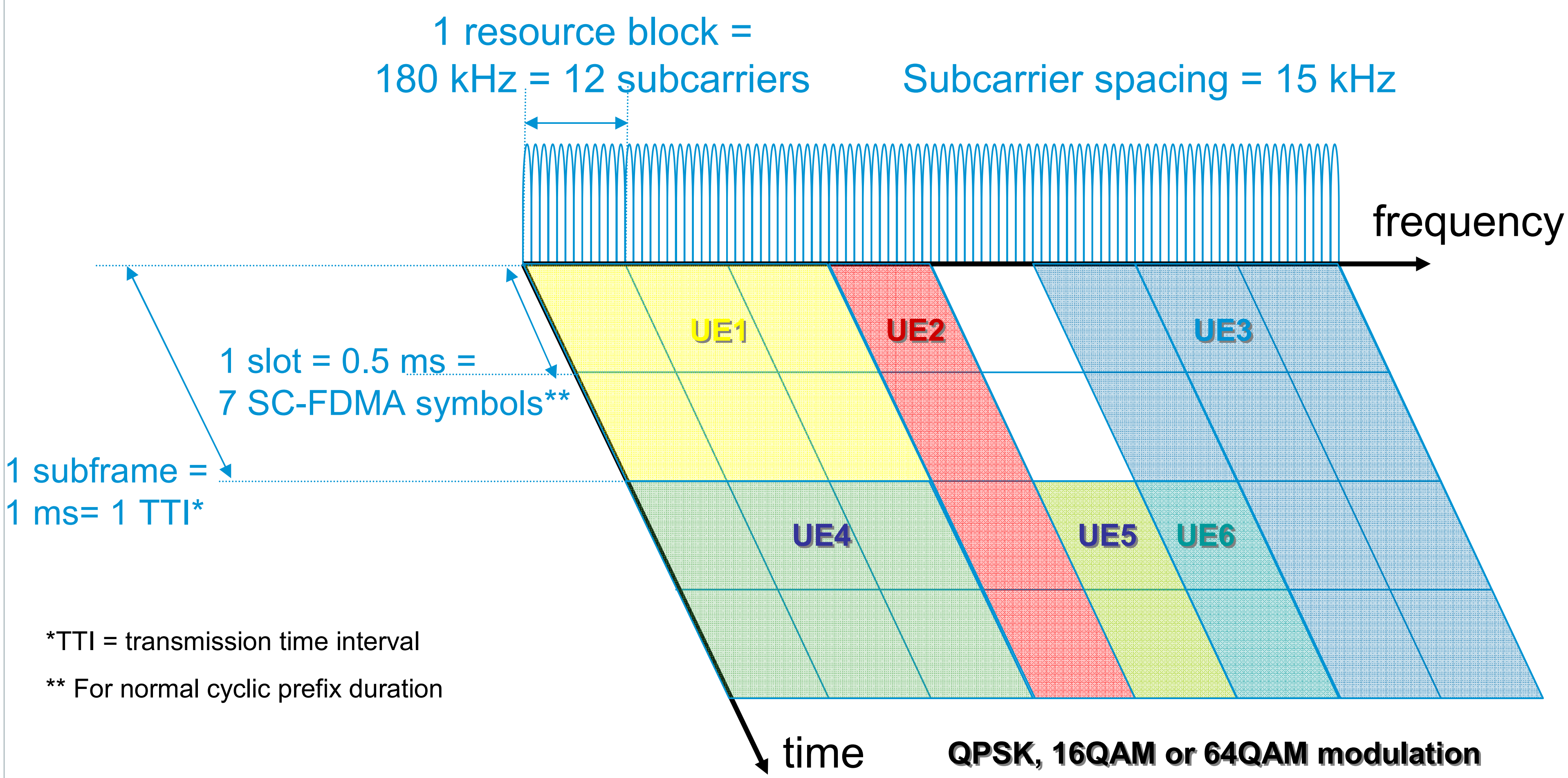


FIGURE 5 Comparison of CCDF of PAPR for IFDMA, LFDMA, and OFDMA with $M = 256$ system subcarriers, $N = 64$ subcarriers per user, and a = 0.5 rolloff factor; (a) QPSK; (b) 16-QAM.

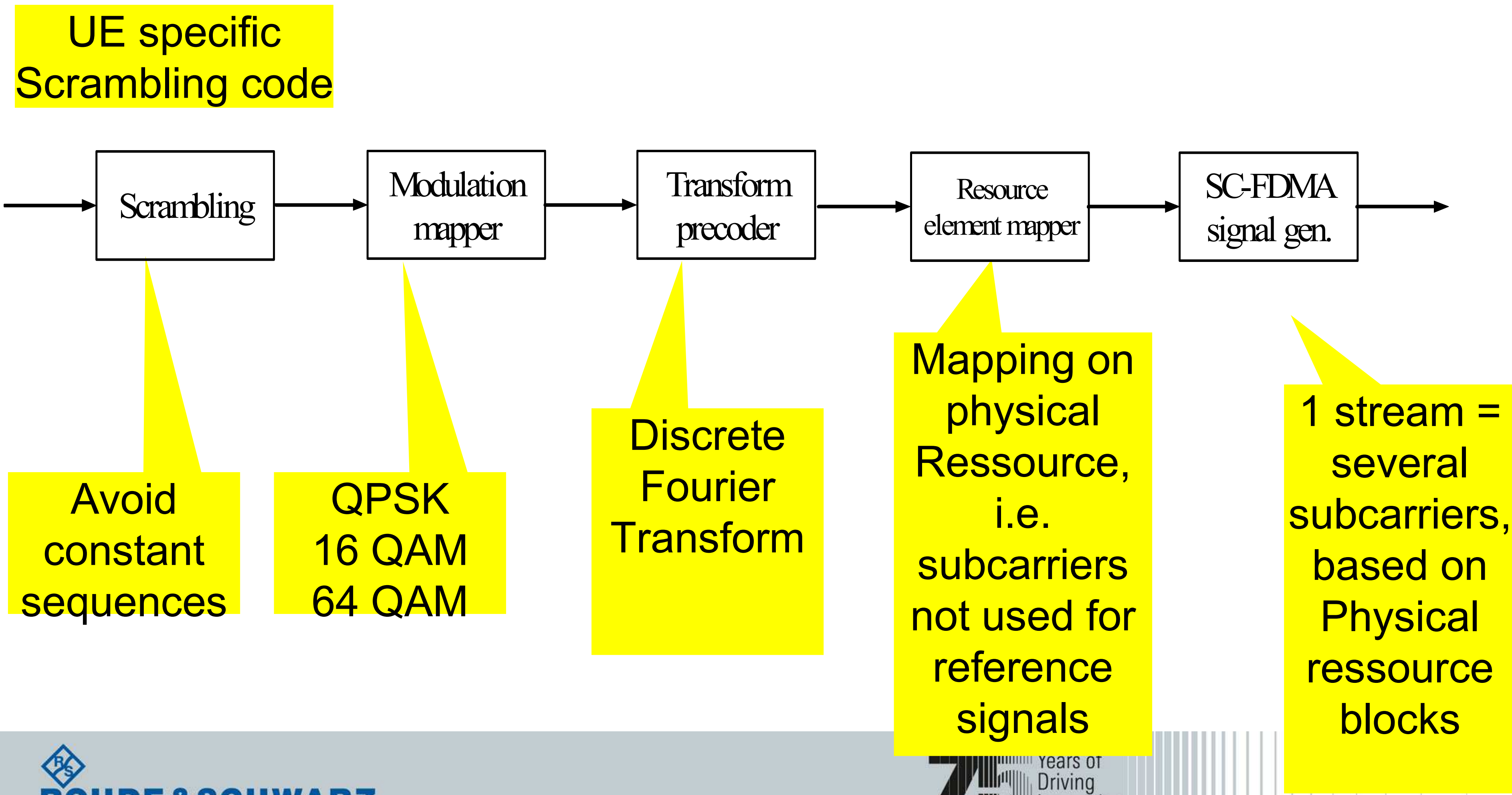
LTE uplink
SC-FDMA time-frequency multiplexing



*TTI = transmission time interval

** For normal cyclic prefix duration

LTE Uplink: baseband signal generation



LTE Uplink: Physical Channels in uplink

- Physical Uplink Shared Channel, PUSCH
- - Physical Uplink Control Channel, PUCCH
- - Physical Random Access Channel, PRACH

Uplink Control Channel (PUCCH)

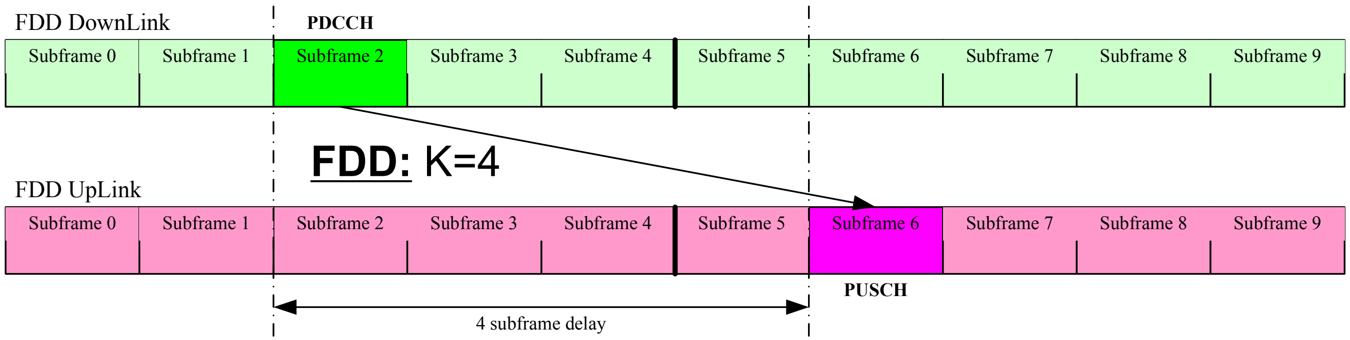
- Carries Uplink Control Information (UCI) when no PDSCH is transmitted
- **TDD:** PUCCH is not transmitted in subframes containing the UpPTS field

PUCCH format	Bits per subframe	Contents
1	On/Off	Scheduling Request (SR)
1a	1	ACK/NACK, ACK/NACK+SR
1b	2	ACK/NACK, ACK/NACK+SR
2	20	CQI/PMI or RI (any CP), (CQI/PMI or RI)+ACK/NACK (long CP only)
2a	21	(CQI/PMI or RI)+ACK/NACK (normal CP only)
2b	22	(CQI/PMI or RI)+ACK/NACK (normal CP only)

- Channel quality reporting comprises Channel Quality Indicator (CQI), Precoding Matrix Indicator (PMI) and Rank Indicator (RI)
- CQI/PMI/RI are only signaled via PUCCH when periodic reporting is requested. Scheduled/aperiodic reporting is only done via PUSCH

PUSCH and PDCCH Timing Relation

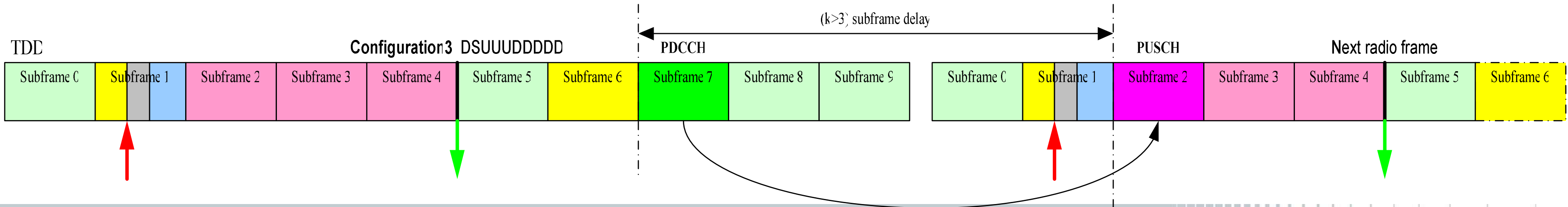
Upon detection of a PDCCH with DCI format 0 and/or a PHICH transmission in sub-frame n intended for the UE, PUSCH is sent in subframe n+K



TDD: PUSCH timing relation depends on TDD frame configuration

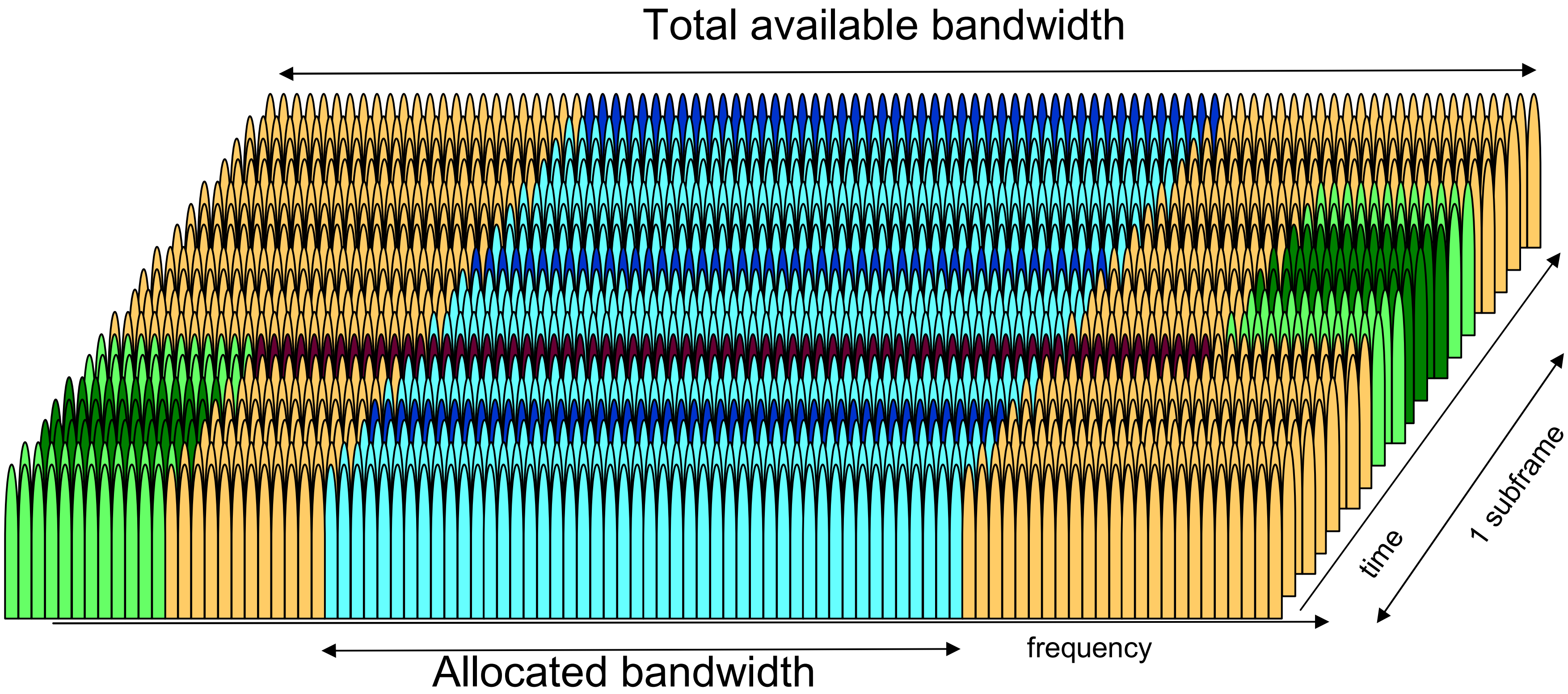
TDD UL/DL Configuration	Delay K for DL subframe number *n*									
	0	1	2	3	4	5	6	7	8	9
0	4(*)	6(*)				4(*)	6(*)			
1		6			4		6			4
2				4					4	
3	4								4	4
4									4	4
5									4	
6	7	7				7	7			5

(*): 7 depending on „UL Index“ signaled in DCI format 0



LTE Uplink: channel mapping example

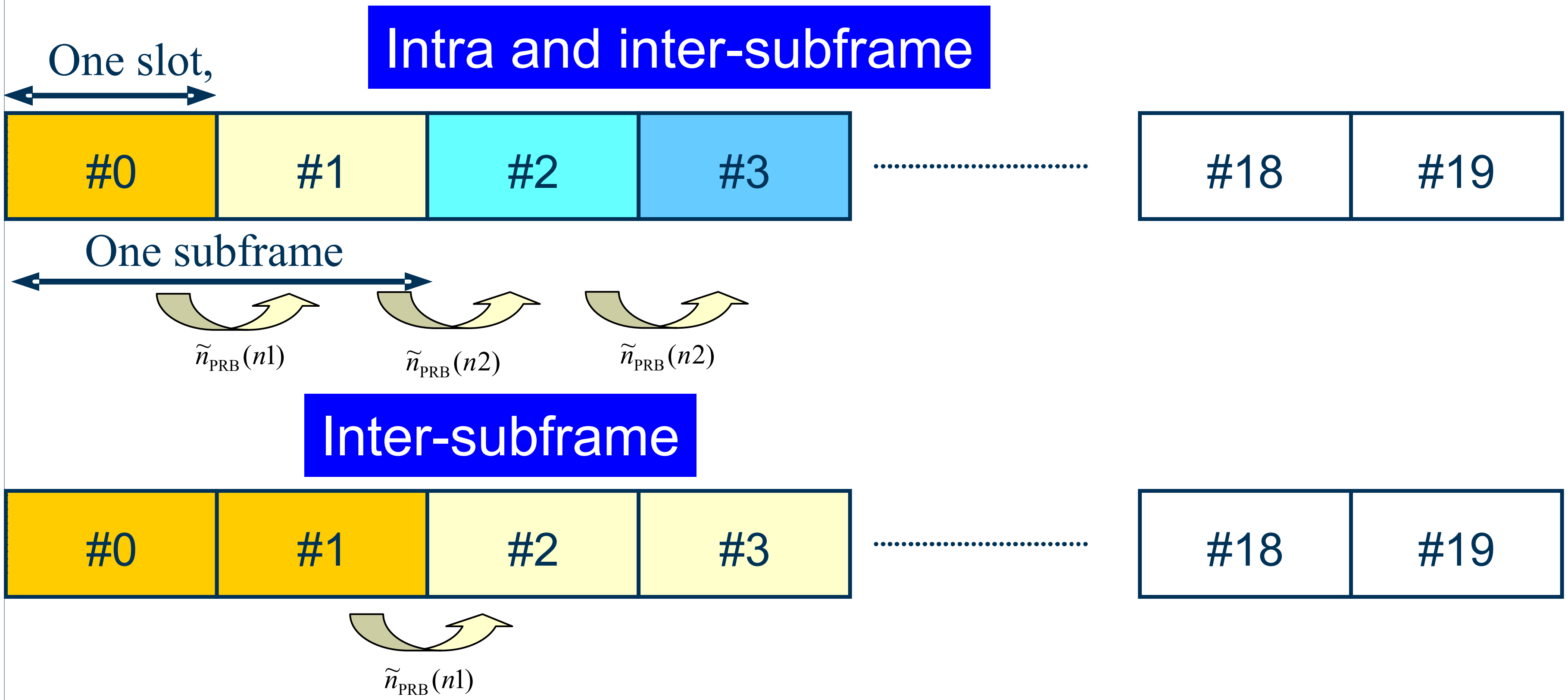
- Unscheduled Resource Blocks
- Scheduled Resource Blocks
- Demodulation Reference Signal PUSCH
- Sounding Reference Signal
- Scheduled PUCCH
- Demodulation Reference Signal PUCCH



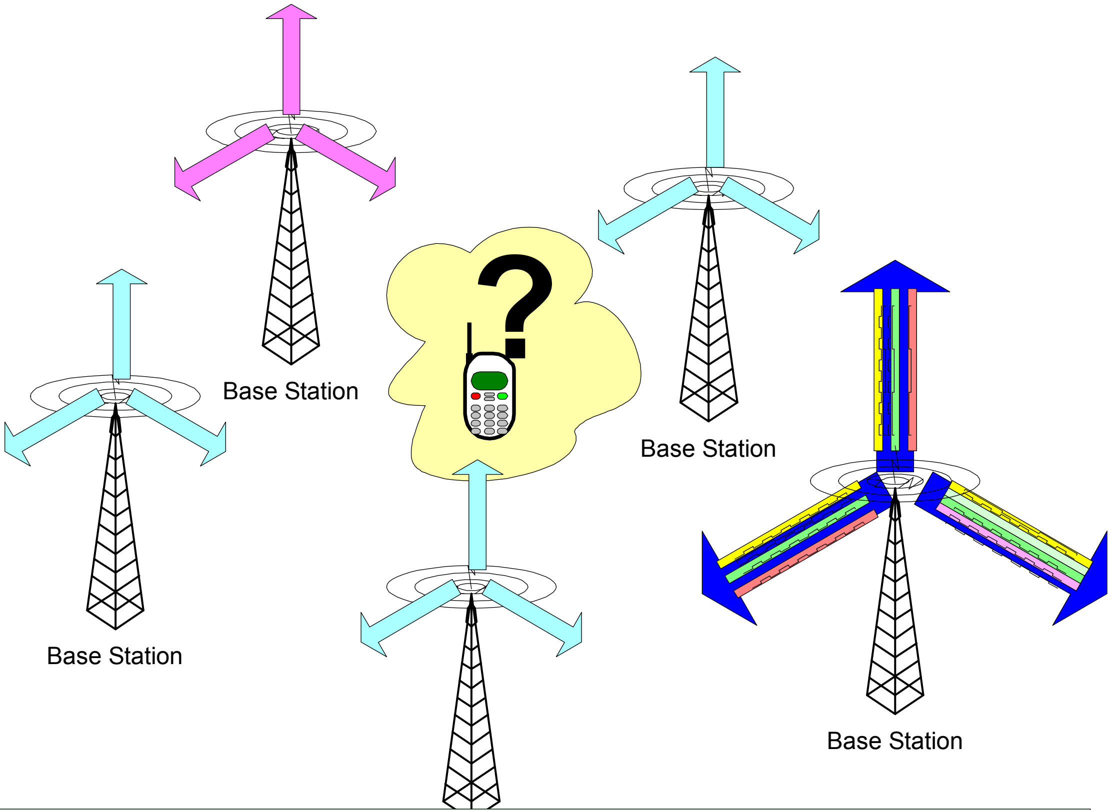
Frequency Hopping for PUSCH

2 hopping types: type 2 = predefined hopping pattern,
type 1 = depends on start RB + hopping index

2 hopping modes: inter-subframe or intra and inter-subframe



LTE Initial Access



What does the mobile need to know?

1) Strongest base station
2) Slot and Frame timing
3) Physical layer cell identity
4) Channel bandwidth
5) BCCH information

LTE cell acquisition process

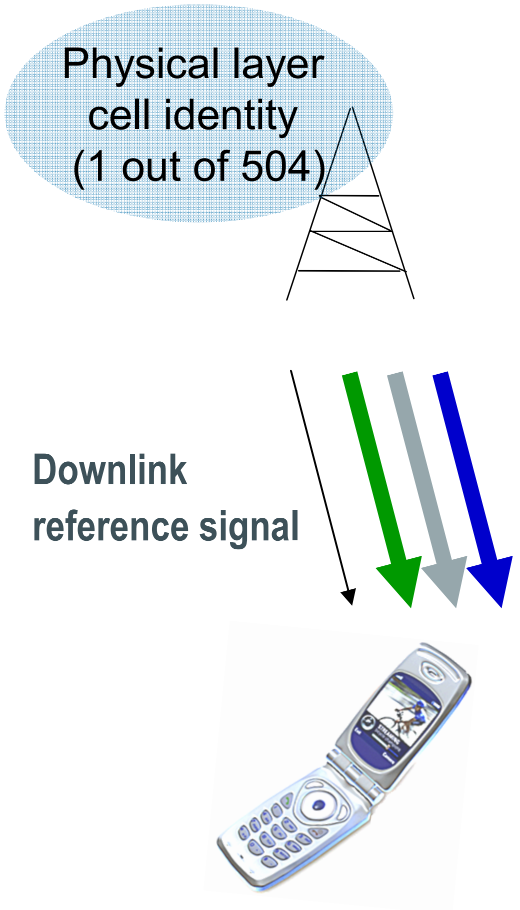
- 1. carrier frequency detection
- 2. primary synchronisation signal - > 5msec timing and $N_{\mathrm{ID}}^{(2)}$
- 3. secondary synchronisation signal -> 10msec timing and $N_{\mathrm{ID}}^{(1)}$
- 4. Derive physical layer cell identity out of PSS and SSS
- 5. Blind detect cyclic prefix duration (extended or normal) and slot boarder
- 6. Using cell identity and channel bandwidth for reference symbol detection
- 7. PBCH detection, reading Master information block
- 8. MIB -> channel bandwidth and system frame number
- 9. PCFICH detection -> PDCCH -> SI-RNTI
- 10. PDCCH -> PDSCH -> SIB1
- 11. SIB1 scheduling information to acquire all other SIBs
- 12. Reading necessary SIB information

LTE cell search – carrier frequency

UE scans all frequency bands according to its capabilities to find carrier frequency of the cell. No priorisation between bands, optionally USIM information will give priority

E-UTRA Band	Uplink (UL) BS receive UE transmit F_{UL_low} – F_{UL_high}			Downlink (DL) BS transmit UE receive F_{DL_low} – F_{DL_high}			Duplex Mode
1	1920 MHz	–	1980 MHz	2110 MHz	–	2170 MHz	FDD
2	1850 MHz	–	1910 MHz	1930 MHz	–	1990 MHz	FDD
3	1710 MHz	–	1785 MHz	1805 MHz	–	1880 MHz	FDD
4	1710 MHz	–	1755 MHz	2110 MHz	–	2155 MHz	FDD
5	824 MHz	–	849 MHz	869 MHz	–	894MHz	FDD
6	830 MHz	–	840 MHz	875 MHz	–	885 MHz	FDD
7	2500 MHz	–	2570 MHz	2620 MHz	–	2690 MHz	FDD
8	880 MHz	–	915 MHz	925 MHz	–	960 MHz	FDD
9	1749.9 MHz	–	1784.9 MHz	1844.9 MHz	–	1879.9 MHz	FDD
10	1710 MHz	–	1770 MHz	2110 MHz	–	2170 MHz	FDD
11	1427.9 MHz	–	1452.9 MHz	1475.9 MHz	–	1500.9 MHz	FDD
12	698 MHz	–	716 MHz	728 MHz	–	746 MHz	FDD
13	777 MHz	–	787 MHz	746 MHz	–	756 MHz	FDD
14	788 MHz	–	798 MHz	758 MHz	–	768 MHz	FDD
...							
17	704 MHz	–	716 MHz	734 MHz	–	746 MHz	FDD
...							
33	1900 MHz	–	1920 MHz	1900 MHz	–	1920 MHz	TDD
34	2010 MHz	–	2025 MHz	2010 MHz	–	2025 MHz	TDD
35	1850 MHz	–	1910 MHz	1850 MHz	–	1910 MHz	TDD
36	1930 MHz	–	1990 MHz	1930 MHz	–	1990 MHz	TDD
37	1910 MHz	–	1930 MHz	1910 MHz	–	1930 MHz	TDD
38	2570 MHz	–	2620 MHz	2570 MHz	–	2620 MHz	TDD
39	1880 MHz	–	1920 MHz	1880 MHz	–	1920 MHz	TDD
40	2300 MHz	–	2400 MHz	2300 MHz	–	2400 MHz	TDD

LTE Downlink
Cell search procedure - hierarchy

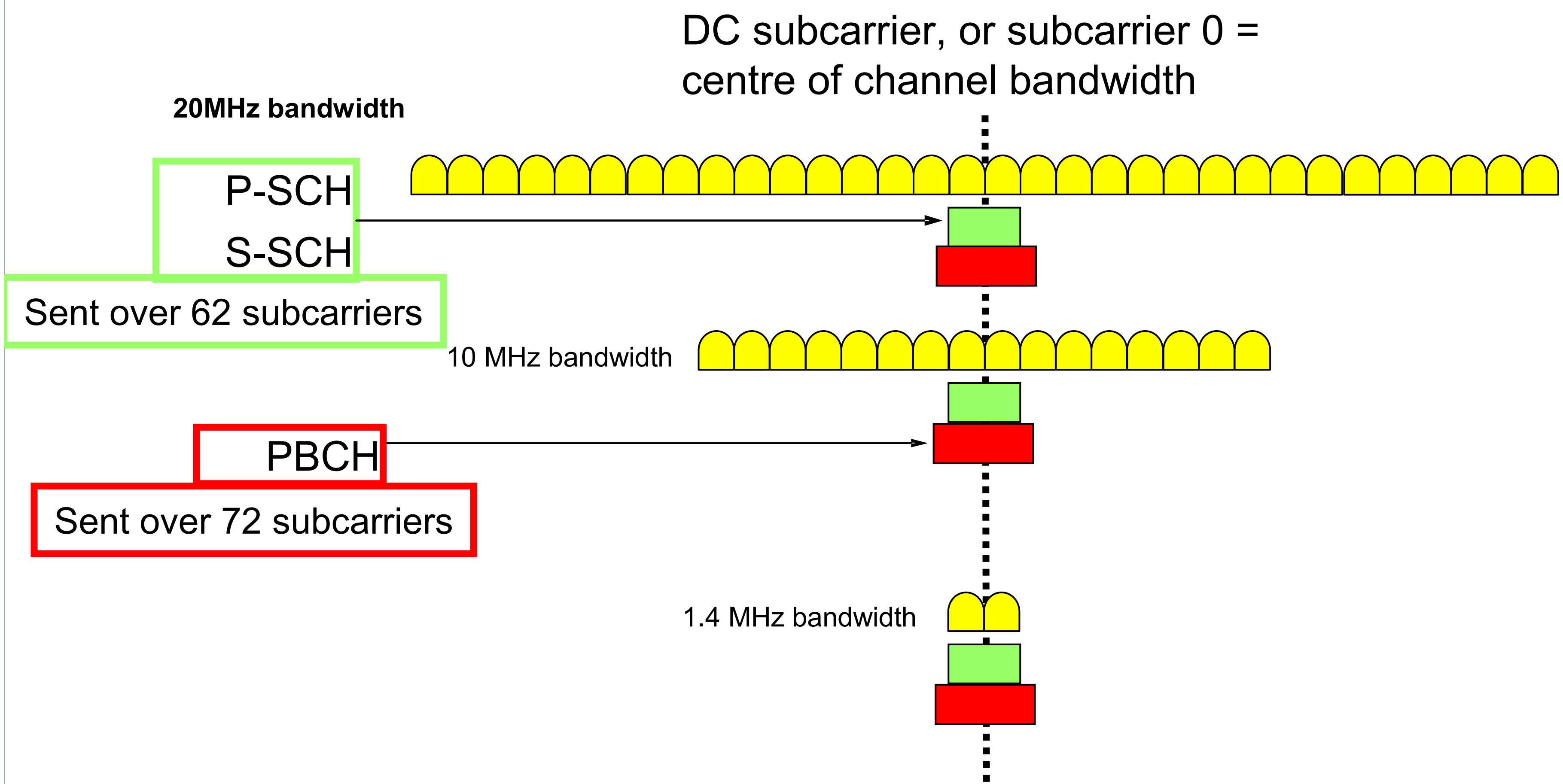


1. **Primary synchronization signal:**
   3 possible sequences to identify the cell's physical layer identity (0, 1, 2)
   Transmitted every 5 ms to identify 5 ms timing

2. **Secondary synchronization signal:**
   168 different sequences to identify physical layer cell identity group
   Transmitted every 5 ms to identify radio frame timing

3. **Physical broadcast channel (PBCH):**
   Carrying broadcast channel with predefined information:
   system bandwidth, number of transmit antennas, reference signal transmit power, system frame number,…

Initial synchronization
BCH and SCH always located at the center

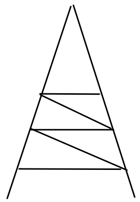


LTE downlink
Hierarchical cell search scheme

Physical layer cell identity

$$N_{\mathrm{ID}}^{\mathrm{cell}} = 3N_{\mathrm{ID}}^{(1)} + N_{\mathrm{ID}}^{(2)}$$

Physical layer cell identity (1 out of 504)



identified by:

Physical layer cell identity group 0 1 ………….. 167

Physical layer identity 0 1 2 0 1 2 0 1 2

LTE cell search scheme

Physical layer
cell identity
$N_{ID}^{cell} = 3N_{ID}^{(1)} + N_{ID}^{(2)}$
=[0..503]

Physical layer cell identity group

Identified by

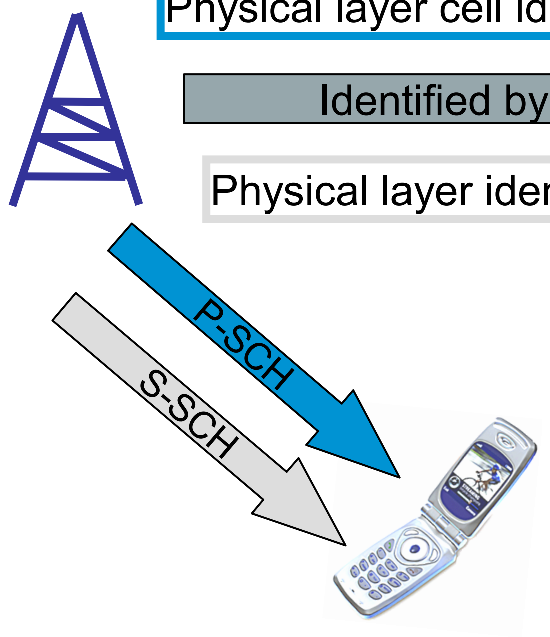
Physical layer identity

„Smith“ 0 — 0 1 2 („Peter“ „Bob“ „John“)

„Miller“ 1 — 0 1 2 („Peter“ „Bob“ „John“)

……………

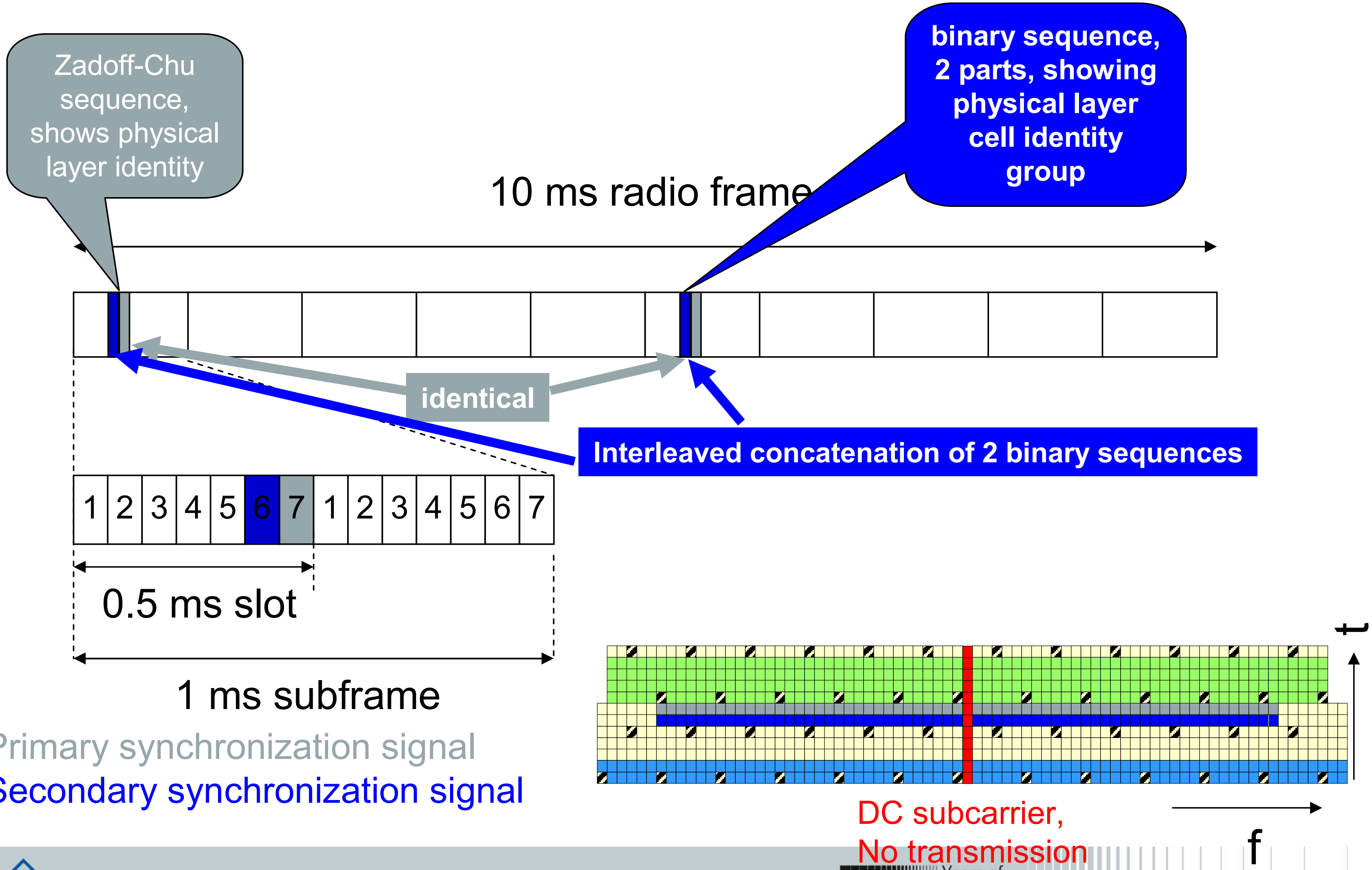
„Kennedy“ 167 — 0 1 2 („Peter“ „Bob“ „John“)



Primary Sync Channel P-SCH: 3 possible sequences to identify physical layer identity $N_{ID}^{(2)}$ = 0,1,2

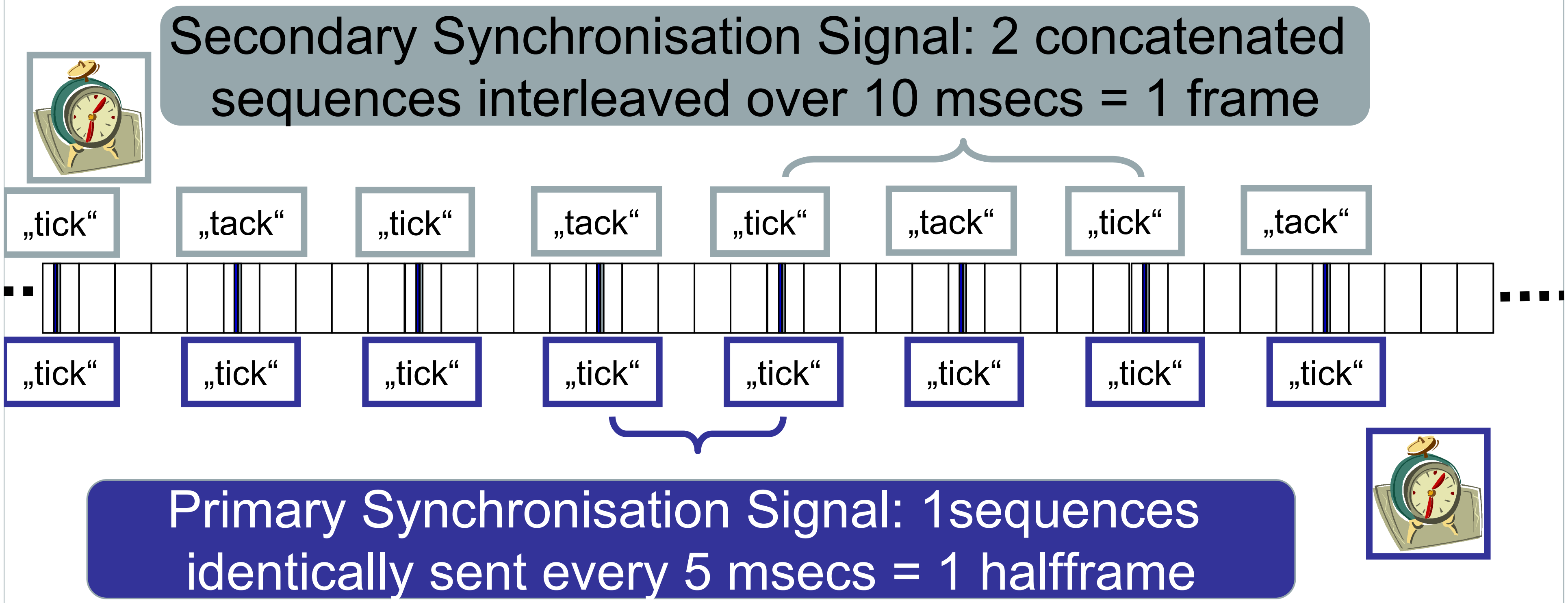
Secondary Sync Channel S-SCH: 168 possible sequences to identify physical layer cell identity group $N_{ID}^{(1)}$ = 0..167

LTE Downlink: P-SCH and S-SCH

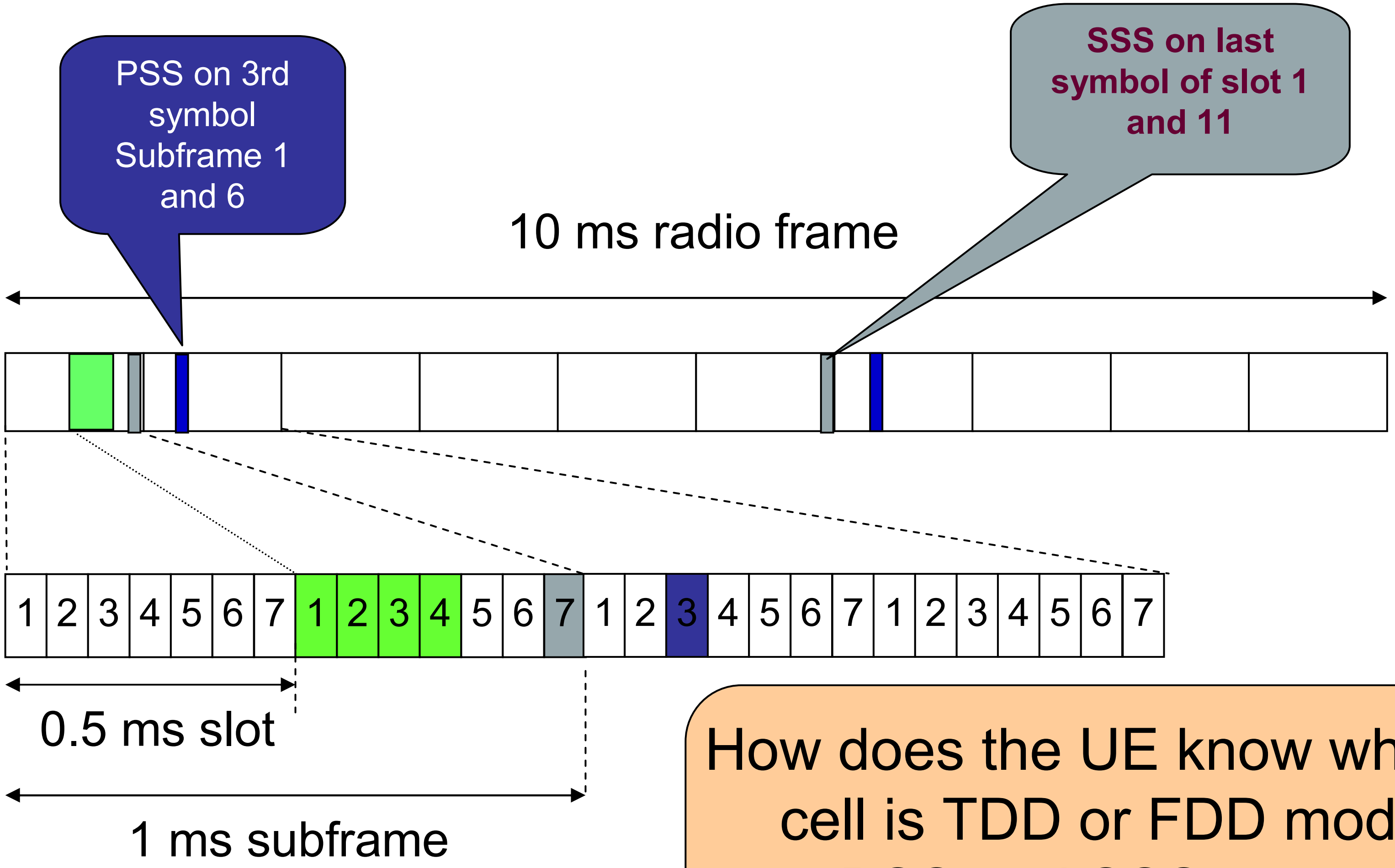


Primary synchronization signal
Secondary synchronization signal

LTE timing due to PSS and SSS



LTE TDD: PSS and SSS position



PSS Primary synchronization signal

SSS Secondary synchronization signal

How does the UE know whether cell is TDD or FDD mode?
PSS and SSS are on different positions!

Primary Synchronisation Signal PSS

- Primary synchronisation signal is a CAZAC sequence, constant amplitude, zero autocorrelation
- Shows good autocorrelation(the 3 selected root indices show best correlation results)
- Has good peak to average power ratio, PAPR
- based on Zadoff-Zhu sequence, sequence $d_u(n)$ given as

$$d_u(n) = \begin{cases} e^{-j\frac{\pi u n(n+1)}{63}} & n = 0,1,\ldots,30 \\ e^{-j\frac{\pi u (n+1)(n+2)}{63}} & n = 31,32,\ldots,61 \end{cases}$$

$N_{\mathrm{ID}}^{(2)}$	Root index u
0	25
1	29
2	34

- Mapping onto physical ressources: 62 subcarriers around DC subcarrier

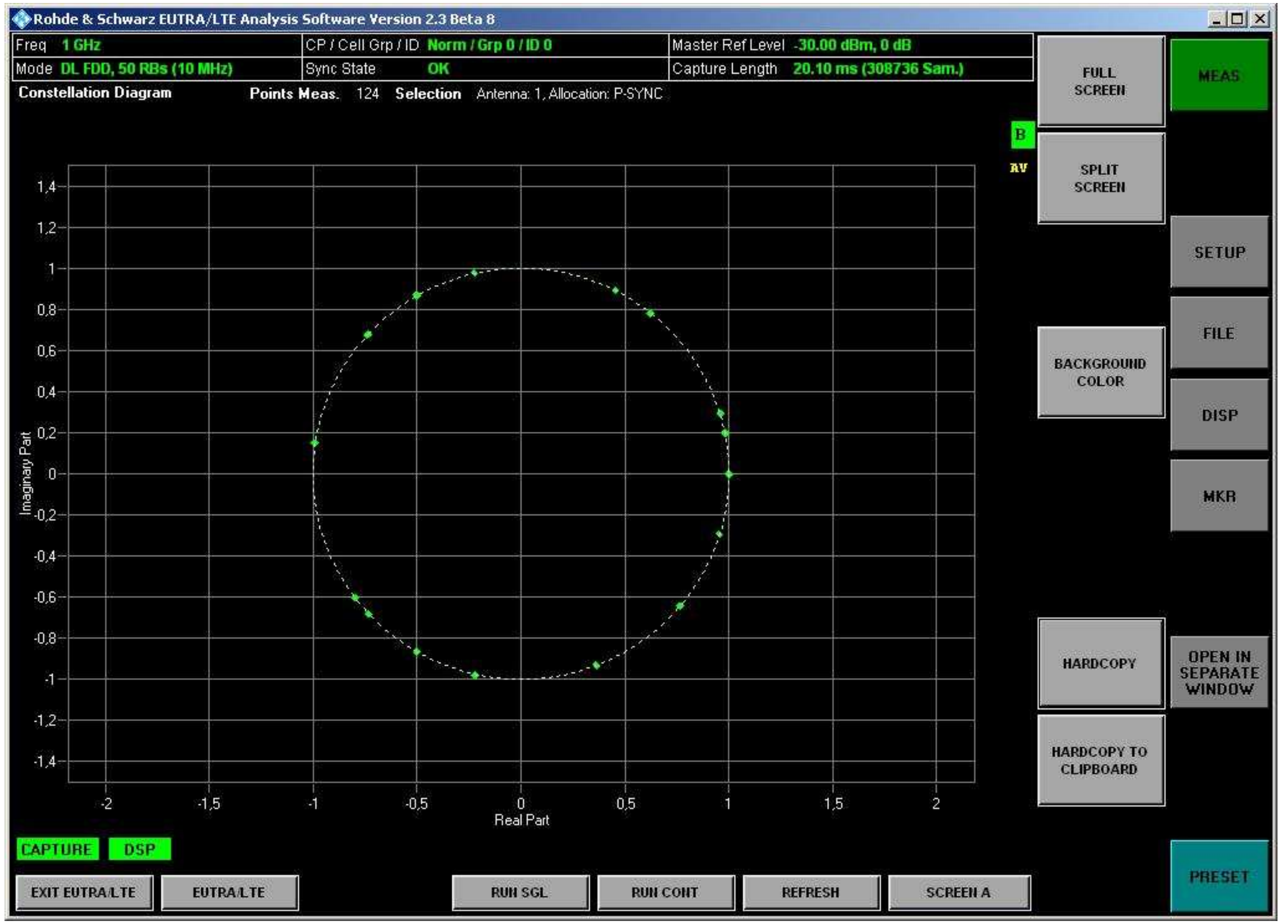
$$a_{k,l} = d(n), \qquad n = 0,\ldots,61$$

$$k = n - 31 + \frac{N_{\mathrm{RB}}^{\mathrm{DL}} N_{\mathrm{sc}}^{\mathrm{RB}}}{2}$$

Alleviates search,
UE can use
size 64 FFT window

Primary Synchronisation Signal PSS

$$\boxed{N_{\mathrm{ID}}^{(2)} = 0}$$



Secondary Synchronisation Signal

- Interleaved concatenation of 2 length-31 binary sequences
- BPSK modulated
- Scrambled based on physical layer identity, derived from primary synchronisation signal PSS
- Identifies the physical layer cell identity group
- Transmitted on 62 subcarriers around the DC subcarrier

$$a_{k,l} = d(n), \qquad n = 0,\ldots,61$$

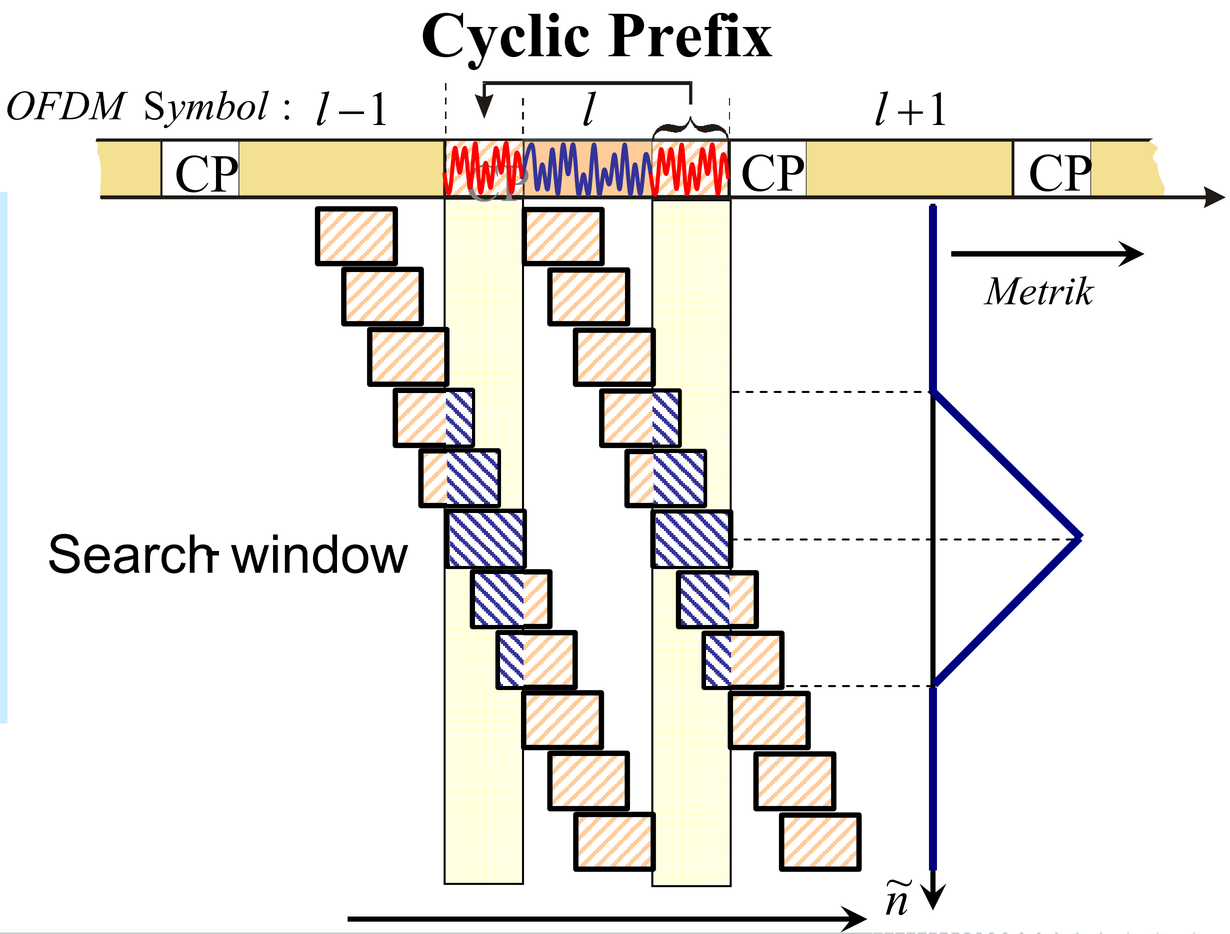
$$k = n - 31 + \frac{N_{\mathrm{RB}}^{\mathrm{DL}} N_{\mathrm{sc}}^{\mathrm{RB}}}{2}$$

$$l = \begin{cases} N_{\mathrm{symb}}^{\mathrm{DL}} - 2 & \text{in slots 0 and 10} \quad \text{for frame structure type 1} \\ N_{\mathrm{symb}}^{\mathrm{DL}} - 1 & \text{in slots 1 and 11} \quad \text{for frame structure type 2} \end{cases}$$

LTE timing slot and symbol duration

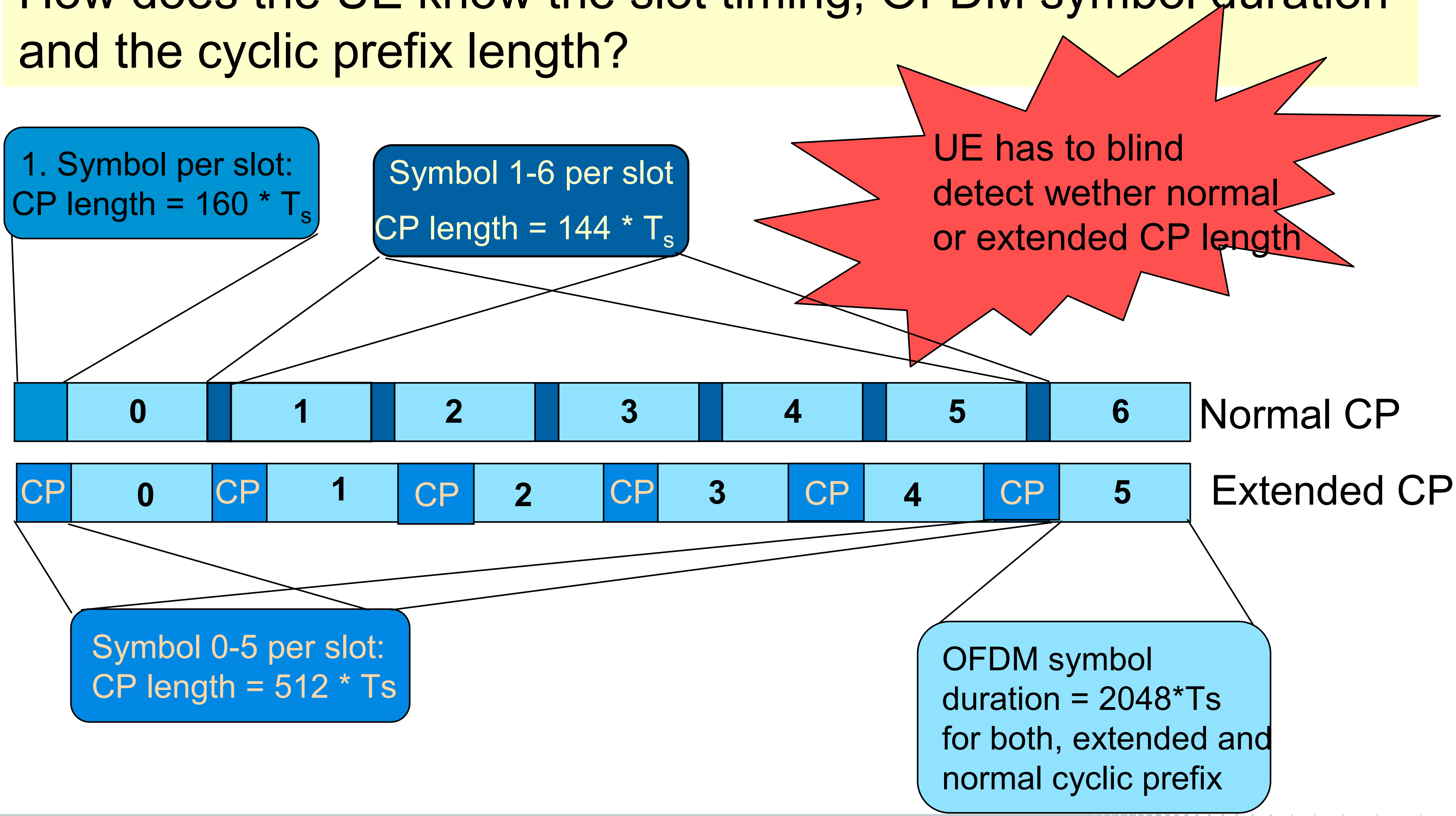
How does the UE know the slot timing, OFDM symbol duration and the cyclic prefix length?

Reminder:
OFDM uses principle of cyclic prefix.
UE can use search window to synchronise to the OFDM Symbol length



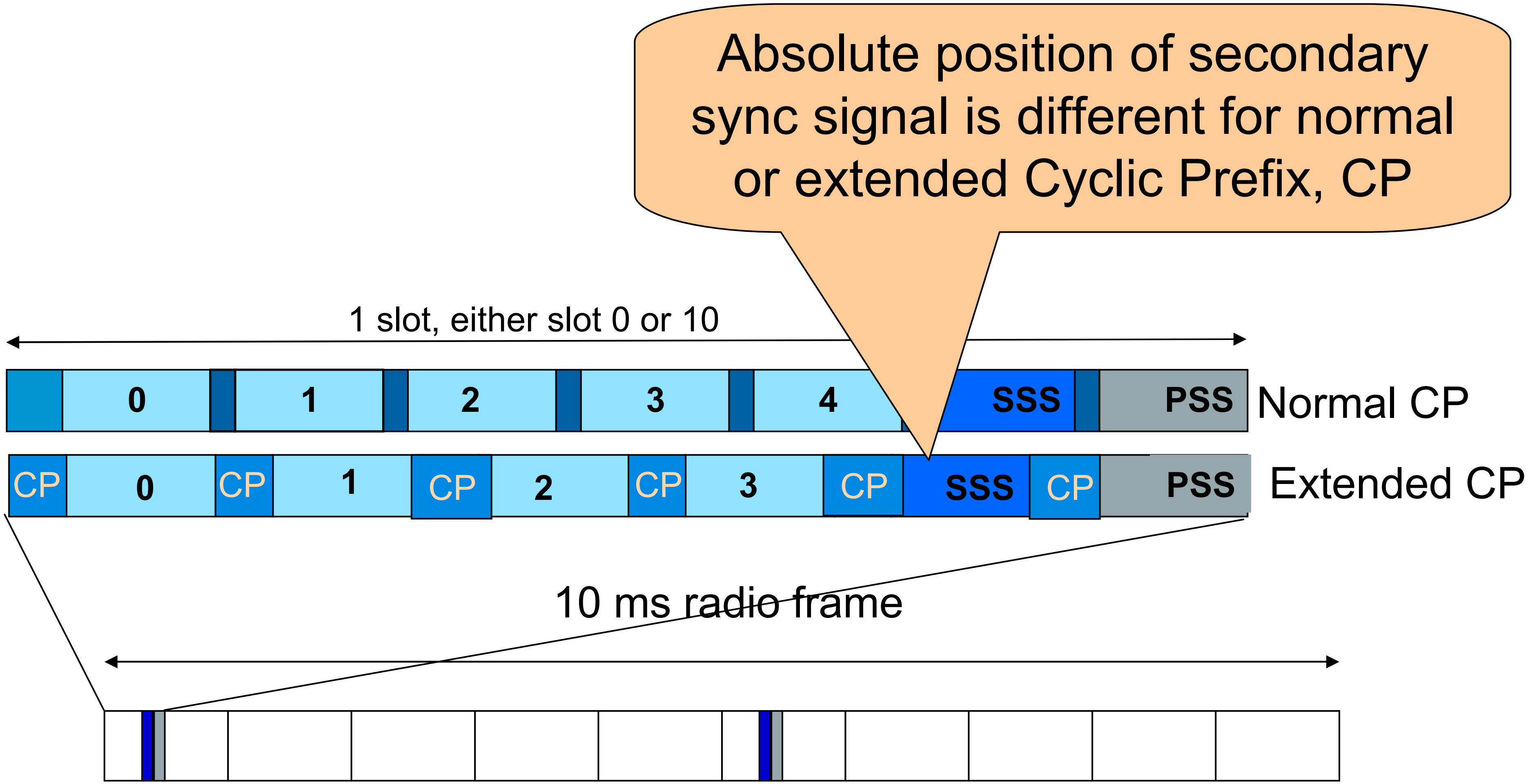
LTE timing + estimate slot and symbol duration

How does the UE know the slot timing, OFDM symbol duration and the cyclic prefix length?

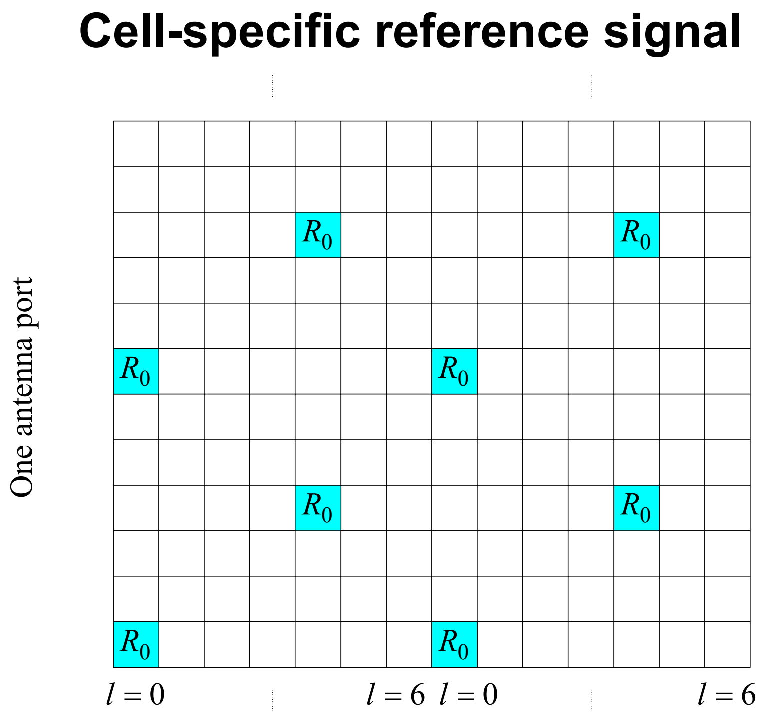


LTE timing + estimate slot and symbol duration

How does the UE know the cyclic prefix length?



Downlink Reference Signals



- <u>UE-specific reference signals</u>
  - UE capability mandatory for TDD and optional for FDD
  - Main intention is beamforming with UE-specific TX antenna settings
  - Transmitted in addition to the cell-specific reference

Cell specific reference signal

- **Reference signal sequence given as:**

$$r_{l,n_s}(m) = \frac{1}{\sqrt{2}}\left(1-2\cdot c(2m)\right)+j\frac{1}{\sqrt{2}}\left(1-2\cdot c(2m+1)\right), \quad m = 0,1,\ldots,2N_{\mathrm{RB}}^{\mathrm{max,DL}}-1$$

- **Based on length-31 Gold pseudo random sequence:**

$$c_{\mathrm{init}} = 2^{10}\cdot\left(7\cdot\left(n_s+1\right)+l+1\right)\cdot\left(2\cdot N_{ID}^{cell}+1\right)+2\cdot N_{ID}^{cell}+N_{CP}$$

Slot number within subframe

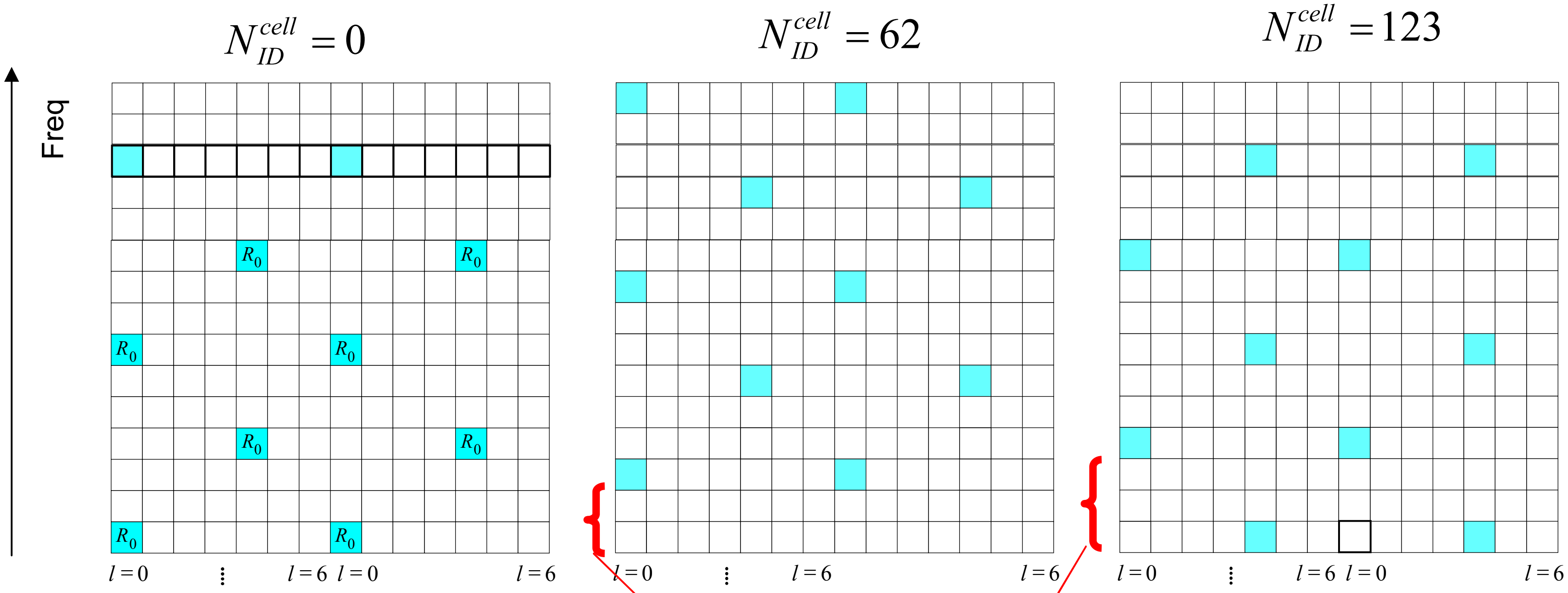
Physical layer cell identity

Cyclic prefix lenght

$$N_{CP} = \begin{cases} 1 & \text{for normal CP} \\ 0 & \text{for extended CP} \end{cases}$$

- **Mapped on frequency subcarriers as shown in graph. Frequency offset variable, depending on cell identity**

Cell specific reference signals

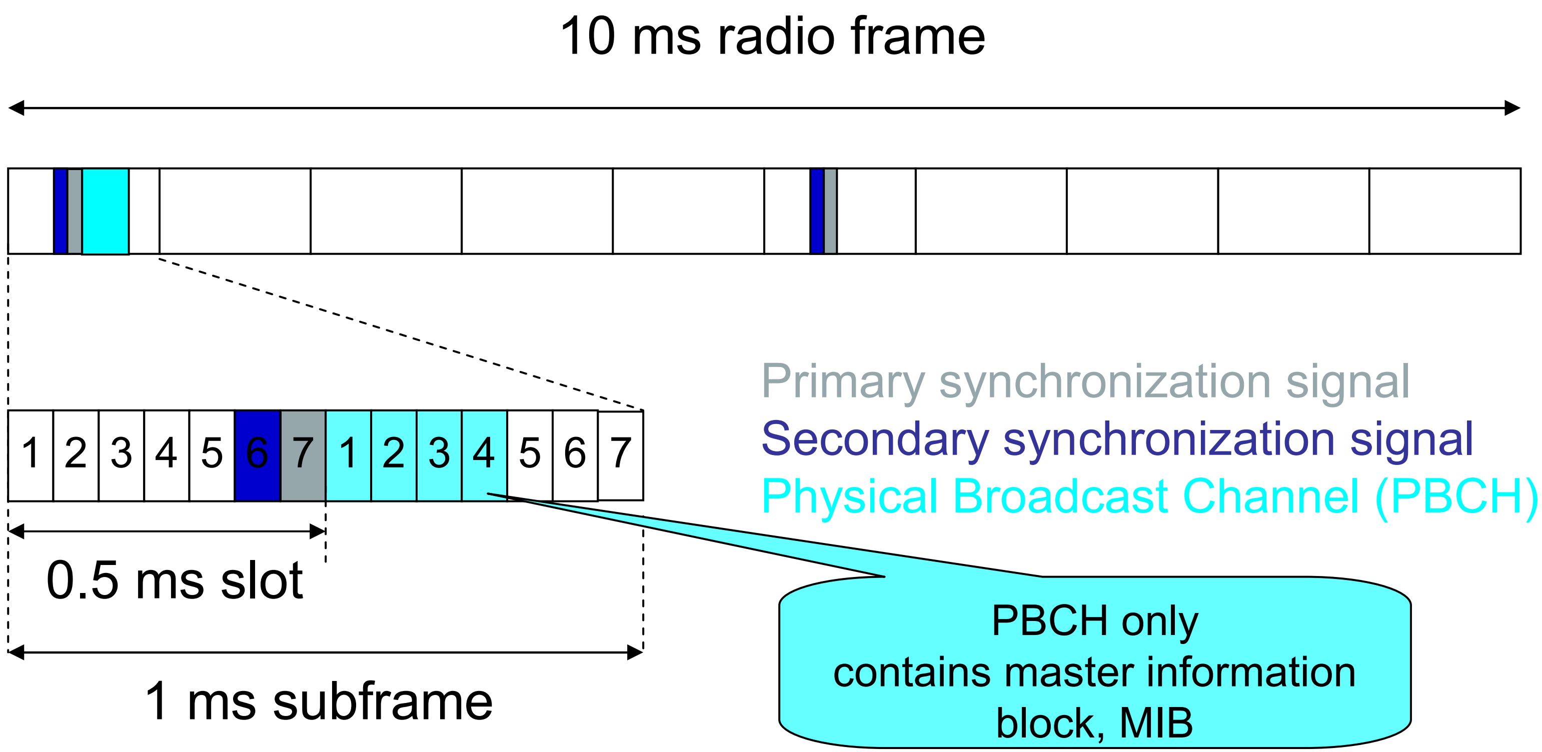


$$v_{\text{shift}} = N_{\text{ID}}^{\text{cell}} \bmod 6$$

Assume normal CP length

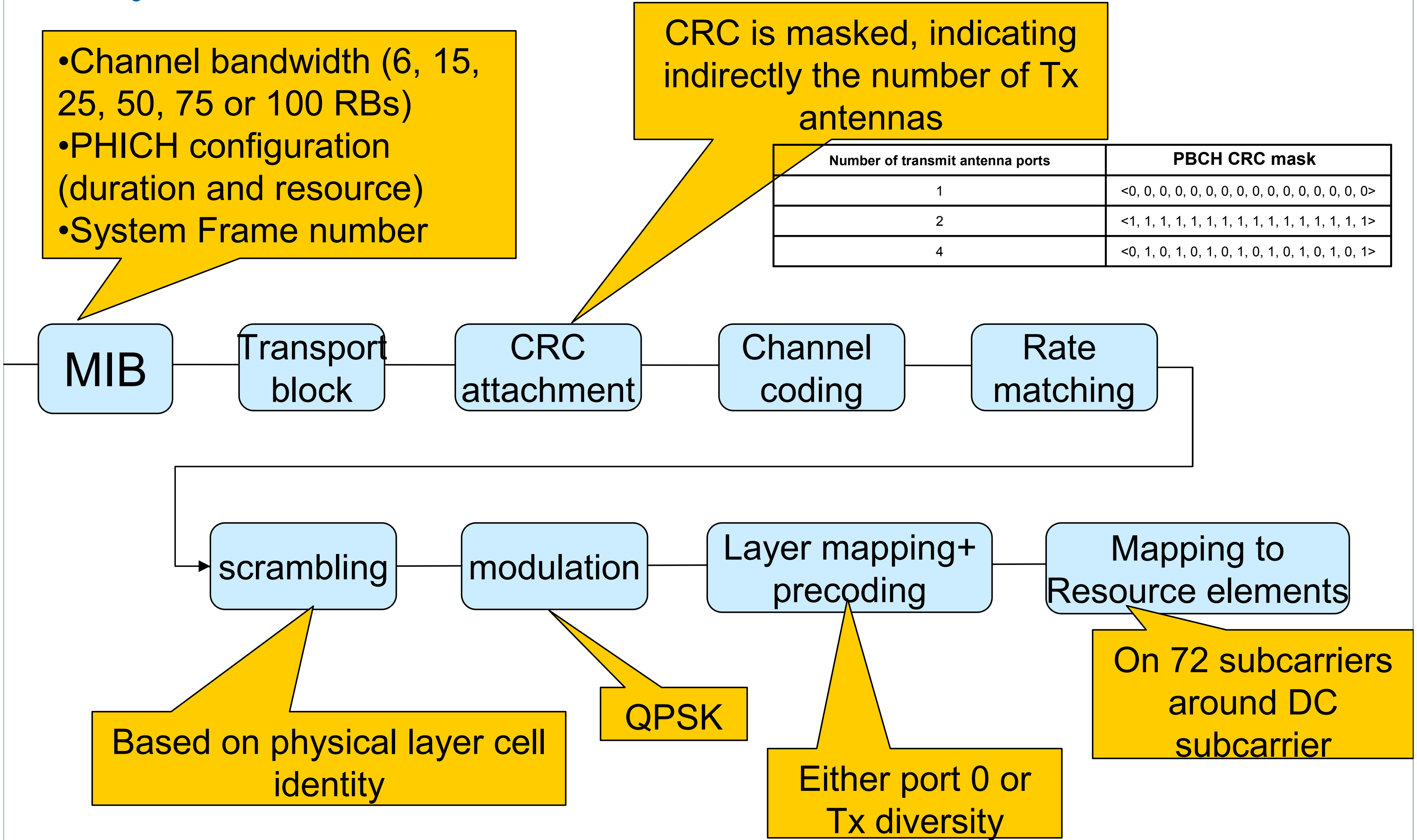
Cell specific reference symbols are frequency staggered with frequency shift depending on cell identity to ease detection. Example here 3 neighbour cells with different identities

LTE Downlink
Configuration of physical broadcast channel



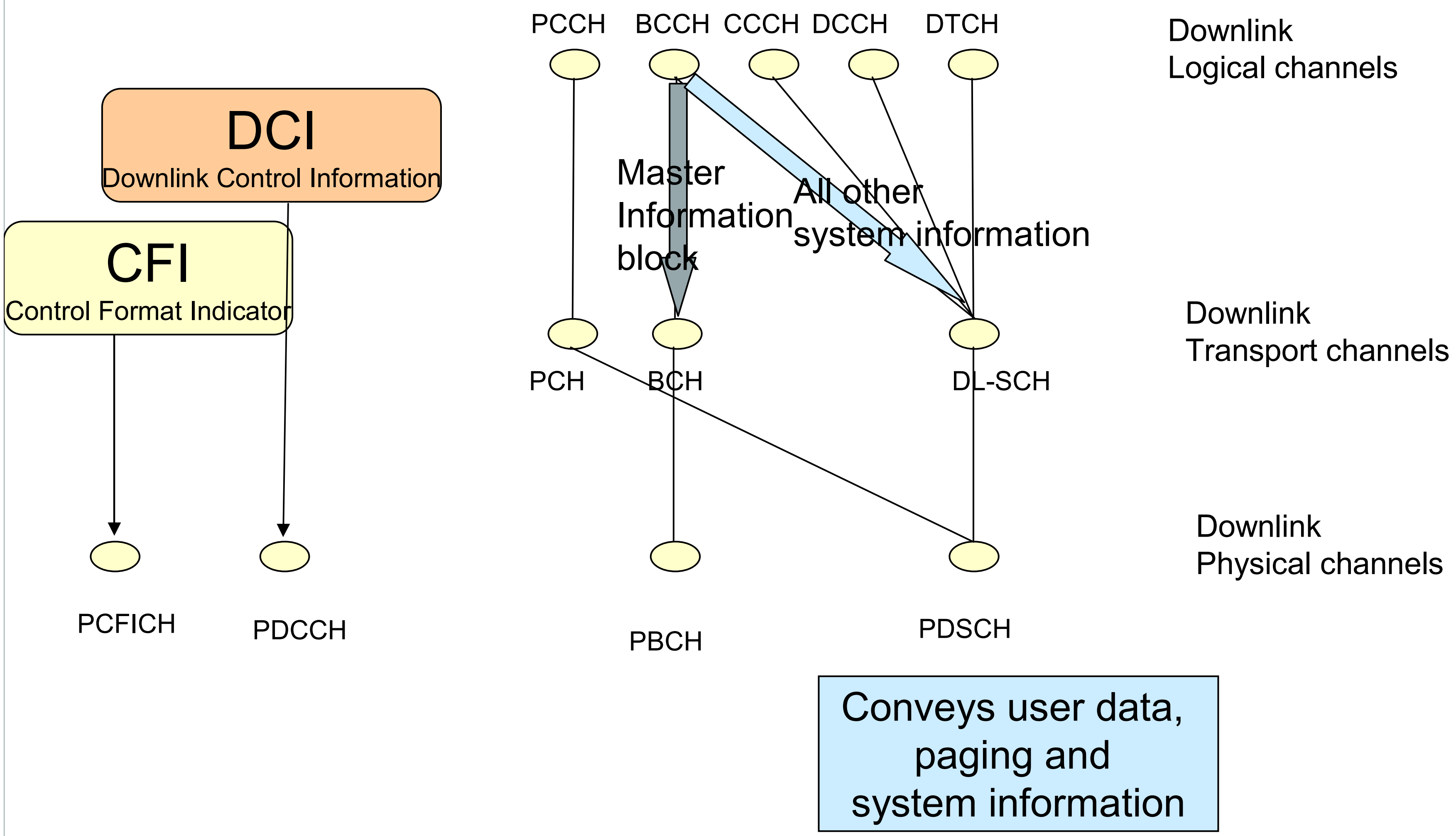
PBCH has 40 ms transmission time interval

Physical Broadcast Channel, PBCH



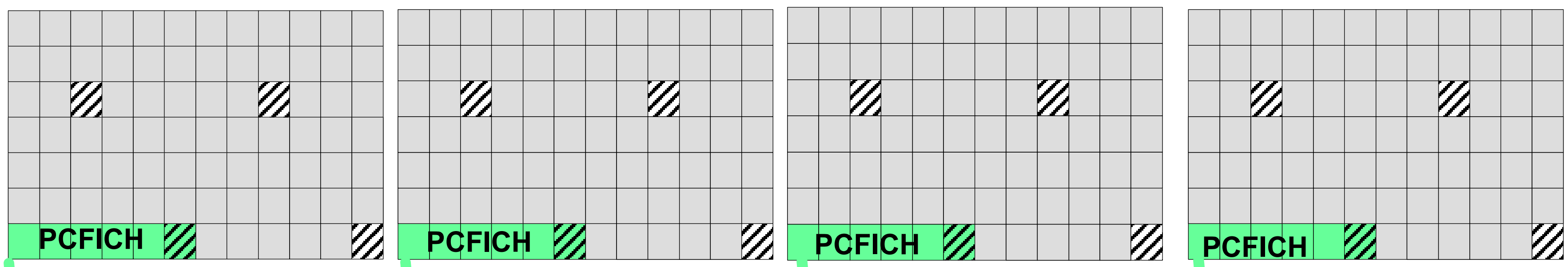
Number of transmit antenna ports	PBCH CRC mask
1	<0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0>
2	<1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1>
4	<0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1>

LTE – acquiring system information



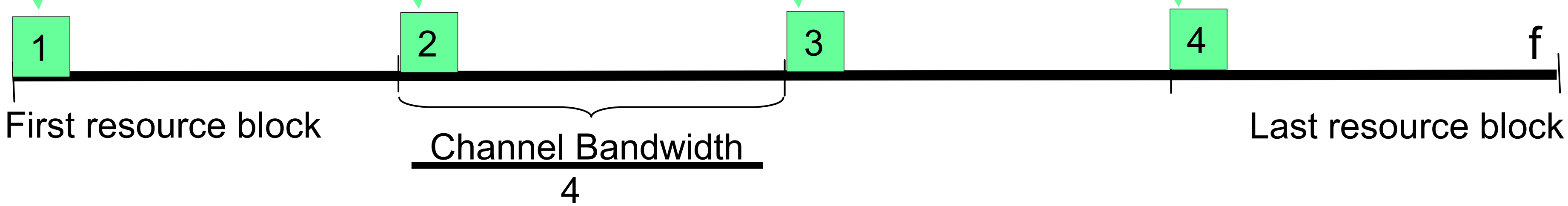
PCFICH mapping on physical resource

Resource block



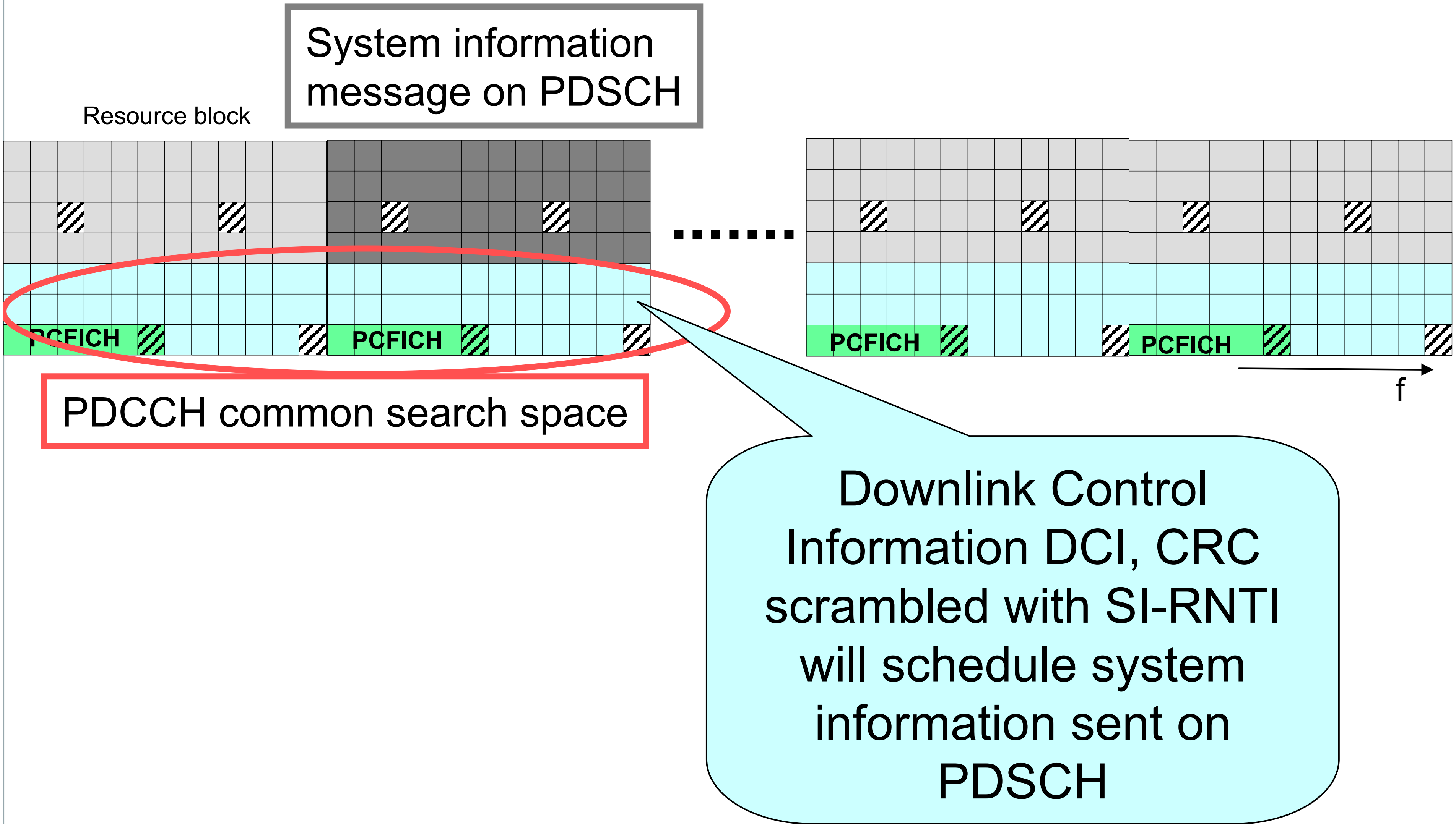
Mapping of PCFICH onto resource elements is based on Physical layer cell Identity!

$\bar{k} = \left(N_{sc}^{RB}/2\right)\cdot\left(N_{ID}^{cell} \bmod 2N_{RB}^{DL}\right)$ Defines variable offset in frequency domain

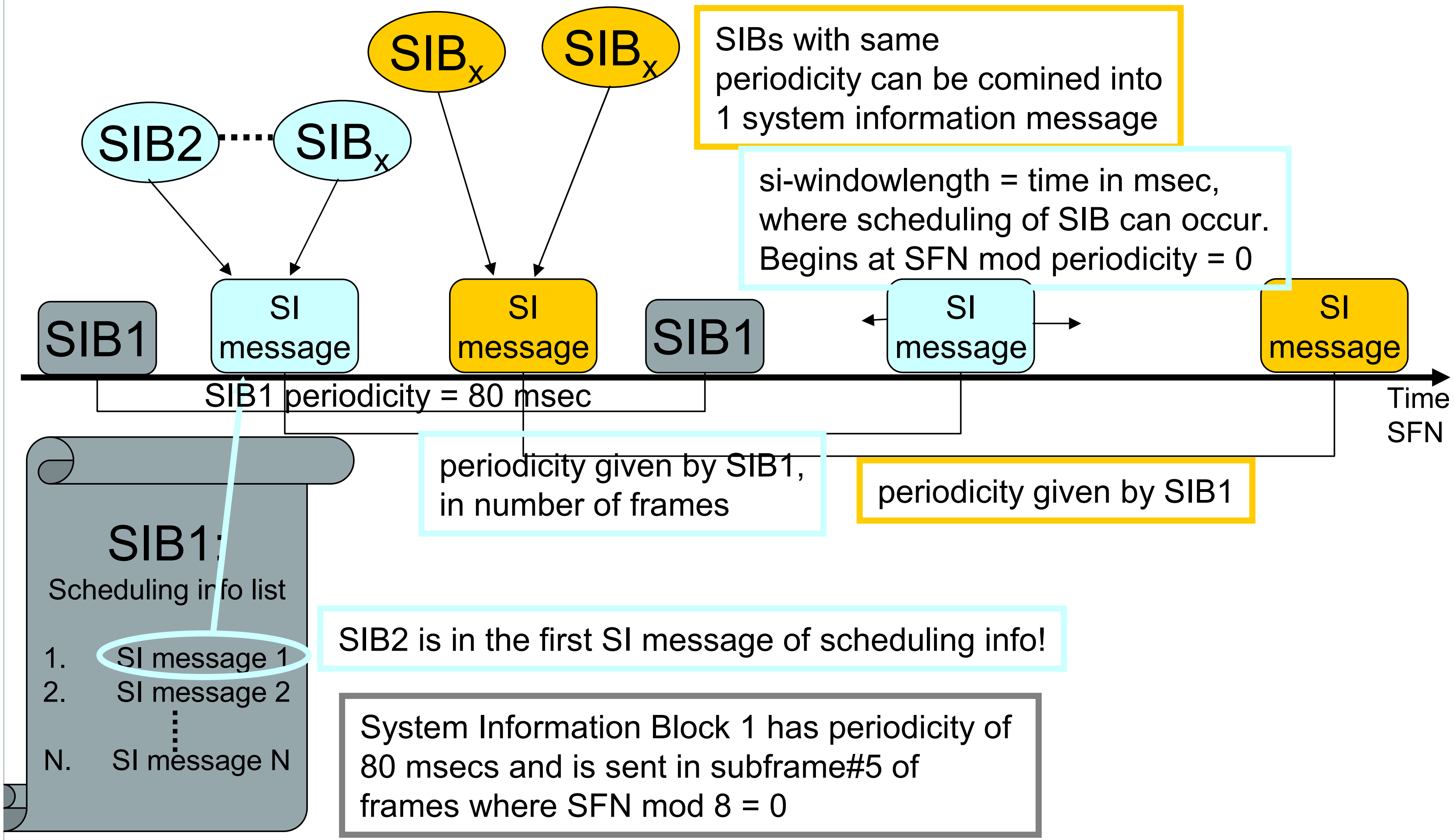


UE knows channel bandwidth and Physical layer cell identity from MIB and sync channels -> UE reads PCFICH to know where PDCCH is

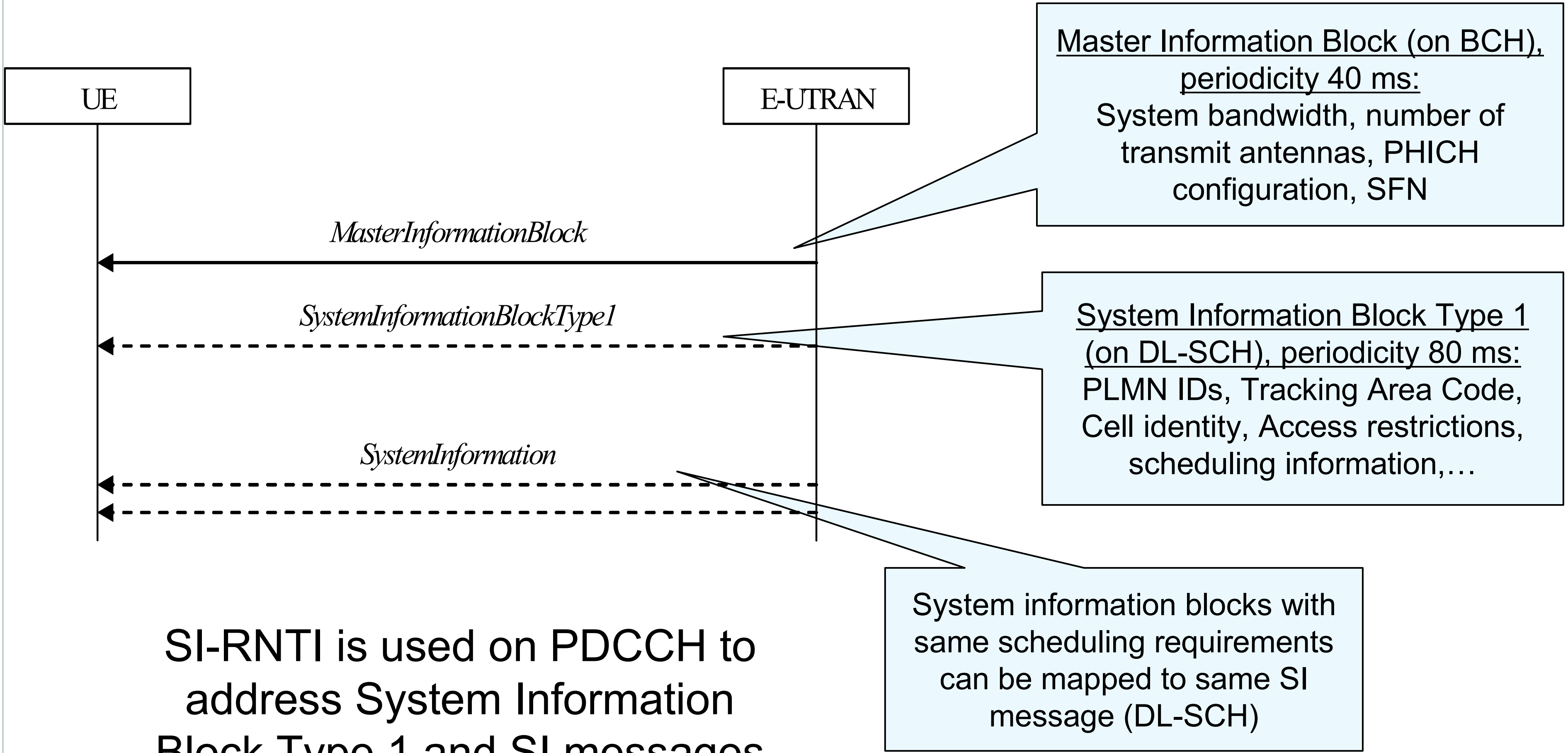
PDCCH scheduling SysInfo on PDSCH



System Information Scheduling



System information broadcast



SI-RNTI is used on PDCCH to address System Information Block Type 1 and SI messages

System Information Block Type 1

```
SystemInformationBlockType1 ::=     SEQUENCE {
    cellAccessRelatedInfo               SEQUENCE {
        plmn-IdentityList                   PLMN-IdentityList,
        trackingAreaCode                    TrackingAreaCode,
        cellIdentity                        CellIdentity,
        cellBarred                          ENUMERATED {barred, notBarred},
        intraFreqReselection                ENUMERATED {allowed, notAllowed},
        csg-Indication                      BOOLEAN,
        csg-Identity                        BIT STRING (SIZE (27))  OPTIONAL    -- Need OR
    },
    cellSelectionInfo                   SEQUENCE {
        q-RxLevMin                          Q-RxLevMin,
        q-RxLevMinOffset                    INTEGER (1..8)          OPTIONAL    -- Need OP
    },
    p-Max                               P-Max                       OPTIONAL,           -- Need OP
    freqBandIndicator                   INTEGER (1..64),
    schedulingInfoList                  SchedulingInfoList,
    tdd-Config                          TDD-Config                  OPTIONAL,   -- Cond TDD
    si-WindowLength                     ENUMERATED {
                                            ms1, ms2, ms5, ms10, ms15, ms20,
                                            ms40},
    systemInfoValueTag                  INTEGER (0..31),
    nonCriticalExtension                SEQUENCE {}                 OPTIONAL    -- Need OP
}

PLMN-IdentityList ::=                   SEQUENCE (SIZE (1..6)) OF PLMN-IdentityInfo

PLMN-IdentityInfo ::=                   SEQUENCE {
    plmn-Identity                           PLMN-Identity,
    cellReservedForOperatorUse              ENUMERATED {reserved, notReserved}
}

SchedulingInfoList ::= SEQUENCE (SIZE (1..maxSI-Message)) OF SchedulingInfo

SchedulingInfo ::=  SEQUENCE {
    si-Periodicity                      ENUMERATED {
                                            rf8, rf16, rf32, rf64, rf128, rf256, rf512},

    sib-MappingInfo                     SIB-MappingInfo
}

SIB-MappingInfo ::= SEQUENCE (SIZE (0..maxSIB-1)) OF SIB-Type

SIB-Type ::=                        ENUMERATED {
                                        sibType3, sibType4, sibType5, sibType6,
                                        sibType7, sibType8, sibType9, sibType10,
                                        sibType11, spare7, spare6, spare5,
                                        spare4, spare3, spare2,
                                        spare1, ...}
```

NAS identity. There can be > 1 PLMN identity

Window where scheduling of SI message can occur

Indicates validity of SIB

Max 32 SI messages

Periodicity of SI message

Which SIBs are contained in SI message

System information

MIB: Physical layer info	SIB Type 1: Access restrictions, SIB scheduling info	SIB Type 2: Common and shared channel info
SIB Type 3: Cell reselection info	SIB Type 4: Cell reselection info, intra-fr. neighbour info	SIB Type 5: Cell reselection info, inter-fr. neighbour info
SIB Type 6: Cell reselection info for UTRA	SIB Type 7: Cell reselection info for GERAN	SIB Type 8: Cell reselection info for CDMA2000
SIB Type 9: Home eNB identifier (HNBID)	SIB Type 10: ETWS primary notification	SIB Type 11: ETWS secondary notification

UE shall have a valid information on those SIBs, depending on the supported RAT

- ETWS = Earthquake and Tsunami Warning System

LTE Physical Layer:

Reference signals – general aspects

Reference signals in Downlink

Reference signals in Uplink

Reference signals

- **Reference signals and preamble are likely to be CAZAC**
  - Constant Amplitude Zero Autocorrelation
- **One special CAZAC sequence is the Zadoff-Chu sequence**

$$a_q(n) = e^{-j2\pi q \frac{n\frac{n+1}{2}+l\cdot n}{N_{ZC}}}$$

Used to generate

Preamble in the random access procedure

Uplink demodulation and sounding reference signals

Primary synchronisation signal in downlink

Reference signals: CAZAC

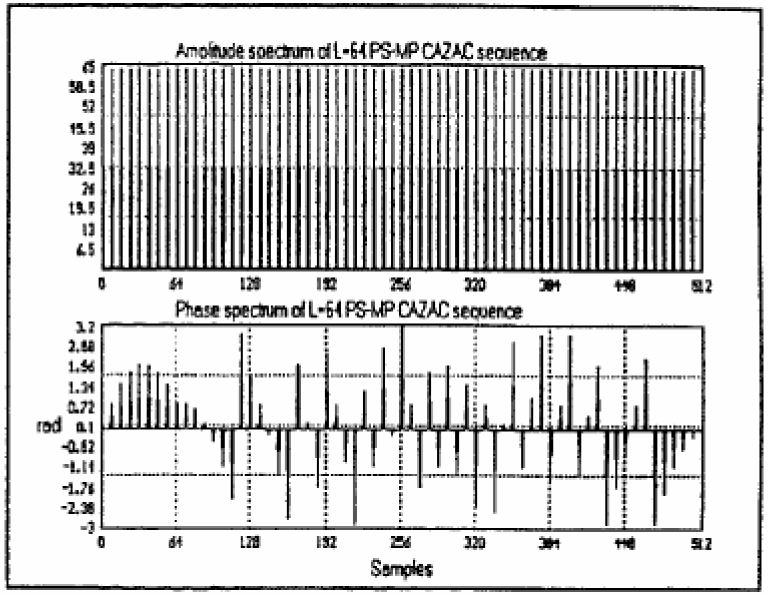
- **CAZAC stands for Constant Amplitude, Zero Autocorrelation**

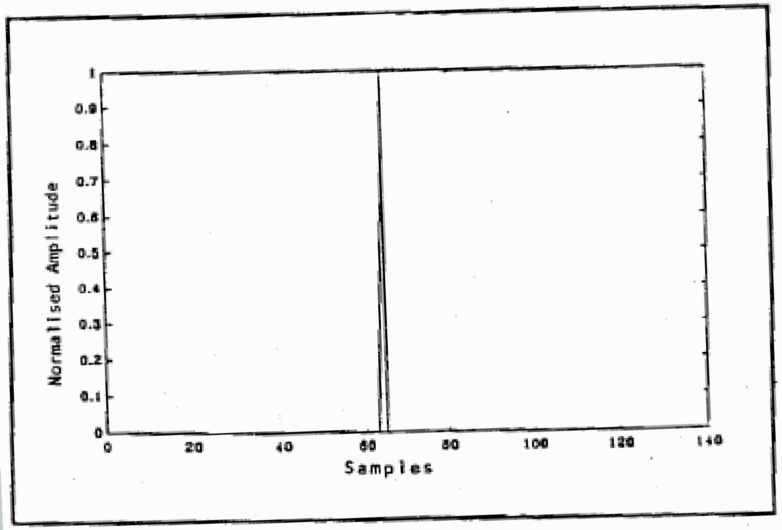
Principle of generating CAZAC,

$$c(n) = e^{j\alpha_0 k(n)} \quad ; \quad n = 0,1,2,\ldots\ldots,L-1$$

where j $\triangleq \sqrt{(-1)}$, $\alpha_0 = 2\pi p/N$ constitutes the basic phase angle in radians, N is the number of distinct phases of the (polyphase) code and p is an integer smaller than and relatively prime with respect to N, e.g. if L=16,

- **CAZAC is not binary data, to be considered like IQ samples**





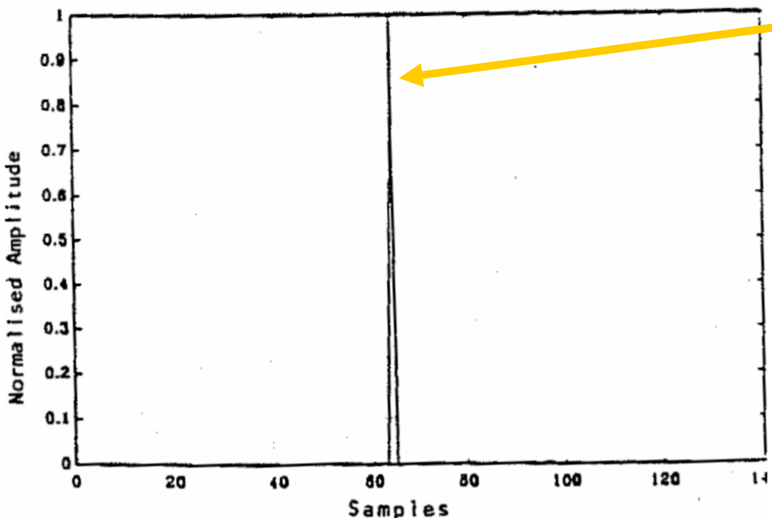
Source: Linde, Röhrs, Class of Polyphase CAZAC sequences IEEE magazine, 1993

CAZAC sequence characteristics – constellation diagram

Constant amplitude

Characteristics of Zadoff-Chu sequences

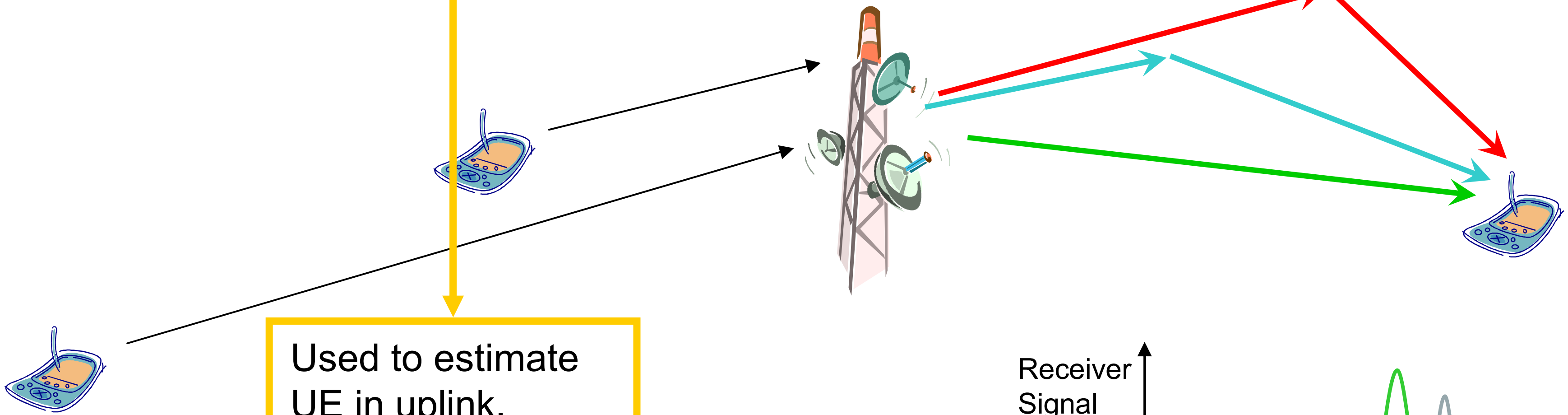
Zero autocorrelation



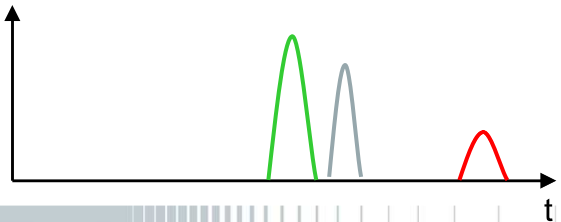
Zero Autocorrelation

e.g. here autocorrelation of length 64 sequence

Used to estimate Channel impulse response

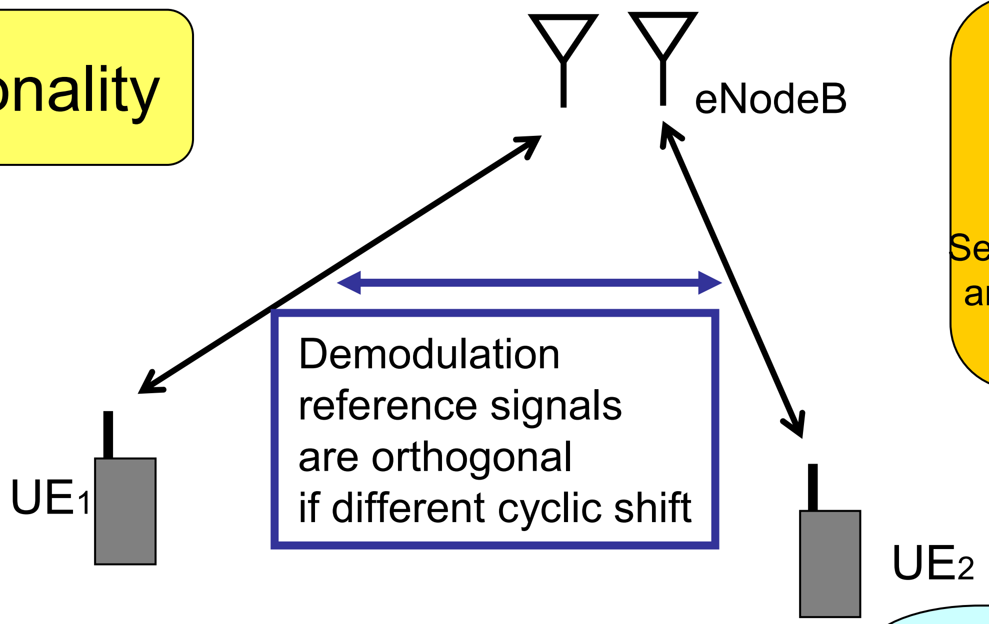


Used to estimate UE in uplink. Near – far situation



Characteristics of Zadoff-Chu sequences

Orthogonality



Multi-User MIMO

Several UE share the same frequency and subframe -> so no orthogonality

Cyclic shift α of a base ZC sequence allows the generation of orthogonal sequences

$$r_{u,v}^{(\alpha)}(n) = e^{j\boxed{\alpha} n} \cdot \boxed{\bar{r}_{u,v}(n)},$$

Zadoff-Chu sequence

Characteristics of Zadoff-Chu sequences

Constant Cross-correlation

$$a_q(n) = e^{-j2\pi q \frac{n\frac{n+1}{2}+l\cdot n}{N_{ZC}}}$$

If N_{ZC} is selected to be a prime number, you get optimum cross correlation between any pair of ZC sequences

Cross correlation between any 2 Zadoff-Chu sequences is constant and equal to: $\frac{1}{\sqrt{N_{ZC}}}$

Zadoff-Chu sequences in LTE

Zadoff-Chu sequence in LTE

$$a_q(n) = e^{-j2\pi q \frac{n\frac{n+1}{2}+l\cdot n}{N_{ZC}}}$$

l is 0 in LTE for simplicity

q is the Zadoff-Chu root index, i.e. this is the variable part how to obtain different sequences. Value is different for cells and indicated by higher layers

If N_{ZC} is selected to be a prime number, but base sequence length is extended by cyclic copy of a root sequence

Example how LTE reference signals are generated based on Zadoff-Chu: here PSS

- **Primary synchronisation signal PSS has CAZAC characteristic**
- **based on Zadoff-Zhu sequence, sequence $d_u(n)$ given as**

$$d_u(n) = \begin{cases} e^{-j\frac{\pi u n(n+1)}{63}} & n = 0,1,\ldots,30 \\ e^{-j\frac{\pi u (n+1)(n+2)}{63}} & n = 31,32,\ldots,61 \end{cases}$$

Not a prime number, but there are only 3 possible sequences -> no cross-correlation variation problems

Here the „variable“ factor u is just one out of 3 possible values

$N_{ID}^{(2)}$	Root index u
0	25
1	29
2	34

LTE Downlink:
Downlink Reference Signals

<u>Of course, there will be reference signals</u>

•Cell-specific reference signals, associated with non-MBSFN transmission

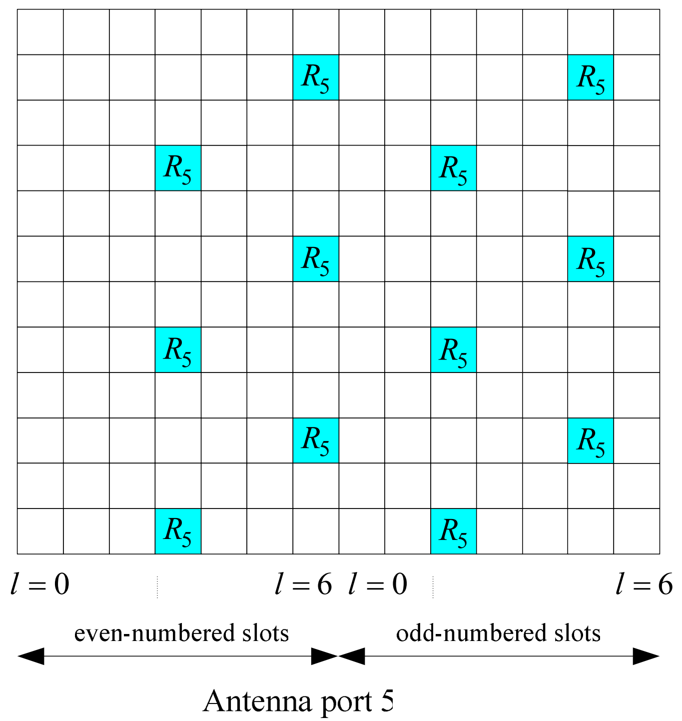
•MBSFN reference signals, associated with MBSFN transmission

•UE-specific reference signals (supported in frame structure type 2 only)

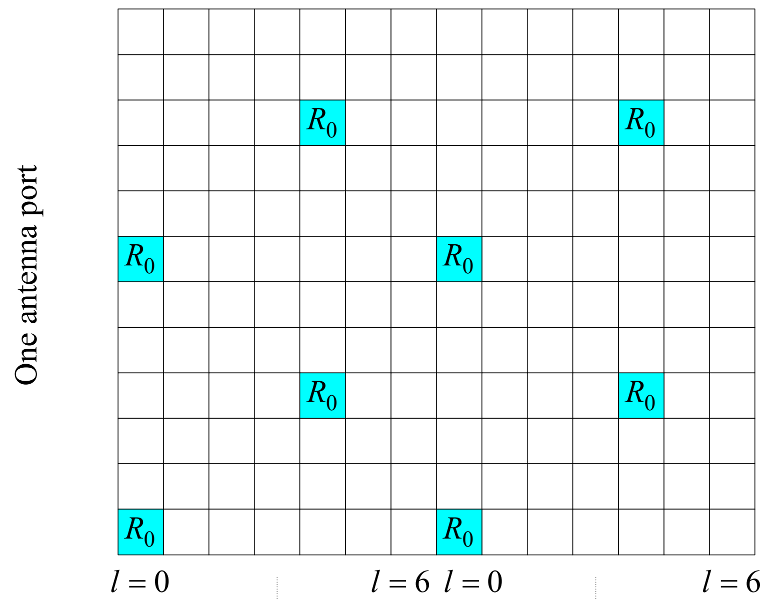
- Downlink reference signal(s) can be used for
  - Downlink-channel-quality measurements
  - Downlink channel estimation for coherent demodulation/detection at the UE
  - Cell search and initial acquisition (carries cell ID)

Downlink Reference Signals

UE-specific reference signal



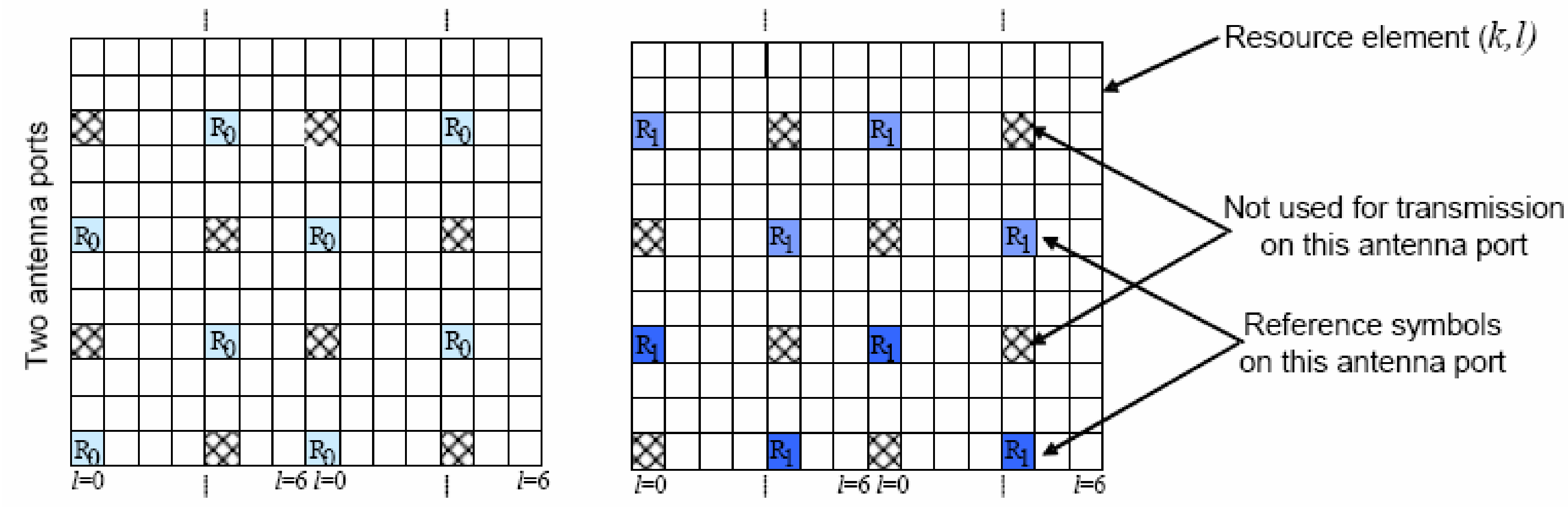
Cell-specific reference signal



- <u>UE-specific reference signals</u>
  - UE capability mandatory for TDD and optional for FDD
  - Main intention is beamforming with UE-specific TX antenna settings
  - Transmitted in addition to the cell-specific reference

MIMO in LTE (DL)
Reference Symbols / Pilots

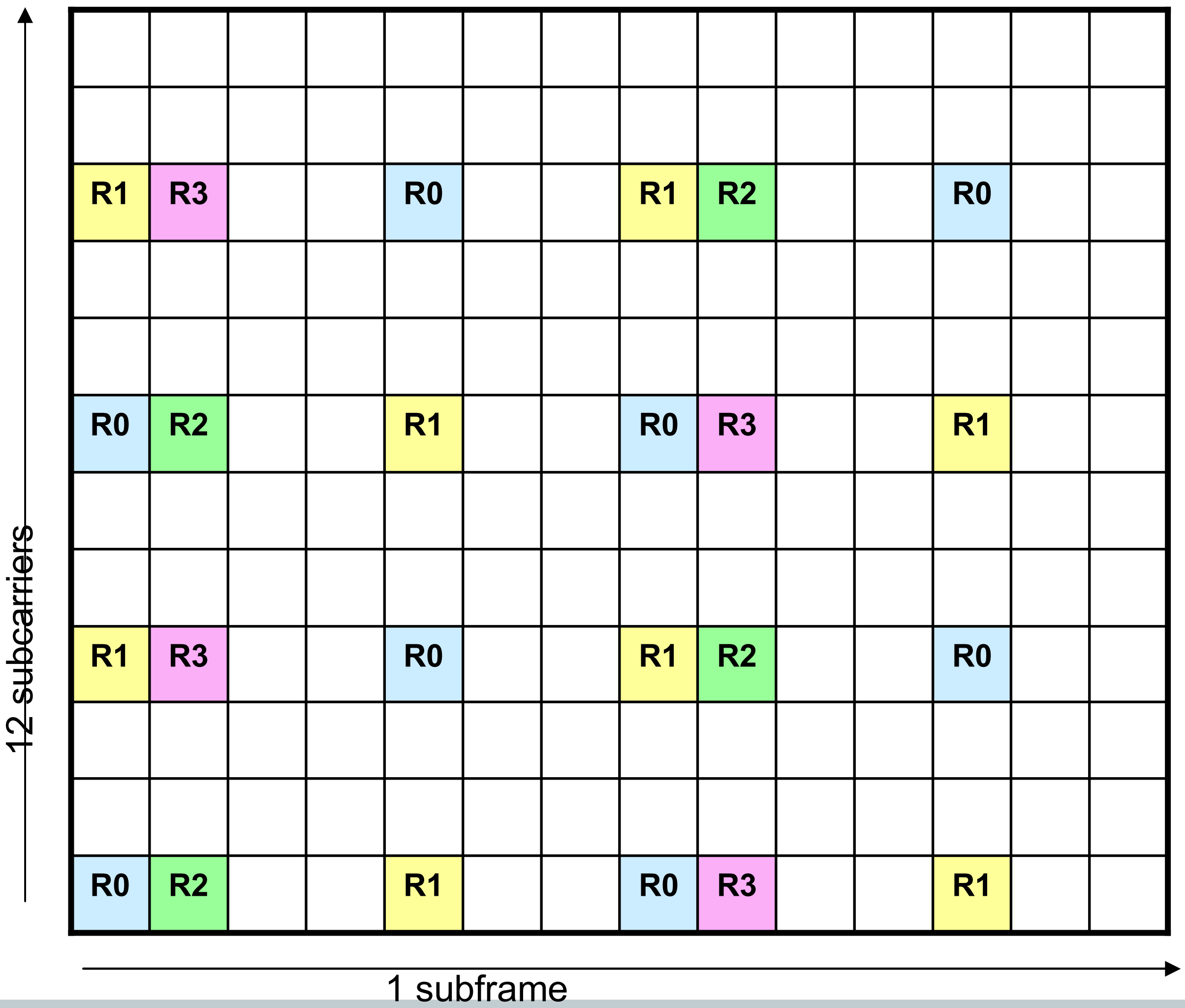
e.g.:



Antenna 1 Antenna 2

MIMO in LTE (DL)

Reference Symbols / Pilots



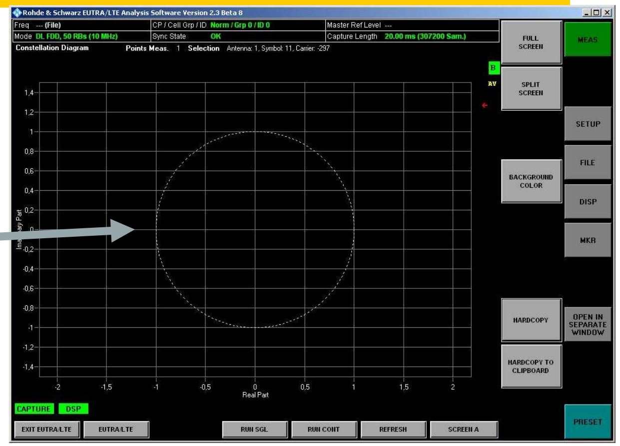
R0	Antenna 0
R1	Antenna 1
R2	Antenna 2
R3	Antenna 3

Different Tx antennas Can be recognized separately

Cell specific reference signals

Cell specific reference signal is a pseudo-random sequence

Define as complex number, to obtain a constant amplitude

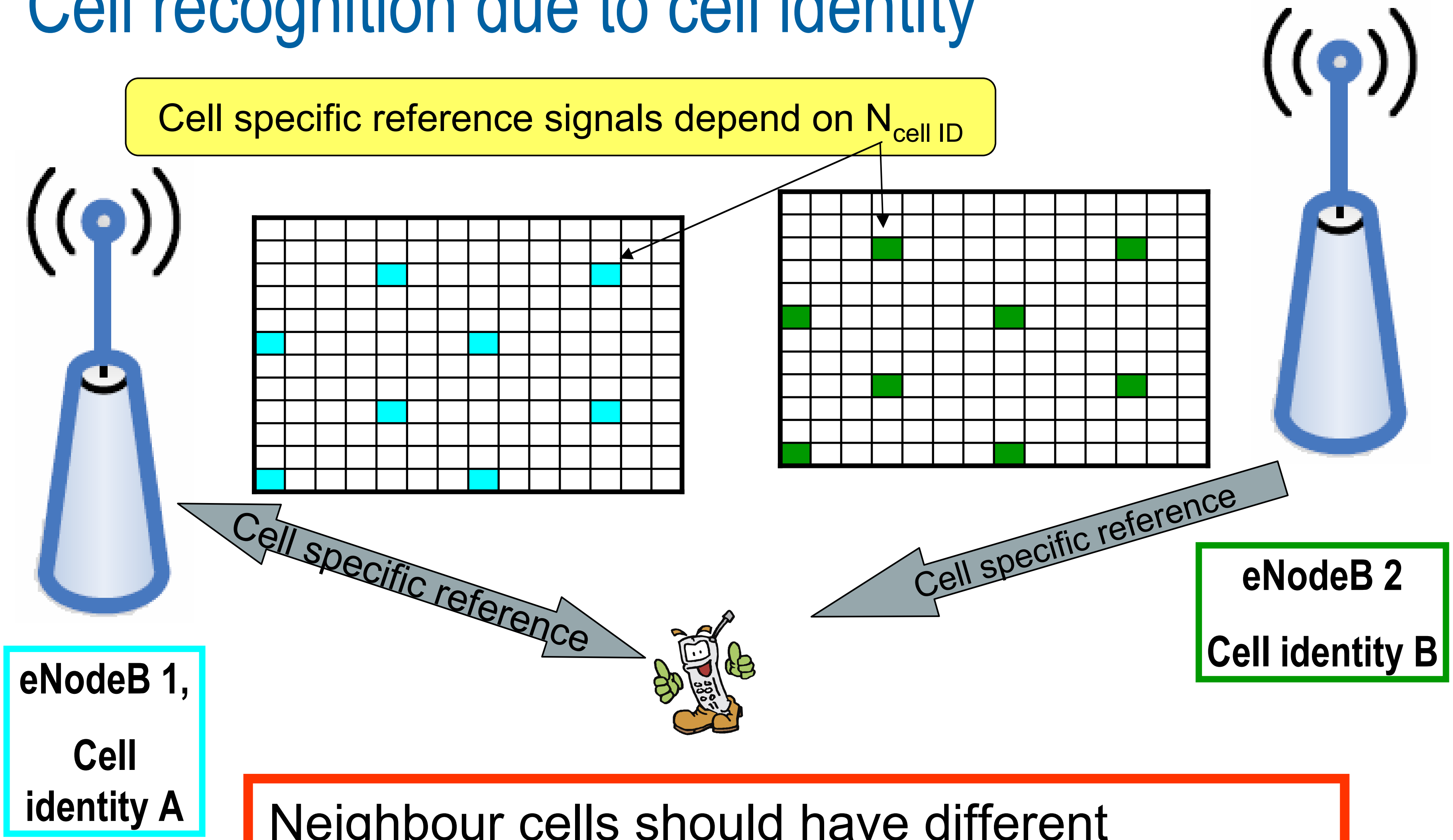


$$r_{l,n_s}(m) = \underbrace{\frac{1}{\sqrt{2}}\left(1-2\cdot c(2m)\right)}_{\text{Real part}} + j\underbrace{\frac{1}{\sqrt{2}}\left(1-2\cdot c(2m+1)\right)}_{\text{Imaginary part}}, \qquad m = 0,1,\ldots,2N_{\text{RB}}^{\text{max,DL}}-1$$

Pseudo random sequence, based on cell identity and slot

$$c_{\text{init}} = 2^{10}\cdot\left(7\cdot\left(n_s+1\right)+l+1\right)\cdot\left(2\cdot N_{ID}^{cell}+1\right)+2\cdot N_{ID}^{cell}+N_{CP}$$

Cell recognition due to cell identity



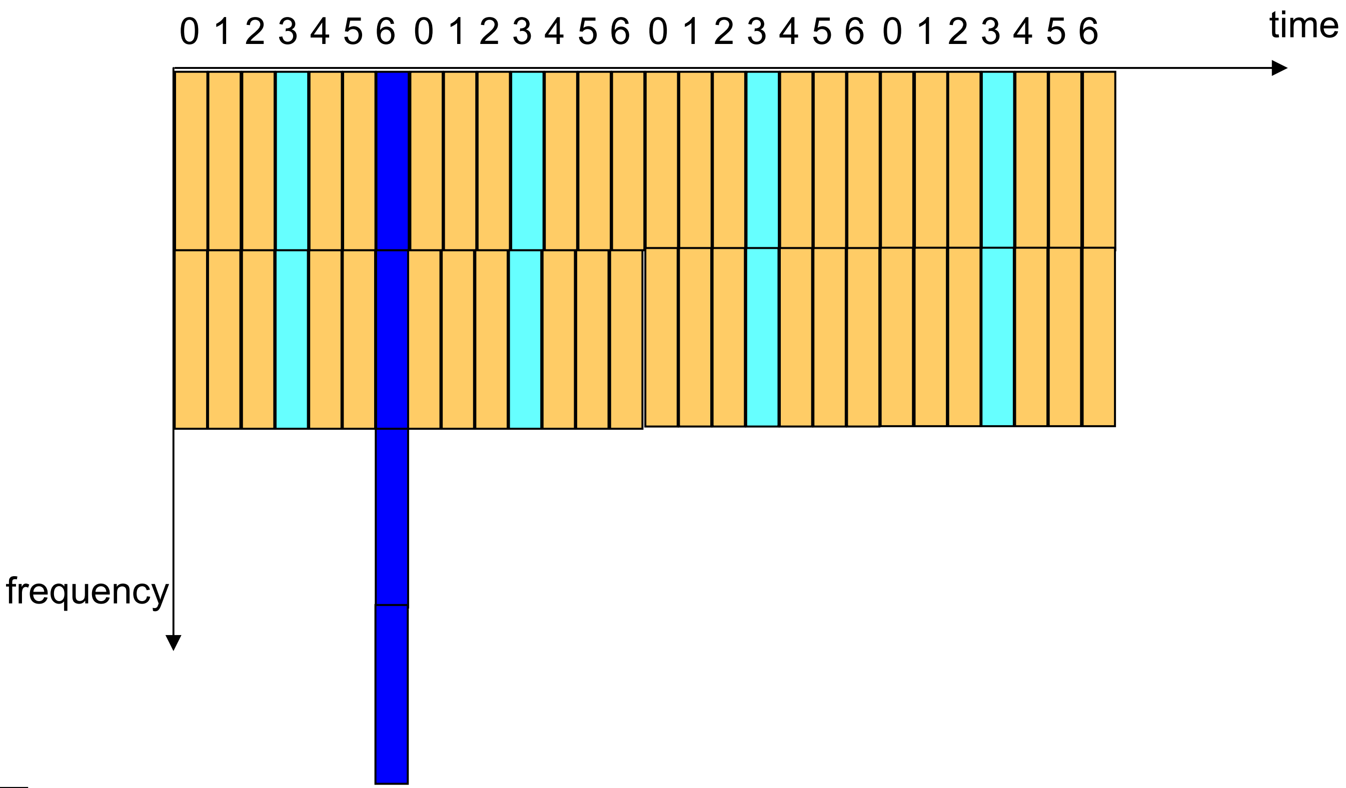
Neighbour cells should have different physical layer cell identities to be distinguished

LTE Uplink:
Reference Signals

2 different purposes:

1. Uplink channel estimation for uplink coherent demodulation/detection
(reference symbol on 4th SC-FDMA symbol)
2. Channel sounding: uplink channel-quality estimation for better scheduling decisions
(position tbd)

LTE Uplink: Reference Signals



Example structure

Demodulation Reference Signal: Uplink channel estimation for uplink coherent demodulation/detection

Sounding Reference Signal SRS: Channel sounding: uplink channel-quality estimation for better scheduling decisions

Uplink reference signals

Generation of uplink reference signals overview

$$r_{u,v}^{(\alpha)}(n) = e^{j\alpha n}\bar{r}_{u,v}(n), \quad 0 \le n < M_{\mathrm{sc}}^{\mathrm{RS}}$$

Reference Signal sequence

Length of sequence is allocated
Uplink resource in terms of resource blocks

$$\bar{r}_{u,v}(n) = x_q(n \bmod N_{\mathrm{ZC}}^{\mathrm{RS}}), \quad 0 \le n < M_{\mathrm{sc}}^{\mathrm{RS}}$$

Base sequence

$$x_q(m) = e^{-j\frac{\pi q m(m+1)}{N_{\mathrm{ZC}}^{\mathrm{RS}}}}, \quad 0 \le m \le N_{\mathrm{ZC}}^{\mathrm{RS}} - 1$$

Root sequence

$$q = \lfloor \bar{q} + 1/2 \rfloor + v \cdot (-1)^{\lfloor 2\bar{q} \rfloor}$$

$$\bar{q} = N_{\mathrm{ZC}}^{\mathrm{RS}} \cdot (u+1)/31$$

u and v are
Cell specific,
Given by higher layers

u = group number
v = base sequence number

Uplink reference signals

Allocated uplink resource in number of resource blocks

Group hopping may be enabled

# RBs		0	1	2	3	4	5	6	7	…	107	108
Sequence number v		0	0	0	0	0	0	0 1	0 1	…	0 1	0 1
Group u	0	●	●	●	●	●	●	● ●	● ●	…	● ●	● ●
	1	●	●	●	●	●	●	● ●	● ●	…	● ●	● ●
	2	●	●	●	●	●	●	● ●	● ●	…	● ●	● ●
	3	●	●	●	●	●	●	● ●	● ●	…	● ●	● ●
	…	●	●	●	●	●	●	● ●	● ●	…	● ●	● ●
	28	●	●	●	●	●	●	● ●	● ●	…	● ●	● ●
	29	●	●	●	●	●	●	● ●	● ●	…	● ●	● ●

$$q = \lfloor \bar{q} + 1/2 \rfloor + v \cdot (-1)^{\lfloor 2\bar{q} \rfloor}$$

$$\bar{q} = N_{ZC}^{RS} \cdot (u+1)/31$$

v = ***sequence number,***
for #RB≤ 5 v = 0,
for #RBs >5 v = 0 or 1 depending on hopping

u = ***groupAssignmentPUSCH, given by higher layers***

Uplink reference signals

If number of allocated resource blocks < 3, instead of a Zadoff-Chu sequence like below, a predefined sequence is used as $x_q(m)$. See TS 36.211 for details.

The length of the Zadoff-Chu sequence is given by the largest prime number such that $N_{ZC}^{RS} < M_{sc}^{RS}$

$$x_q(m) = e^{-j\frac{\pi q m(m+1)}{N_{ZC}^{RS}}}, \quad 0 \le m \le N_{ZC}^{RS} - 1$$

Root sequence

Possible values are (prime numbers < 110):

2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37,
41, 43, 47, 53, 59, 61, 67, 71,
73, 79, 83, 89, 97, 101, 103, 107, 109,

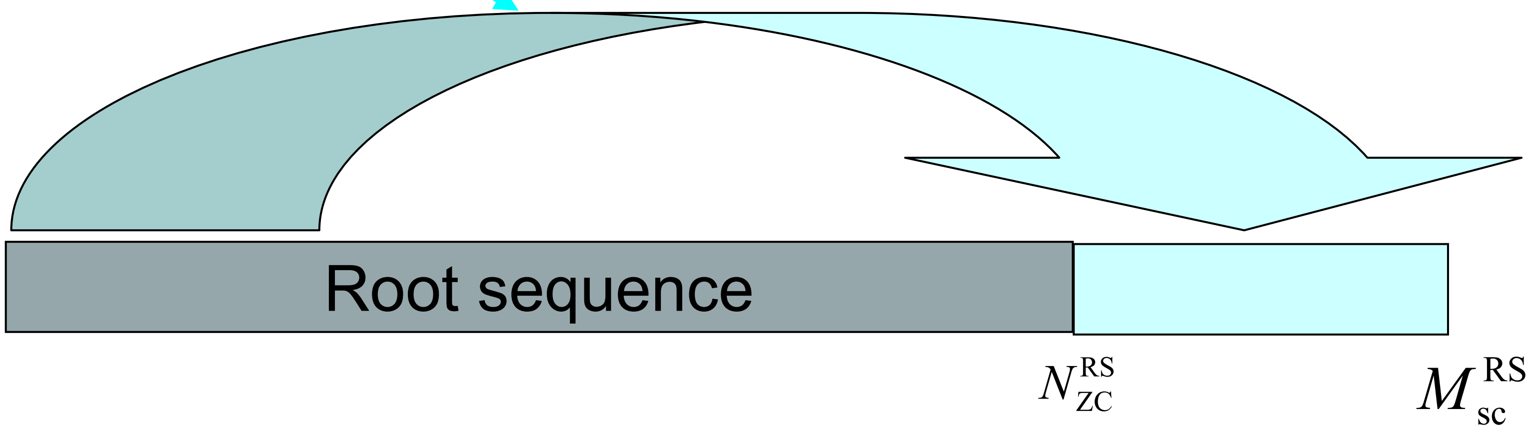
Uplink reference signals

Due to fact with prime numbers,
not all possible length can be obtained
-> cyclic extension

Length of sequence is the allocated uplink resource in terms of resource blocks

$$\bar{r}_{u,v}(n) = x_q(n \bmod N_{ZC}^{RS}), \quad 0 \le n < M_{sc}^{RS}$$

Base sequence



Largest prime number < M_{sc}^{RS}

Uplink reference signals

$$r_{u,v}^{(\alpha)}(n) = e^{j\alpha n}\bar{r}_{u,v}(n), \quad 0 \le n < M_{sc}^{RS}$$

Reference Signal sequence

Length of sequence is the allocated uplink resource in terms of resource blocks

Due to α, different orthogonal sequences can be generated, based on the same base sequence. This is needed in case of Multi User MIMO or in case of PUCCH, where several UEs share the uplink resource

Higher layer value ***cyclicShift*** indicates α

Demodulation reference for PUSCH

30 base sequence groups, group hopping optionally enabled

1 point ● or ● defines 1 base sequence of certain length

# RBs		0	1	2	3	4	5	6	7	…	107	108
Sequence number v		0	0	0	0	0	0	0 1	0 1	…	0 1	0 1
Group u	0	●	●	●	●	●	●	● ●	● ●	...	● ●	● ●
	1	●	●	●	●	●	●	● ●	● ●	...	● ●	● ●
	2	●	●	●	●	●	●	● ●	● ●	...	● ●	● ●
	3	●	●	●	●	●	●	● ●	● ●	...	● ●	● ●
	…	●	●	●	●	●	●	● ●	● ●	...	● ●	● ●
	28	●	●	●	●	●	●	● ●	● ●	...	● ●	● ●
	29	●	●	●	●	●	●	● ●	● ●	...	● ●	● ●

12 cyclic shifts per base sequence

1 or 2 base sequences for each length (length depends on allocated bandwidth), sequence hopping optionally enabled

Demodulation reference for PUSCH + PUCCH

Details on how group hopping and cyclic shift is performed

Group hopping

$$c_{\text{init}} = \left\lfloor \frac{N_{\text{ID}}^{\text{cell}}}{30} \right\rfloor$$

$$f_{\text{gh}}(n_s) = \begin{cases} 0 & \text{if group hopping is disabled} \\ \left(\sum_{i=0}^{7} c(8n_s + i) \cdot 2^i\right) \bmod 30 & \text{if group hopping is enabled} \end{cases}$$

If PUCCH

$$f_{\text{ss}}^{\text{PUCCH}} = N_{\text{ID}}^{\text{cell}} \bmod 30$$

If PUSCH

$$f_{\text{ss}}^{\text{PUSCH}} = \left(f_{\text{ss}}^{\text{PUCCH}} + \Delta_{\text{ss}}\right) \bmod 30$$

$\Delta_{\text{ss}} \in \{0,1,\ldots,29\}$

groupAssignmentPUSCH from RRC

$$\boxed{u = \left(f_{\text{gh}}(n_s) + f_{\text{ss}}\right) \bmod 30}$$

Cyclic shift

$$c_{\text{init}} = \left\lfloor \frac{N_{\text{ID}}^{\text{cell}}}{30} \right\rfloor \cdot 2^5 + f_{\text{ss}}^{\text{PUSCH}}$$

$$n_{\text{cs}} = \left(n_{\text{DMRS}}^{(1)} + n_{\text{DMRS}}^{(2)} + n_{\text{PRS}}(n_s)\right) \bmod 12$$

$$n_{\text{PRS}}(n_s) = \sum_{i=0}^{7} c(8N_{\text{symb}}^{\text{UL}} \cdot n_s + i) \cdot 2^i$$

$$\boxed{\alpha = 2 \cdot \pi \cdot \frac{n_{cs}}{12}}$$

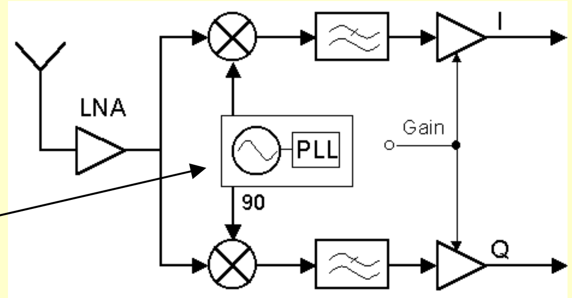
RRC parameter: *cyclicShift*

Parameter *cyclic shift* in most recent DCI format 0

LTE Physical Layer Procedures

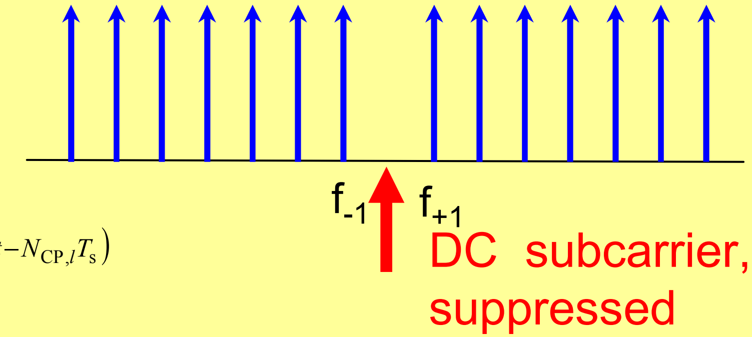
Subcarrier zero handling

Subcarrier 0 or DC subcarrier causes problems in DAC for direct receiver strategies, DC offset!



Downlink:

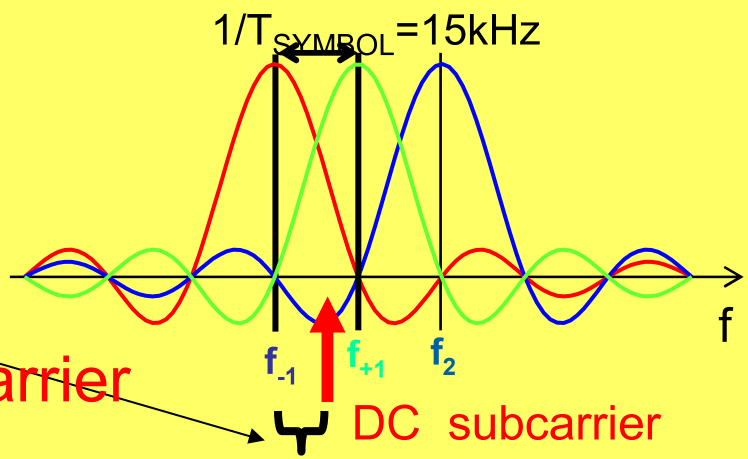
$$s_l^{(p)}(t)=\sum_{k=-\lfloor N_{RB}^{DL}N_{sc}^{RB}/2\rfloor}^{-1} a_{k^{(-)},l}^{(p)}\cdot e^{j2\pi k\Delta f(t-N_{CP,l}T_s)}+\sum_{k=1}^{\lceil N_{RB}^{DL}N_{sc}^{RB}/2\rceil} a_{k^{(+)},l}^{(p)}\cdot e^{j2\pi k\Delta f(t-N_{CP,l}T_s)}$$



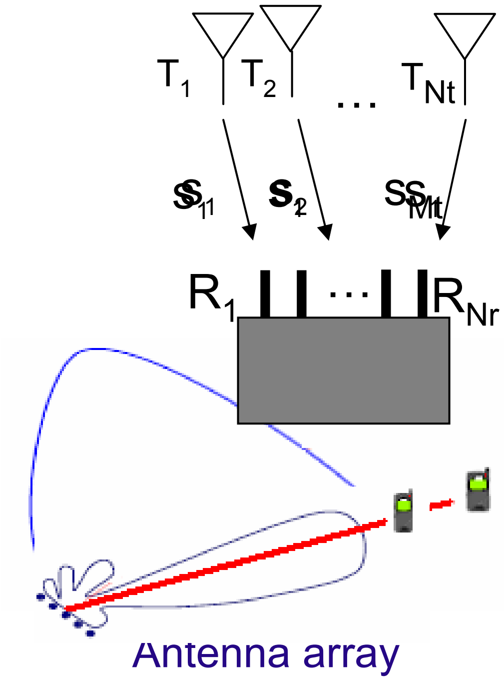
Uplink:

$$s_l(t)=\sum_{k=-\lfloor N_{RB}^{UL}N_{sc}^{RB}/2\rfloor}^{\lceil N_{RB}^{UL}N_{sc}^{RB}/2\rceil-1} a_{k^{(-)},l}\cdot e^{j2\pi(k+1/2)\Delta f(t-N_{CP,l}T_s)}$$

½ subcarrier offset

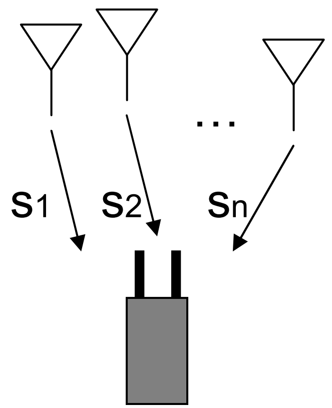


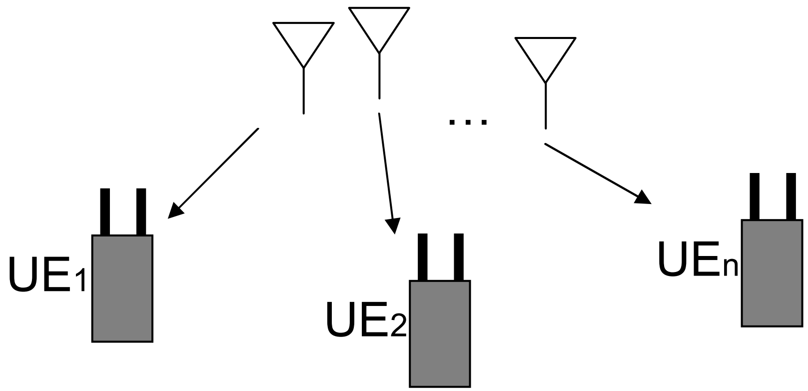
MIMO modes



- **Transmit diversity (TxD)**
  - Combat fading
  - Replicas of the same signal sent on several Tx antennas
  - Get a higher SNR at the Rx
- **Spatial multiplexing (SM)**
  - Different data streams sent simultaneously on different antennas
  - Higher data rate
  - No diversity gain
  - Limitation due to path correlation
- **Beamforming**

SU-MIMO versus MU-MIMO





- **SU (Single User)-MIMO**
  - Goal: to increase user data rate
  - Simultaneous transmission of different data streams to 1 user
  - Efficient when the user experiences good channel conditions
- **MU (Multiple User)-MIMO**
  - Goal: to increase sector capacity
  - Selection of the users experiencing good channel conditions
  - Efficient when a large number of users have an active data transmission simultaneously

LTE MIMO
Downlink modes

- **Transmit diversity:**
  - Space Frequency Block Coding (SFBC)
  - Increasing robustness of transmission
- **Spatial multiplexing:**
  - Codebook based precoding
  - Transmission of different data streams simultaneously over multiple spatial layers
  - Open loop mode for high mobile speeds possible
- **Cyclic delay diversity (CDD):**
  - Addition of antenna specific cyclic shifts
  - Zero, small delay, and large delay CDD
  - Results in additional multipath / increased frequency diversity

LTE UE categories (downlink and uplink)

UE Category	Maximum number of DL-SCH transport block bits received within a TTI	Maximum number of bits of a DL-SCH transport block received within a TTI	Total number of soft channel bits	Maximum number of supported layers for spatial multiplexing in DL
Category 1	10296	10296	250368	1
Category 2	51024	51024	1237248	2
Category 3	102048	75376	1237248	2
Category 4	150752	75376	1827072	2
Category 5	302752	151376	3667200	4

~300 Mbps peak DL data rate for 4x4 MIMO

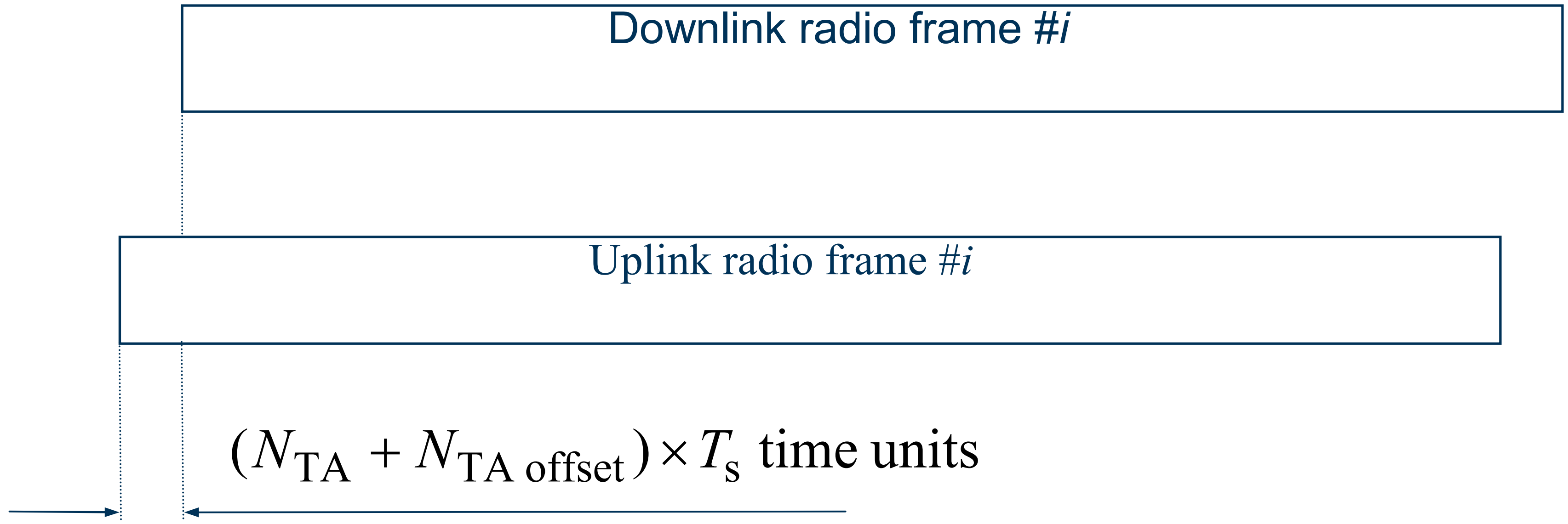
~150 Mbps peak DL data rate for 2x2 MIMO

UE Category	Maximum number of bits of an UL-SCH transport block transmitted within a TTI	Support for 64QAM in UL
Category 1	5160	No
Category 2	25456	No
Category 3	51024	No
Category 4	51024	No
Category 5	75376	Yes

~75 Mbps peak UL data rate

MIMO = Multiple Input Multiple Output
UL-SCH = Uplink Shared Channel
DL-SCH = Downlink Shared Channel
UE = User Equipment
TTI = Transmission Time Interval

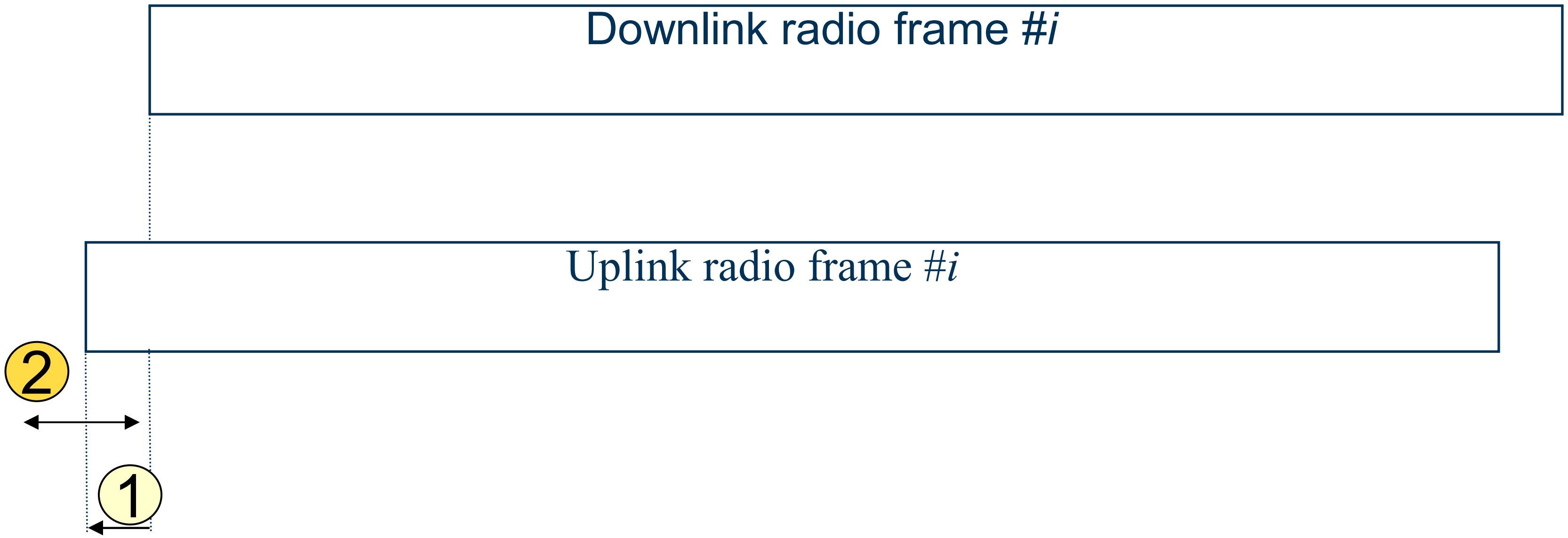
Uplink – Downlink Timing



N_{TA} is to be considered as Transmit Timing Advance, as we know from GSM will be a multiple of 0.52 μ s and is applied as a 1 step adjustment relative to current uplink timing

$N_{\text{TA offset}} = 0, \ for \ FDD$ $\quad$ $N_{\text{TA offset}} = 624, \ for \ TDD$ $\quad$ $N_{\text{TA}} = 16 * T_s$

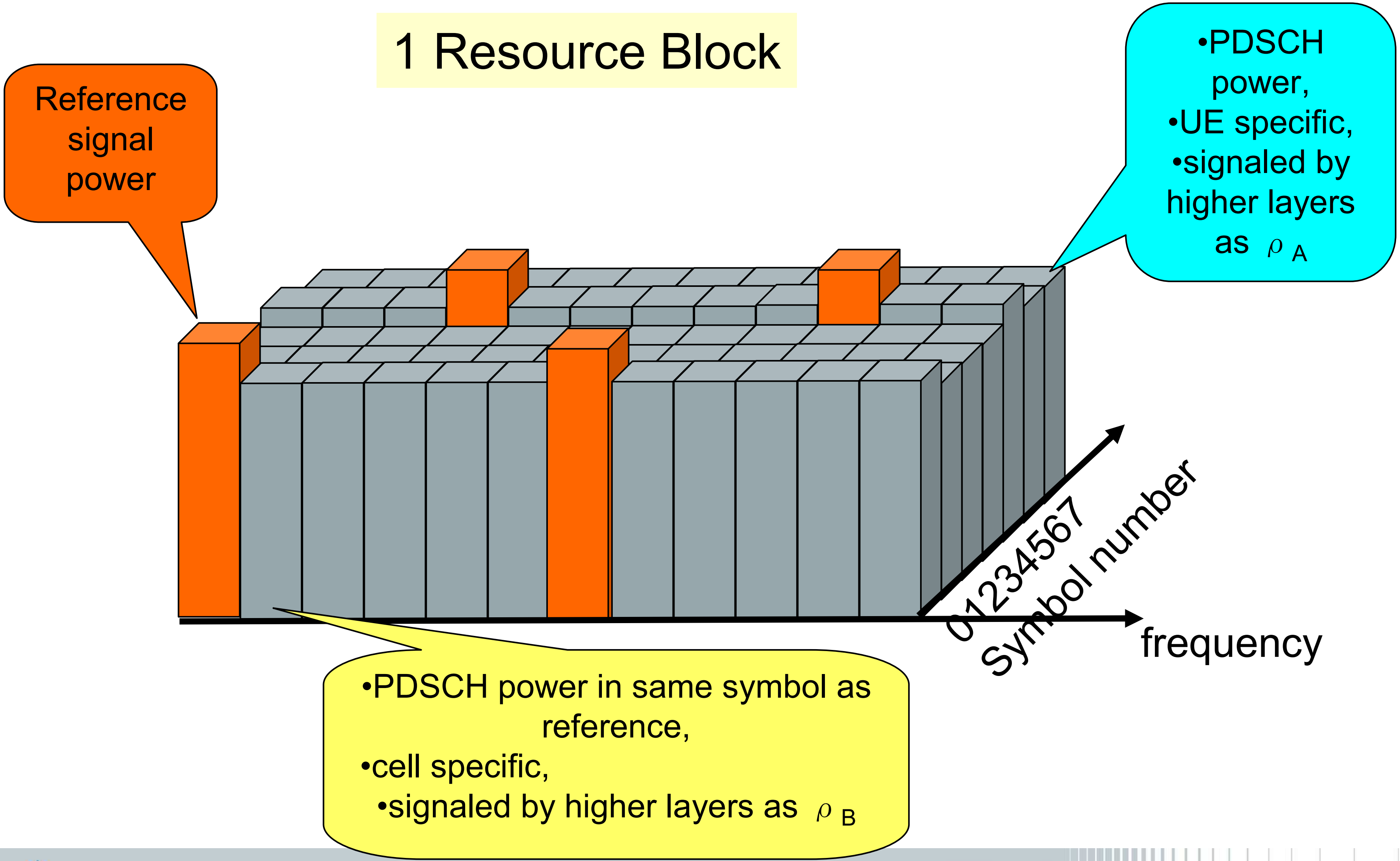
Timing advance control



Initial timing advance in random access response, 11 bit value , TA ranging from 0 … 1282

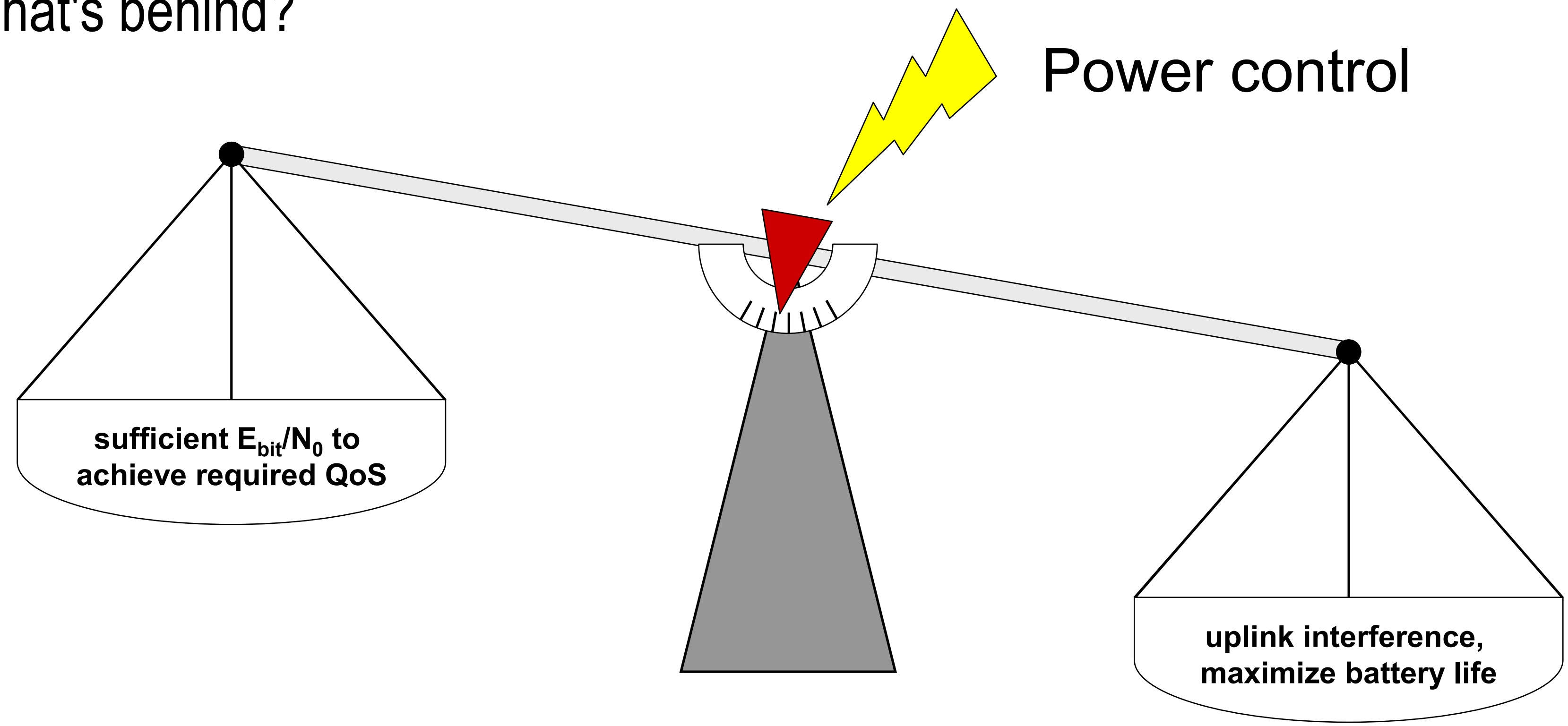
In connected mode, 6 bit value , TA ranging from 0 … 63, where $N_{TA,new} = N_{TA,old} + (TA - 31) \times 16$.
Dynamic change via MAC layer commands

Downlink power



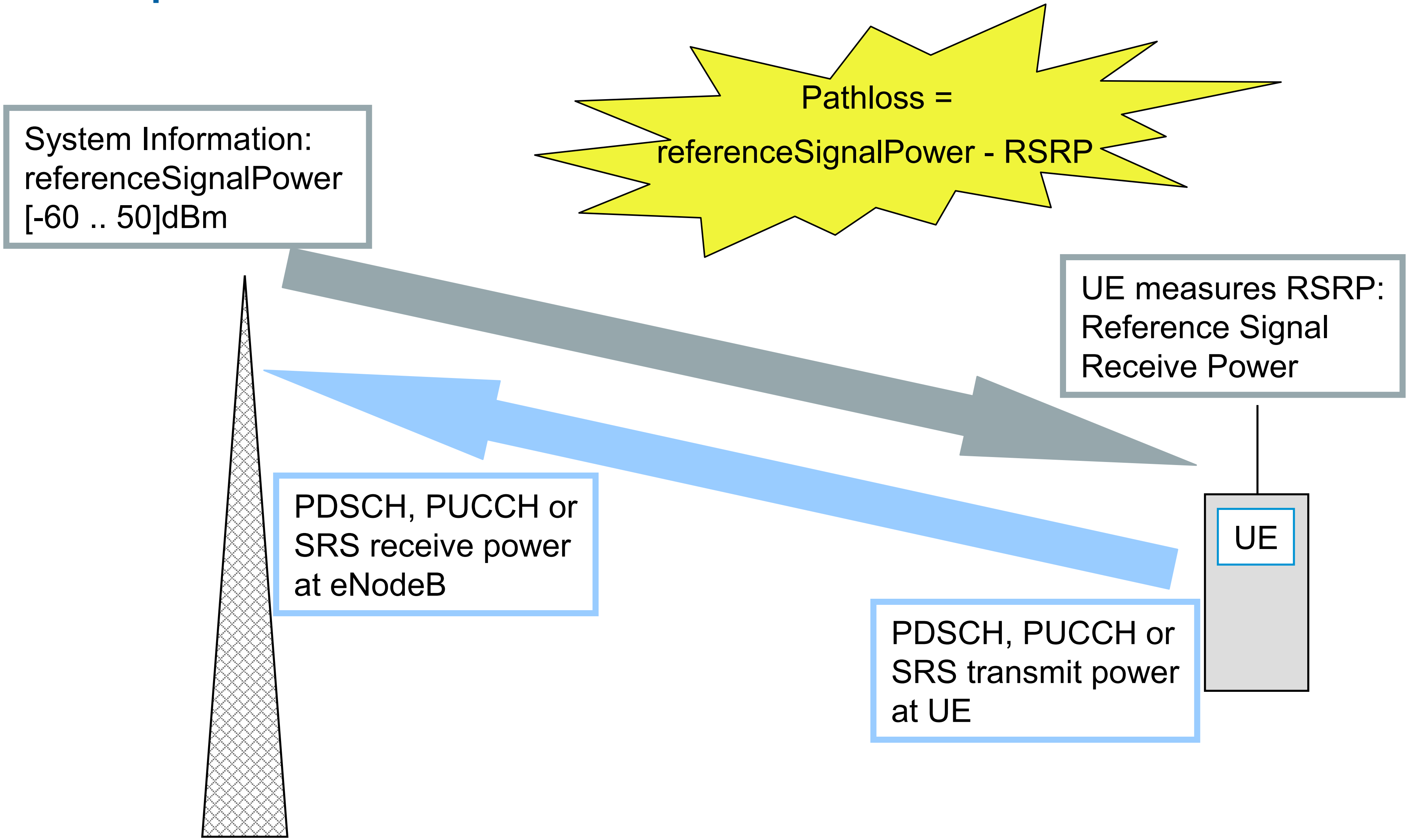
Uplink power control

What's behind?



- Characteristic of radio channel with multipath propagation (path loss, shadowing, fast fading) as well as the interference “provided” through other users – both within the same cell and from neighboring cells – needs to be considered to find the balance,

LTE power control



Types of transmit power control

TPC

(Transmit Power Control)

open loop Power Control

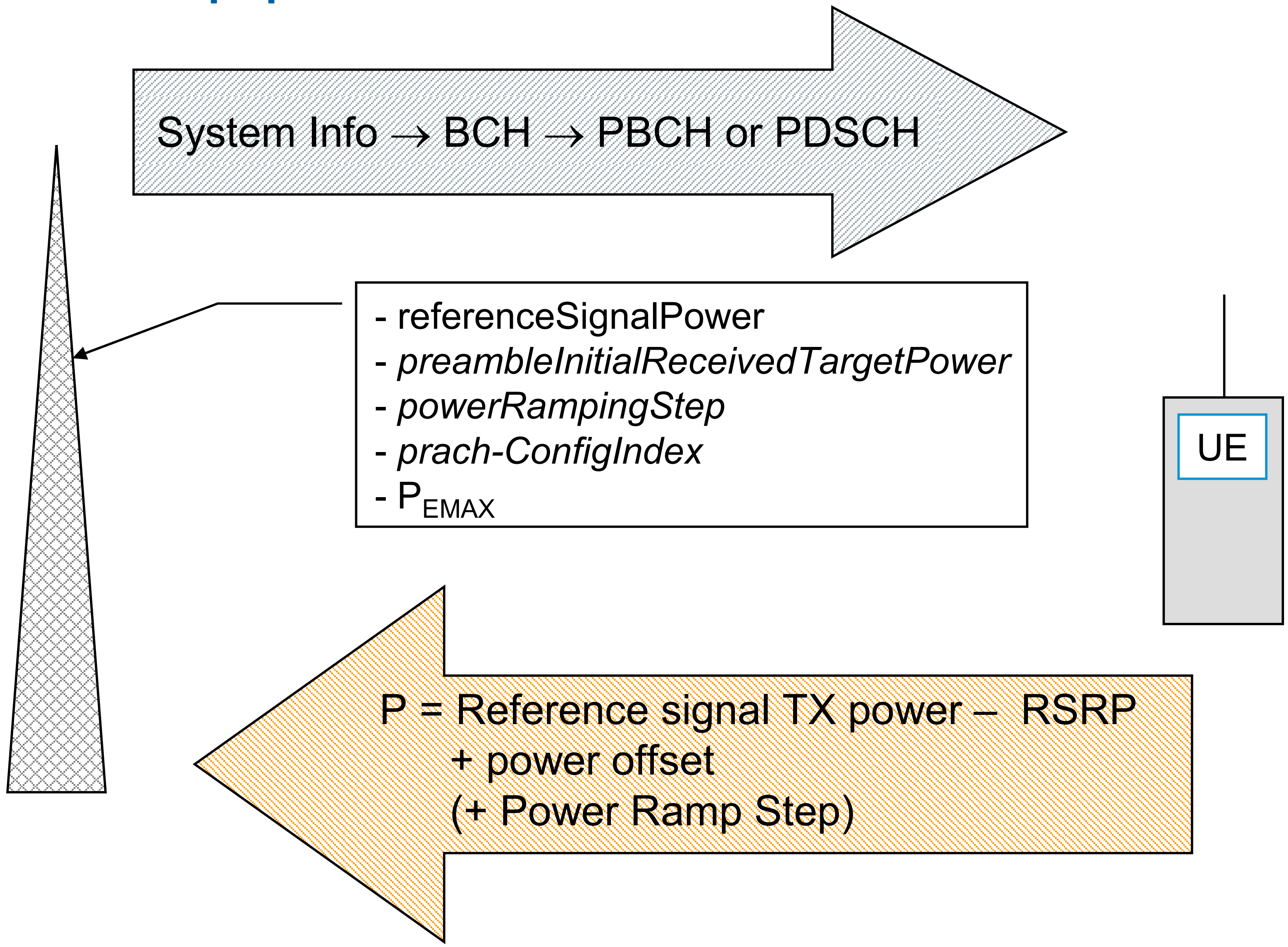
closed loop Power Control

For random access procedure

In connected mode:

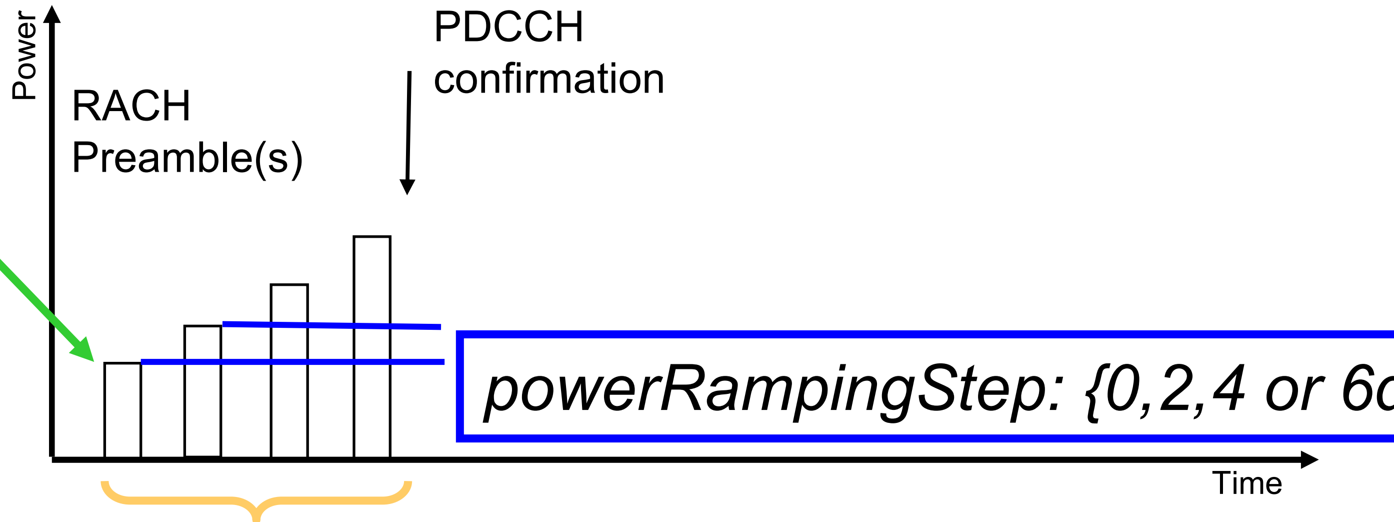
Power control to compensate fading

LTE Open loop power control



PRACH procedure

preambleInitialReceivedTargetPower {-120..-90dBm}
+ *DELTA_PREAMBLE* {-3, 0, 8dB} from preamble_index.



Preamble contains RA-RNTI

powerRampingStep: {0,2,4 or 6dB}

preambleTransMax in SIB2 indicates maximum number of PRACH preambles

RA-RNTI = Random Acces Radio Network Transaction Identifier

PRACH Power

Max. power for that cell

Max. UE power

Pathloss estimation at UE

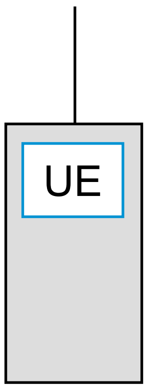
$P_{CMAX}=\min\{P_{EMAX}; P_{UMAX}\}$

$P_{PRACH} = \min\{P_{CMAX},\ \text{PREAMBLE\_RECEIVED\_TARGET\_POWER} + PL\}$

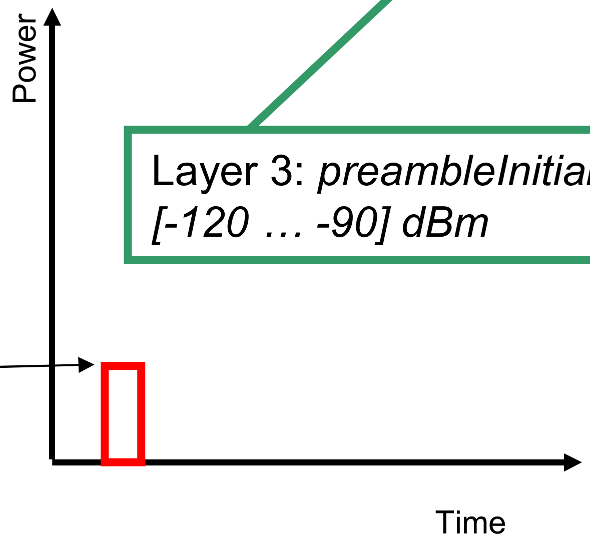
PREAMBLE_RECEIVED_TARGET_POWER = *preambleInitialReceivedTargetPower* + DELTA_PREAMBLE

Layer 3: *prach-ConfigIndex*
[-3, 0, 8] dB

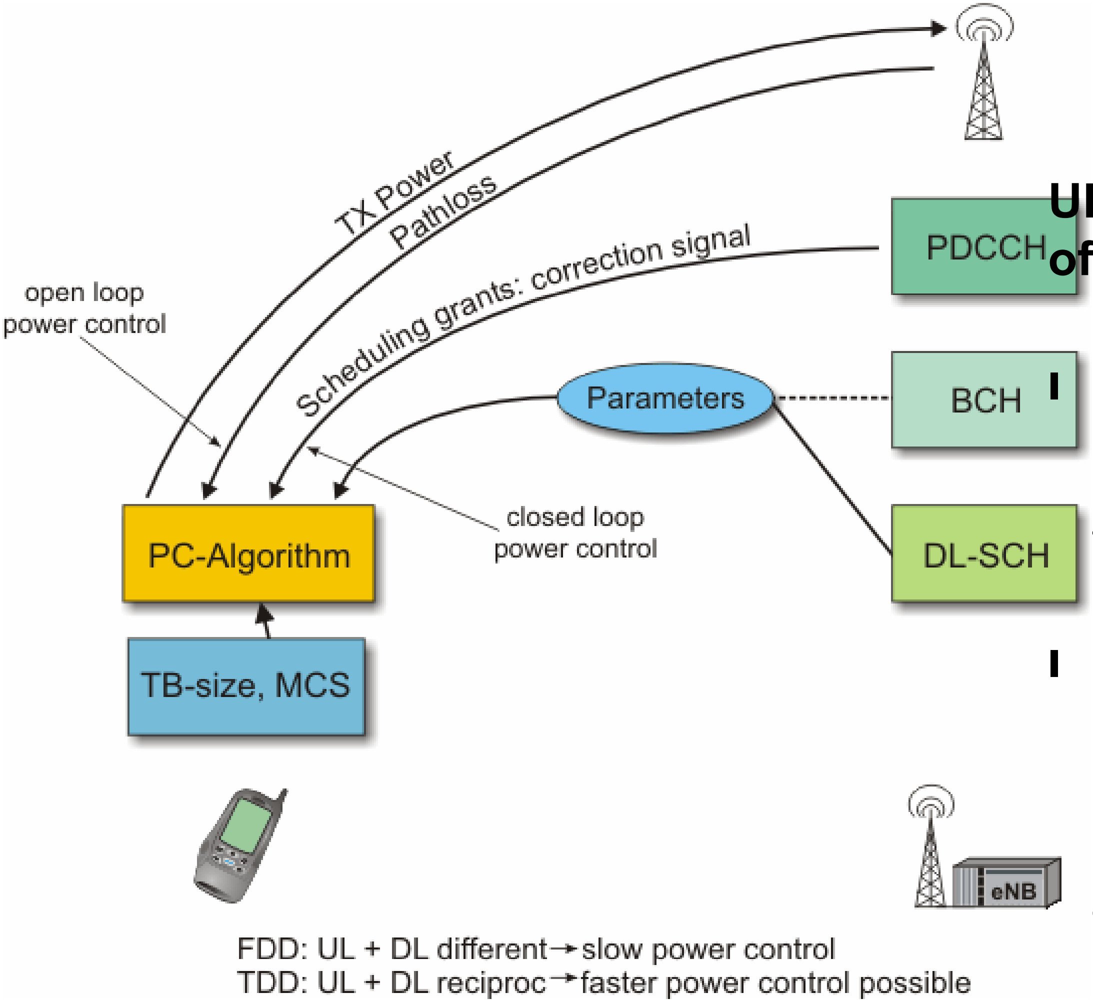
Layer 3: *preambleInitialReceivedTargetPower*
[-120 … -90] dBm



Open Loop: UE sends PRACH preamble at certain power level



UL Power Control: Overview

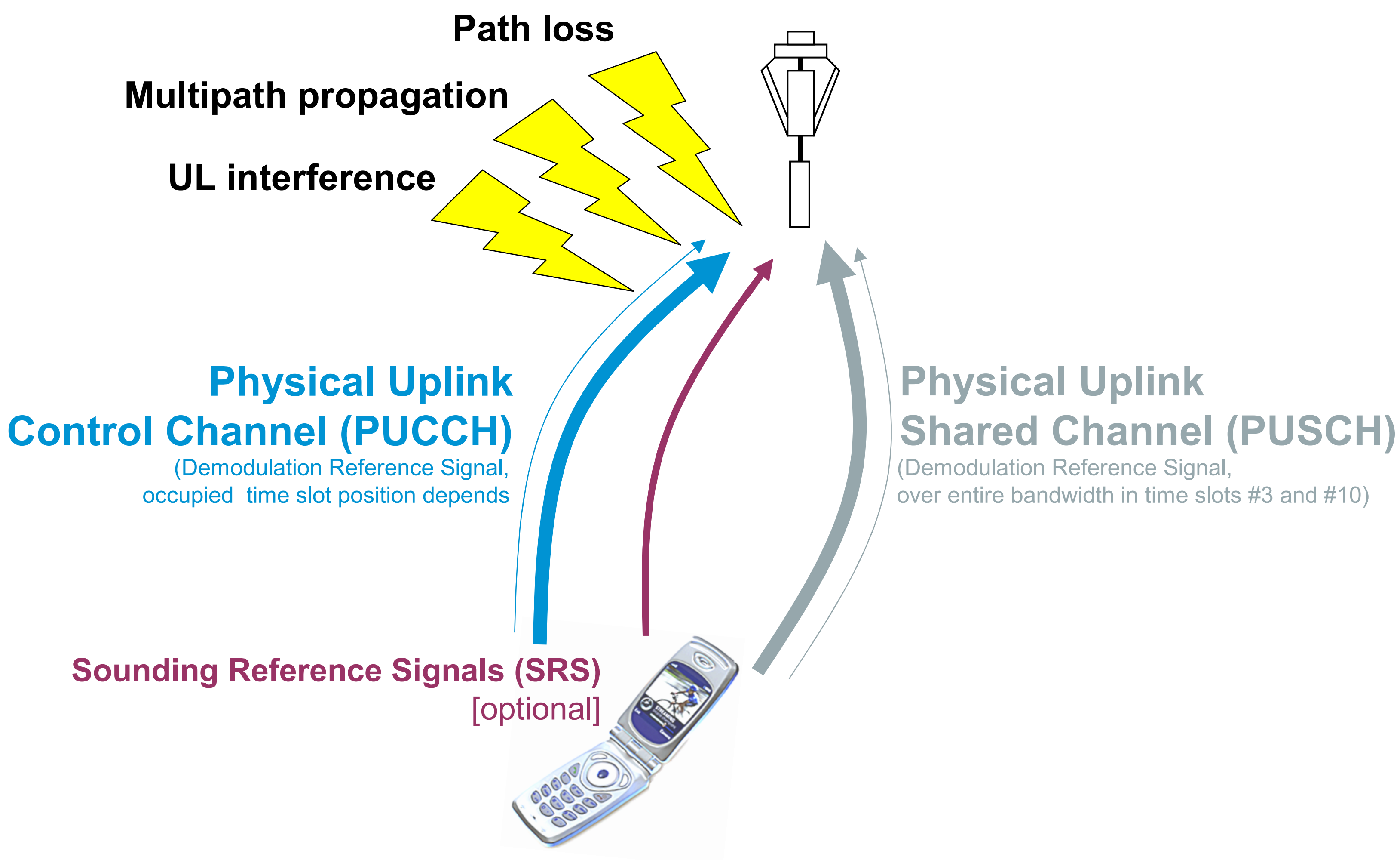


UL-PC is a combination of:

- Open-loop:
  UE estimates the DL-Path-loss and *compensates* it for the UL
- Closed-loop:
  in addition, the eNB controls directly the UL-Power through *power-control commands* transmitted on the DL

What is power controlled in the uplink?

Physical channels and signals in the uplink



PUSCH power control

Physical Uplink Shared Channel

- Power level [dBm] of PUSCH is calculated every subframe i based on the following formula out of TS 36.213 V8.7.0 (June '09 baseline),

Maximum allowed UE power in this particular cell, but at maximum +23 dBm[1)]

Combination of cell- and UE-specific components configured by L3

PUSCH transport format

$$P_{\mathrm{PUSCH}}(i) = \min\{P_{\mathrm{CMAX}}, \boxed{10\log_{10}(M_{\mathrm{PUSCH}}(i))} + \boxed{P_{\mathrm{O\_PUSCH}}(j) + \alpha(j)\cdot PL} + \boxed{\Delta_{\mathrm{TF}}(i) + f(i)}\}$$

Transmit power for PUSCH in subframe i in dBm

Number of allocated resource blocks (RB)

Cell-specific parameter configured by L3

Downlink path loss estimate

Power control adjustment derived from TPC command received in subframe (i-4)

Bandwidth factor **Basic open-loop starting point** **Dynamic offset (closed loop)**

1) +23 dBm is maximum allowed power in LTE according to TS 36.101, corresponding to power class 3bis in WCDMA

PUSCH power control

P_{CMAX}

$$P_{PUSCH}(i) = \min\{\boxed{P_{CMAX}}, 10\log_{10}(M_{PUSCH}(i)) + P_{O\_PUSCH}(j) + \alpha(j)\cdot PL + \Delta_{TF}(i) + f(i)\}$$

- **P_{CMAX}=min{P_{EMAX}; P_{UMAX}}**
  - P_{EMAX} is the maximum allowed power for this particular radio cell configured by higher layers and corresponds to P-MAX information element (IE) provided in SIB Type 1,

SystemInformationBlockType1 message

```
-- ASN1START

SystemInformationBlockType1 ::=     SEQUENCE {
    cellAccessRelatedInfo               SEQUENCE {
        plmn-IdentityList                   PLMN-IdentityList,
        trackingAreaCode                    TrackingAreaCode,
        cellIdentity                        CellIdentity,
        cellBarred                          ENUMERATED {barred, notBarred},
        intraFreqReselection                ENUMERATED {allowed, notAllowed},
        csg-Indication                      BOOLEAN,
        csg-Identity                        BIT STRING (SIZE (27))  OPTIONAL    -- Need OR
    },
    cellSelectionInfo                   SEQUENCE {
        q-RxLevMin                          Q-RxLevMin,
        q-RxLevMinOffset                    INTEGER (1..8)          OPTIONAL    -- Need OP
    },
    p-Max                               P-Max                       OPTIONAL,         -- Need OP
    freqBandIndicator                   INTEGER (1..64),
    schedulingInfoList                  SchedulingInfoList,
    tdd-Config                          TDD-Config                  OPTIONAL,   -- Cond TDD
    si-WindowLength                     ENUMERATED {
                                            ms1, ms2, ms5, ms10, ms15, ms20,
                                            ms40}
                                                                    OPTIONAL    -- Need OP
```

P-Max information element

```
-- ASN1START

P-Max ::=                   INTEGER (-30..33)

-- ASN1STOP
```

  - P_{UMAX} is the maximum UE power, defined as +23 dBm ± 2dB corresponding to power class 3bis in WCDMA,
    - Based on higher order modulation schemes and used transmission bandwidth a Maximum Power Reduction (MPR) is applied and the UE maximum transmission power is further reduced (see TS 36.101, table 6.2.3-1),
    - Network signaling (NS_0x) might be used in a cell to further reduce maximum UE transmission power (= Additional MPR (A-MPR); see TS 36.101, Table 6.2.4-1)

PUSCH power control

M_{PUSCH}

$$P_{PUSCH}(i) = \min\{P_{CMAX}, 10\log_{10}(M_{PUSCH}(i)) + P_{O\_PUSCH}(j) + \alpha(j)\cdot PL + \Delta_{TF}(i) + f(i)\}$$

- **Power calculation depends also on allocated resource blocks for uplink data transmission,**
  - Number of RB depends on configured bandwidth, but further not each number of RB is a suitable allocation,
  - DCI format 0 and resource allocation type 2 is used to allocated resource blocks to the UE
    - Resource allocation type 2 means in general allocation of contiguously RB,
    - *Resource Indication Value* (RIV) is signaled to the UE, calculated as follows:

Bandwidth,
e.g. 10 MHz = 50 RB

$$\boxed{(L_{CRBs}} - 1) \le \left\lfloor \boxed{N_{RB}^{UL}} / 2 \right\rfloor \quad then$$

Offset in # of RB, e.g. 15 RB

# of allocated RB,
e.g. 27 RB,…

$$RIV = N_{RB}^{UL}(L_{CRBs} - 1) + \boxed{RB_{START}} \quad else$$

$$RIV = N_{RB}^{UL}(N_{RB}^{UL} - L_{CRBs} + 1) + (N_{RB}^{UL} - 1 - RB_{START})$$

…must fulfill this requirement!

$$\boxed{M_{RB}^{PUSCH} = 2^{\alpha_2}\cdot 3^{\alpha_3}\cdot 5^{\alpha_5} \le N_{RB}^{UL}}$$

- where α_2, α_3 and α_5 are any integer value,

PUSCH power control

$P_{0\_PUSCH}(j)$

$$P_{PUSCH}(i) = \min\{P_{CMAX}, 10\log_{10}(M_{PUSCH}(i)) + \boxed{P_{O\_PUSCH}(j)} + \alpha(j)\cdot PL + \Delta_{TF}(i) + f(i)\}$$

- **$P_{0\_PUSCH}(j)$ is a combination of cell- and UE-specific components, configured by higher layers[1]:**

  Full path loss compensation is considered…
  …no path loss compensation is used.

  - $P_{0\_PUSCH}(j) = P_{0\_NOMINAL\_PUSCH}(j) + P_{0\_UE\_PUSCH}(j)$, ⇨ j = {0, 1},
    - $P_{0\_NOMINAL\_PUSCH}(j)$ in the range of -126…+24 dBm is used to have different BLER operating points to achieve lower probability of retransmissions,
    - $P_{0\_UE\_PUSCH}(j)$ in the range of -8…7 dB is used by the eNB to compensate systematic offsets in the UE's transmission power settings arising from a wrongly estimated path loss,
  - j = 0 ⇨ for semi-persistent scheduling (SPS), j = 1 ⇨ for dynamic scheduling,
  - j = 2 ⇨ for transmissions corresponding to the retransmission of the random access response,
    - For j = 2: $P_{0\_UE\_PUSCH}(2) = 0$ and $P_{0\_NOMINAL\_PUSCH}(2) = P_{0\_PRE} + \Delta_{PREAMBLE\_Msg3}$, where P_{0_PRE} and $\Delta_{PREAMBLE\_Msg3}$ are provided by higher layers,
      - P_{0_PRE} is understood as *Preamble Initial Received Target Power* provided by higher layers and is in the range of -120…-90 dBm,
      - $\Delta_{PREAMBLE\_Msg3}$ is in the range of -1…6, where the signaled integer value is multiplied by 2 and is than the actual power value in dB,

[1] see next slide(s) respectively TS 36.331 V8.6.0 Radio Resource Control specification

PUSCH power control

$P_{0\_PUSCH}(j)$

$$P_{PUSCH}(i) = \min\{P_{CMAX}, 10\log_{10}(M_{PUSCH}(i)) + \boxed{P_{O\_PUSCH}(j)} + \alpha(j)\cdot PL + \Delta_{TF}(i) + f(i)\}$$

- *UplinkPowerControl* IE contains the required information about $P_{0\_Nominal\_PUSCH}$, $P_{0\_UE\_PUSCH}$, $\Delta_{PREAMBLE\_Msg3}$ are part of *RadioResourceConfigCommon,*

- Via *RadioResourceConfigCommon* the terminal gets also access to *RACH-ConfigCommon* to extract from there information like *Preamble Initial Received Target Power* (P_{0_PRE}),

- *RadioResourceConfigCommon* IE is part of *System Information Block Type 2* (SIB Type 2),
  - System information (SI) in LTE are organized in System Information Blocks and are grouped in SI Messages when they do have same periodicity,
  - In contrast to WCDMA SI are not signaled on a dedicated channel, instead the shared channel transmission principle is used and they are transmitted on PDSCH,
  - SIB Type contains at all information about shared and common channels and is therefore part of each SI message and listed as first entry,

PUSCH power control

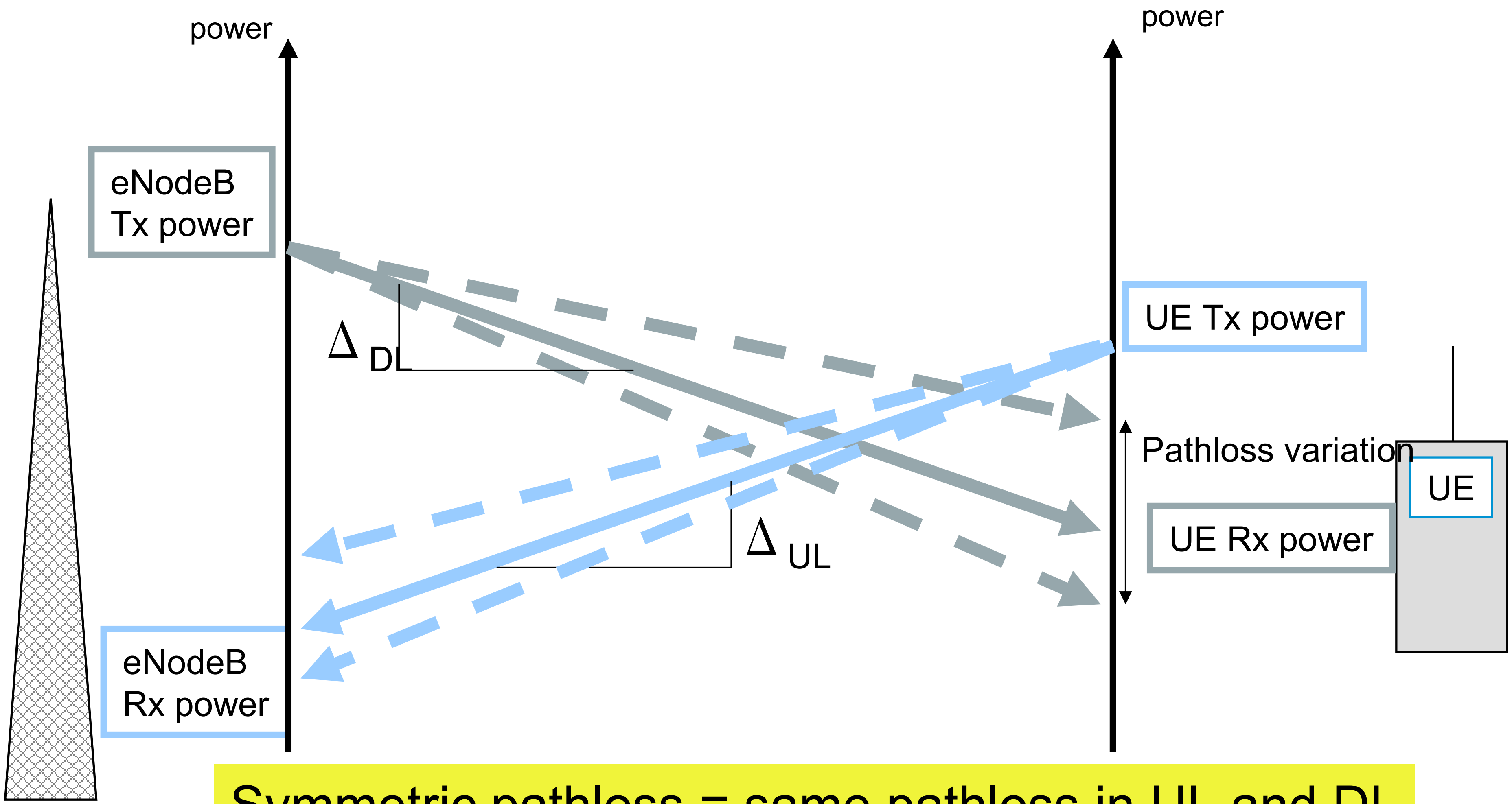
α (j) and PL

$$P_{\text{PUSCH}}(i) = \min\{P_{\text{CMAX}}, 10\log_{10}(M_{\text{PUSCH}}(i)) + P_{\text{O\_PUSCH}}(j) + \boxed{\alpha(j)\cdot PL} + \Delta_{\text{TF}}(i) + f(i)\}$$

- Path loss (PL) is estimated by measuring the power level (Reference Signal Receive Power, RSRP) of the cell-specific downlink reference signals (DLRS) and subtracting the measured value from the transmit power level of the DLRS provided by higher layers,
  - *SIB Type 2* ⇨ *RadioResourceConfigCommon* ⇨ *PDSCH-ConfigCommon*,

- α (j) is used as path-loss compensation factor as a trade-off between total uplink capacity and cell-edge data rate,
  - Full path-loss compensation maximizes fairness for cell-edge UE’s,
  - Partial path-loss compensation may increase total system capacity, as less resources are spent ensuring the success of transmissions from cell-edge UEs and less inter-cell interference is caused to neighboring cells,
    - For α (j=0, 1) can be 0, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0, where 0.7 or 0.8 give a close-to-maximum system capacity by providing an acceptable cell-edge performance,
    - For α (j=2) = 1.0,

LTE path loss compensation



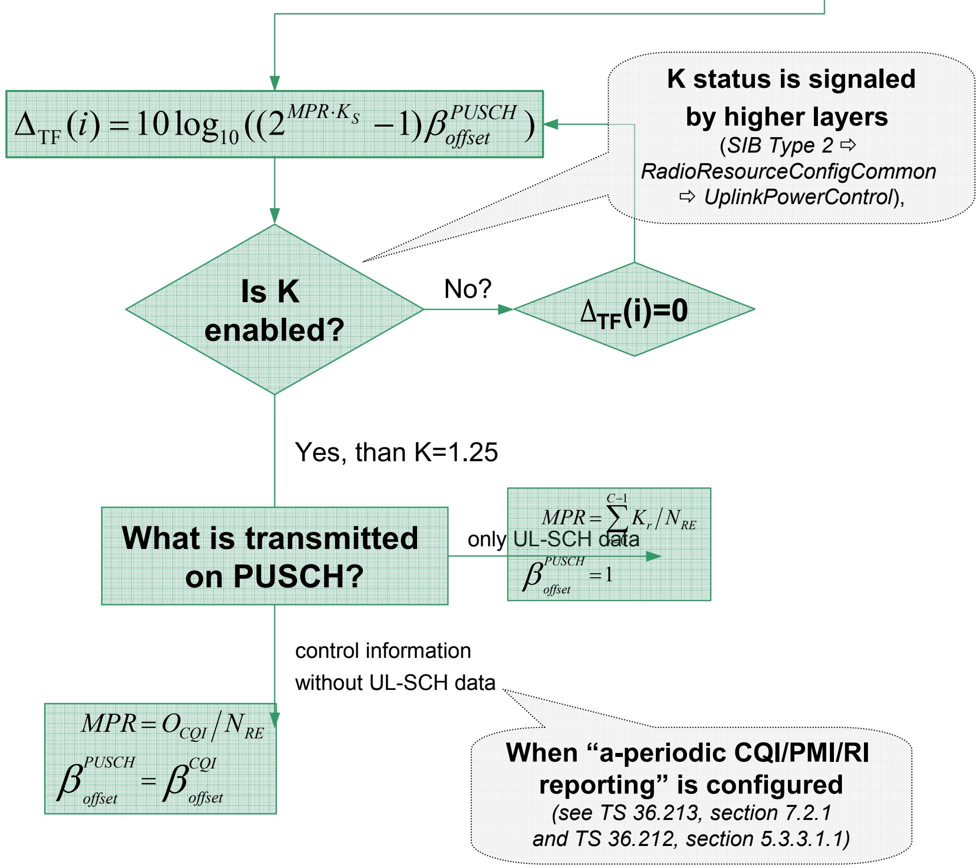
Symmetric pathloss = same pathloss in UL and DL

PUSCH power control

$\Delta_{TF}(i)$

$$P_{PUSCH}(i) = \min\{P_{CMAX}, 10\log_{10}(M_{PUSCH}(i)) + P_{O\_PUSCH}(j) + \alpha(j)\cdot PL + \boxed{\Delta_{TF}(i)} + f(i)\}$$

- $\Delta_{TF}(i)$ can be first seen as MCS-dependent component in the power control as it depends in the end on number of code blocks respectively bits per code blocks, which translates to a specific MCS,
- MCS the UE uses is under control of the eNB
  - Signaled by DCI format 0 on PDCCH, parameter can be understood as another way to control the power: when the MCS is changed, the power will increase or decrease,
- For the case that control information are send instead of user data (= "Aperiodic CQI reporting"), which is signaled by a specific bit in the UL scheduling grant, power offset are set by higher layers (see next slide),



O_{CQI}	Number of CQI bits incl. CRC bits
N_{RE}	Resource Elements
C	Number of code blocks,
K_r	Size of code block r,

PUSCH power control

f(i)

$$P_{\text{PUSCH}}(i) = \min\{P_{\text{CMAX}}, 10\log_{10}(M_{\text{PUSCH}}(i)) + P_{\text{O\_PUSCH}}(j) + \alpha(j)\cdot PL + \Delta_{\text{TF}}(i) + \boxed{f(i)}\}$$

- f(i) is the other component of the dynamic offset, UE-specific *Transmit Power Control* (TPC) commands, signaled with the uplink scheduling grant (PDCCH DCI format 0); two modes are defined: accumulative and absolute,
- ***Accumulative*** **TPC commands (for PUSCH, PUCCH, SRS).**
  – Power step relative to previous step, comparable with close-loop power control in WCDMA, difference available step sizes, which are δ_{PUSCH}={±1 dB or -1, 0, +1, +3 dB} for LTE, larger power steps can be achieved by combining TPC- and MCS-dependent power control, Activated at all by dedicated RRC signaling, disabled when minimum (-40 dBm) or maximum power (+23 dBm) is reached,
  – $f(i) = f(i-1) + \delta_{\text{PUSCH}}(i - K_{\text{PUSCH}})$, where K_{PUSCH} = 4 for FDD and depends on the UL-DL configuration for TD-LTE (see TS 36.213, table 5.1.1.1-1),
- ***Absolute*** **TPC commands (for PUSCH only).**
  – Power step of {-4, -1, +1, +4 dB} relative to the basic operating point (⇒ set by $P_{\text{O\_PUSCH}}(j) + \alpha(j)\cdot PL$; see previous slides),
  – $f(i) = \delta_{\text{PUSCH}}(i - K_{\text{PUSCH}})$, where K_{PUSCH}=4 for FDD and depends on the UL-DL configuration for TD-LTE (see TS 36.213, table 5.1.1.1-1),

PUSCH power control

UL scheduling grant (= PDCCH DCI format 0)

TPC commands (δ_{PUSCH})

- **Flag for format 0 and 1A differentiation – 1 bit,**
  - Indicates DCI format to the UE,
- **Hopping flag – 1 bit,**
  - Indicates whether uplink frequency hopping is used or not,
- **Resource block assignment and hopping resource allocation,**
  - Depending on resource allocation type,
- **Modulation and coding scheme, redundancy version – 5 bit,**
  - Indicates modulation scheme and, together with the number of allocated physical resource blocks the TBS,
- **New data indicator – 1 bit,**
  - Indicates whether a new transmission shall be sent
- **TPC command for scheduled PUSCH – 2 bit,**
  - Transmit Power Control (TPC) command for adapting the transmit power on PUSCH,
- **Cyclic shift for demodulation reference signal,**
  - Indicates the cyclic shift to use for deriving the uplink demodulation reference signal from base sequences,
- **UL Index – 2 bit,**
  - Indicates the UL subframe where the scheduling grant has to be applied,
- **DL Assignment Index (DAI) – 2 bit,**
  - Total # of subframes for PDSCH transmission,
- **CQI request – 1 bit,**
  - Requests the UE to send a CQI,

Modulation and Coding Scheme (MCS)

This bit configures APERIODIC CQI REPORTING

How to test PUSCH power control?

Parameters are signaled by higher layers, a *RRCConnectionReconfiguration* would be required to change parameters!

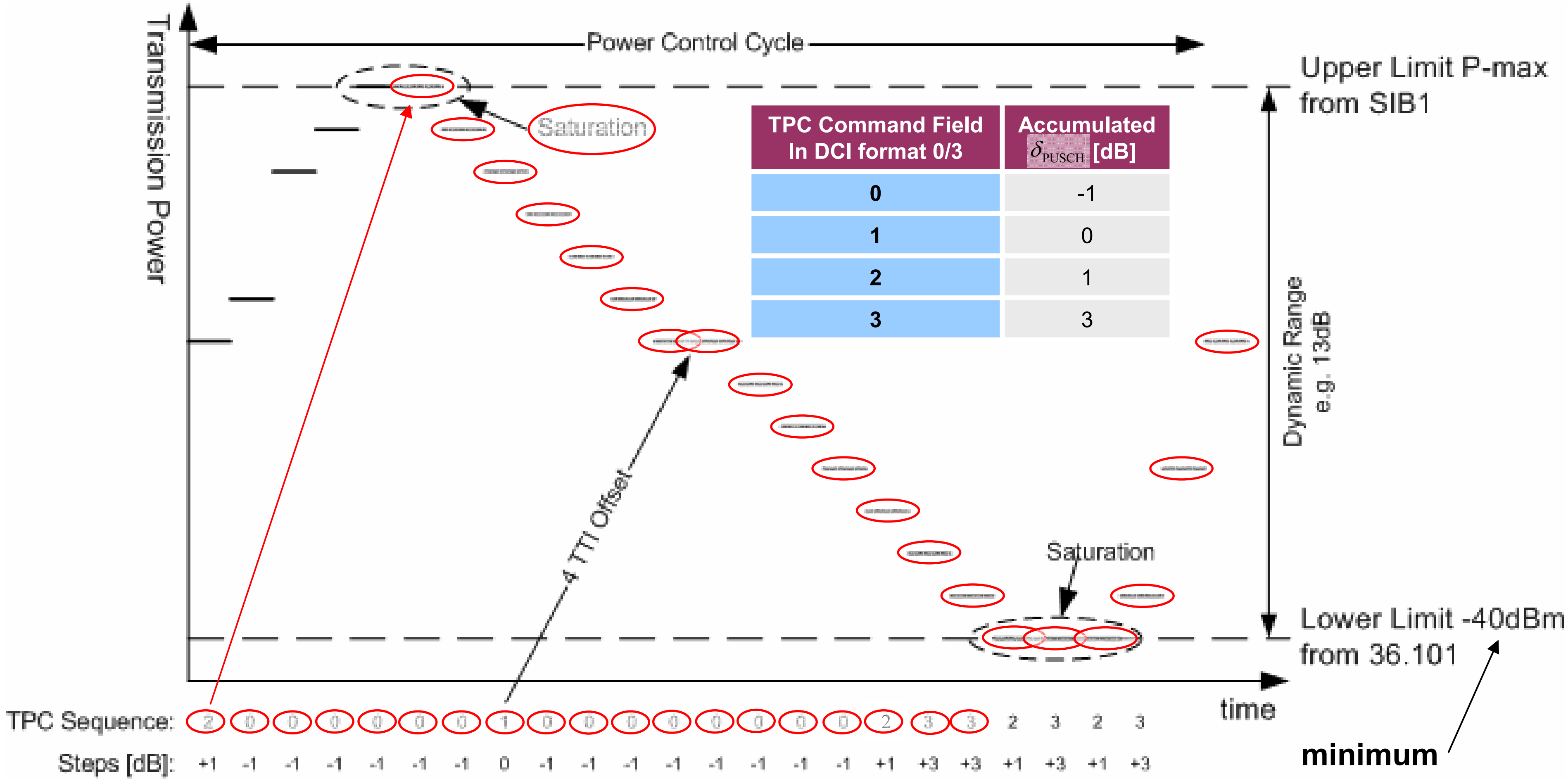
- **PUSCH power reaction on…**
  - TPC commands (accumulative and absolute),
  - PUSCH transport format changes,
  - Content to be transmitted (user data or control information),
  - Path loss changes (changing DL RS power),

$$P_{\mathrm{PUSCH}}(i) = \min\{P_{\mathrm{CMAX}}, \underbrace{\boxed{10\log_{10}(M_{\mathrm{PUSCH}}(i))}}_{\text{Bandwidth factor}} + \underbrace{\boxed{P_{\mathrm{O\_PUSCH}}(j) + \alpha(j)\cdot PL}}_{\text{Basic open-loop starting point}} + \underbrace{\boxed{\Delta_{\mathrm{TF}}(i) + f(i)}}_{\text{Dynamic offset (closed loop)}}\}$$

Bandwidth factor **Basic open-loop starting point** **Dynamic offset (closed loop)**

How to test power control?

PUSCH power control for accumulative TPC commands

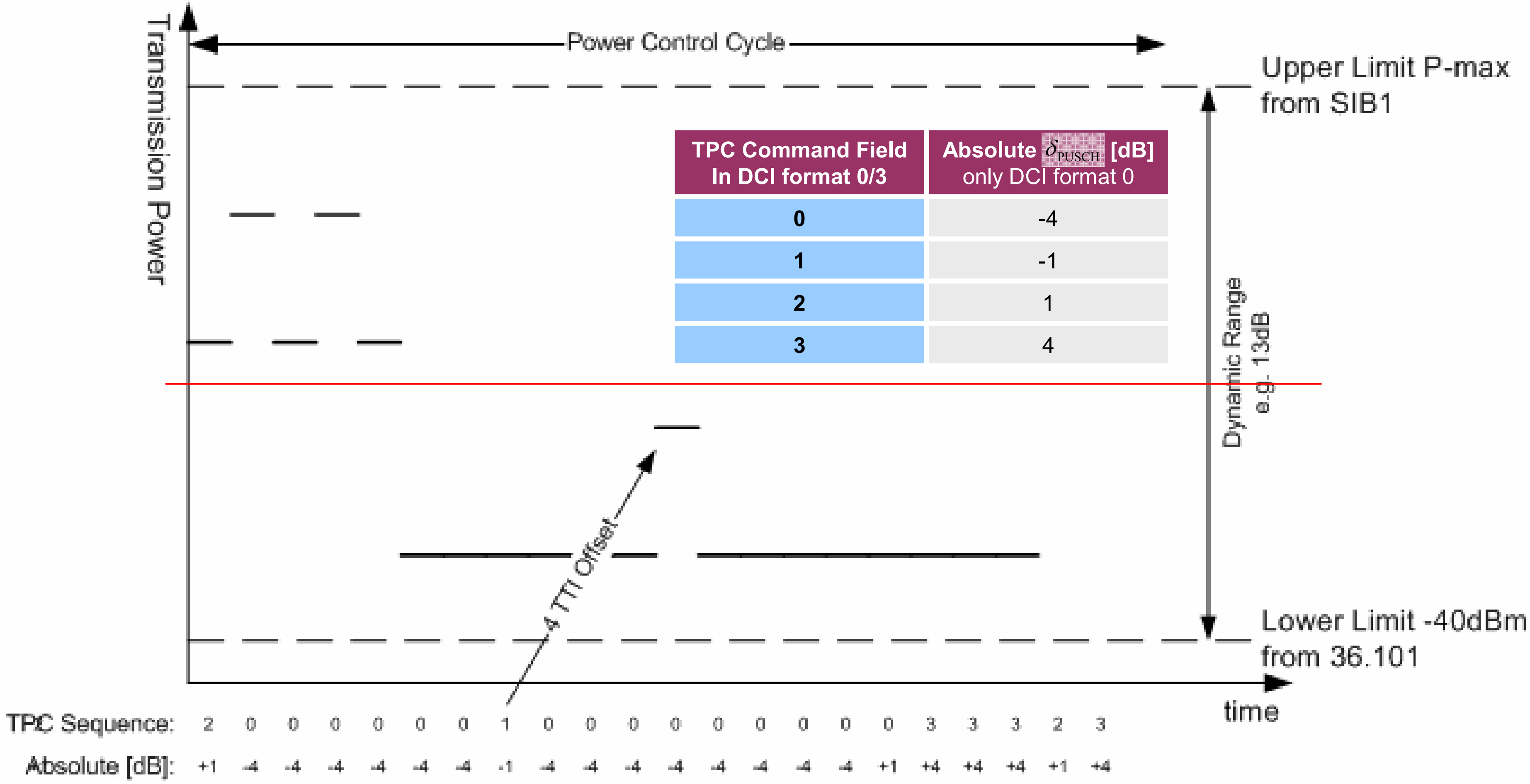


TPC Command Field In DCI format 0/3	Accumulated δ_{PUSCH} [dB]
0	-1
1	0
2	1
3	3

minimum power in LTE

How to test power control?

PUSCH power control for absolute TPC commands

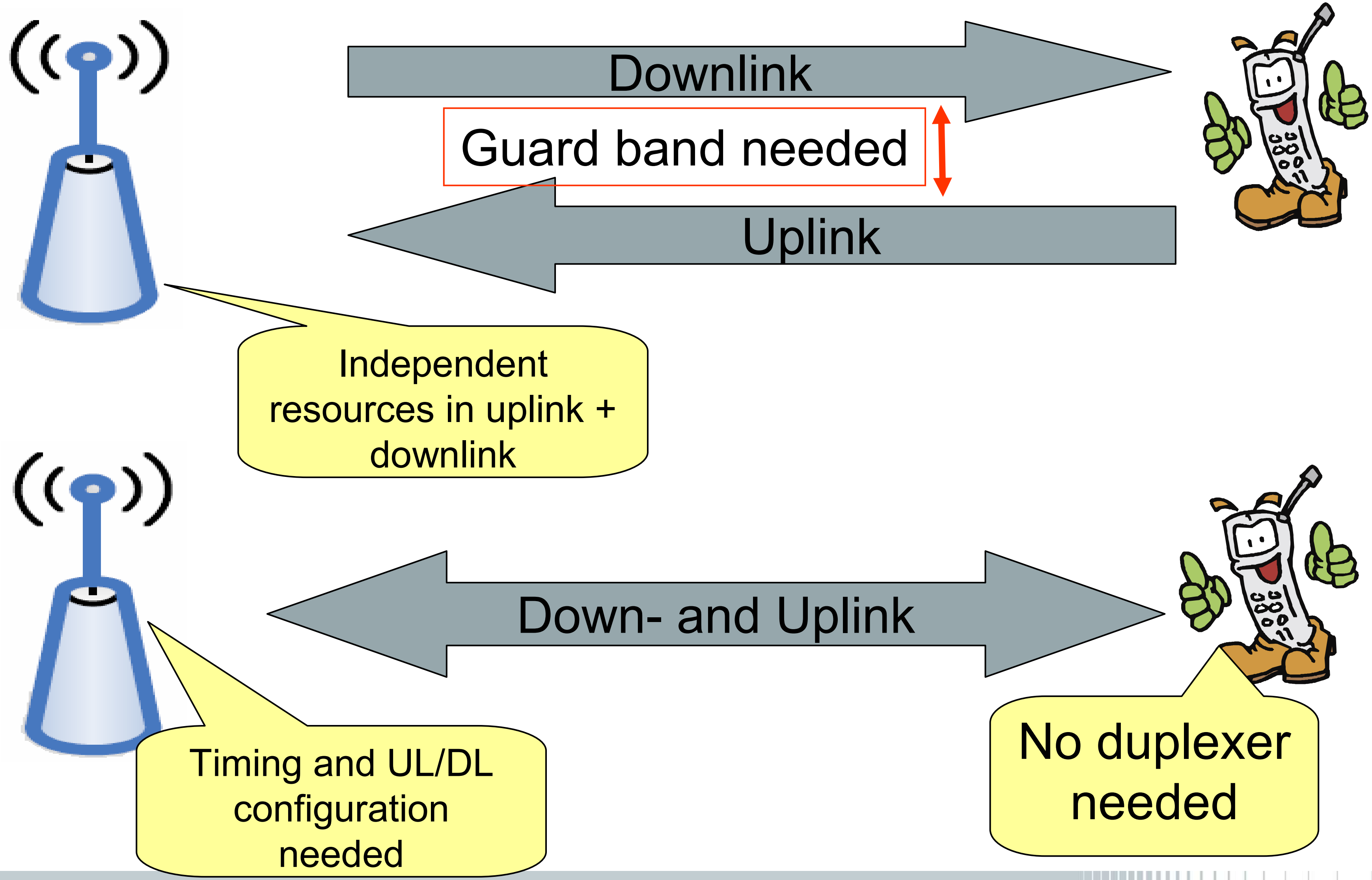


TPC Command Field In DCI format 0/3	Absolute δ_{PUSCH} [dB] only DCI format 0
0	-4
1	-1
2	1
3	4

75 Years of Driving Innovation

LTE TDD and FDD mode of operation

TDD versus FDD



Frequency band

- **For TDD mode, uplink and downlink is on the same frequency band**

E-UTRA BAND	Uplink (UL) eNode b receive UE transmit	Downlink (DL) eNode b transmit UE receive
	F_{UL_low} – F_{UL_high}	F_{DL_low} – F_{DL_high}
33	1900 MHz–1920 MHz	1900 MHz–1920 MHz
34	2010 MHz–2025 MHz	2010 MHz–2025 MHz
35	1850 MHz – 1910 MHz	1850 MHz – 1910 MHz
36	1930 MHz – 1990 MHz	1930 MHz – 1990 MHz
37	1910 MHz – 1930 MHz	1910 MHz – 1930 MHz
38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz
39	1880 MHz - 1920 MHz	1880 MHz - 1920 MHz
40	2300 MHz - 2400 MHz	2300 MHz - 2400 MHz

- **Bandwidth**

Channel bandwidth [MHz]	1.4	3	5	10	15	20
FDD mode	6	15	25	50	75	100
TDD mode	6	15	25	50	75	100

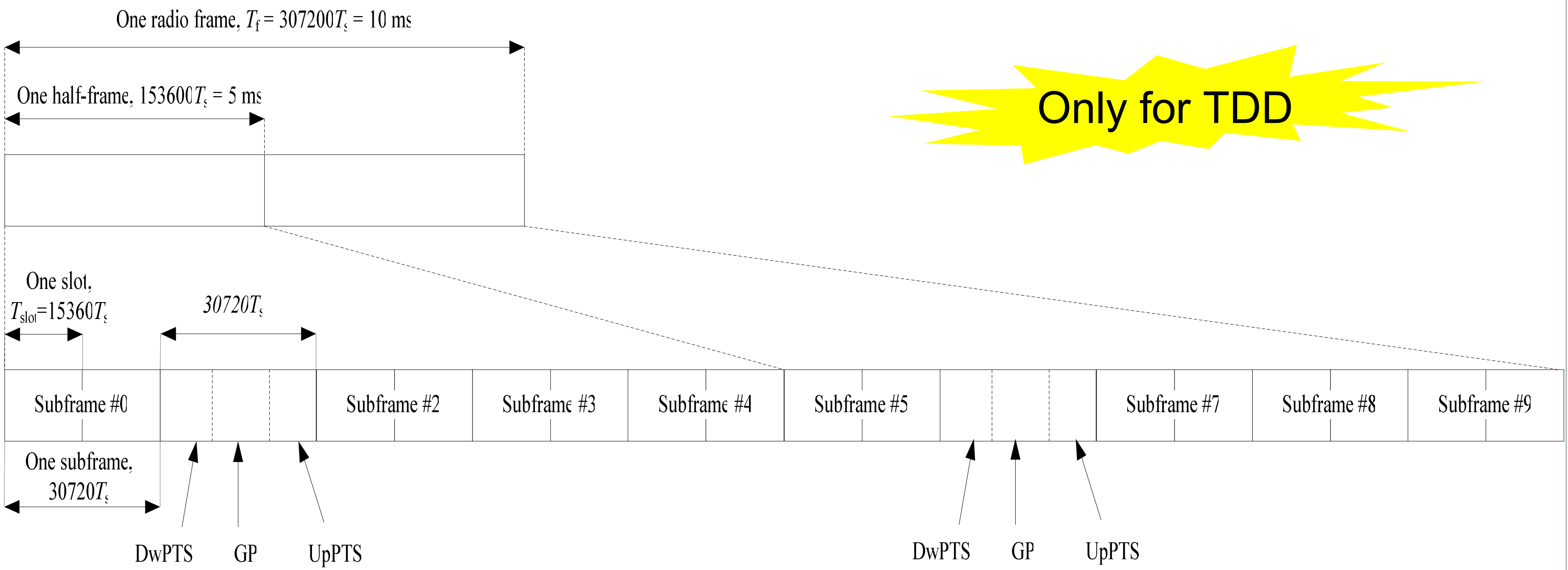
number of resource blocks

LTE TDD mode – frequency bands

TD-LTE frequency bands and their regions

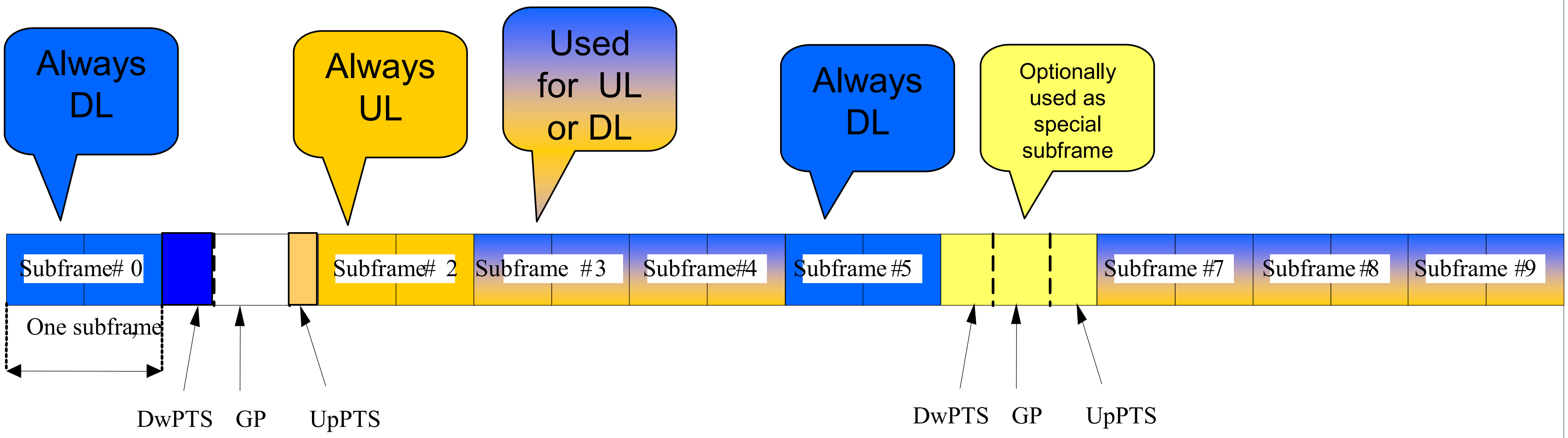
E-UTRA Operating Band	Operating Frequency	Main region(s)
33	1900 MHz - 1920 MHz	Europe, Asia (not Japan)
34	2010 MHz - 2025 MHz	Europe, Asia
35	1850 MHz - 1910 MHz	-
36	1930 MHz - 1990 MHz	-
37	1910 MHZ - 1930 MHz	-
38	2570 MHz - 2620 MHz	Europe
39	1880 MHz - 1920 MHz	China
40	2300 MHz - 2400 MHz	Europe, Asia

LTE Downlink:
Downlink slot and frame structure: type 2



DwPTS = Downlink Pilot Time Slot
UpPTS = Uplink Pilot Time Slot

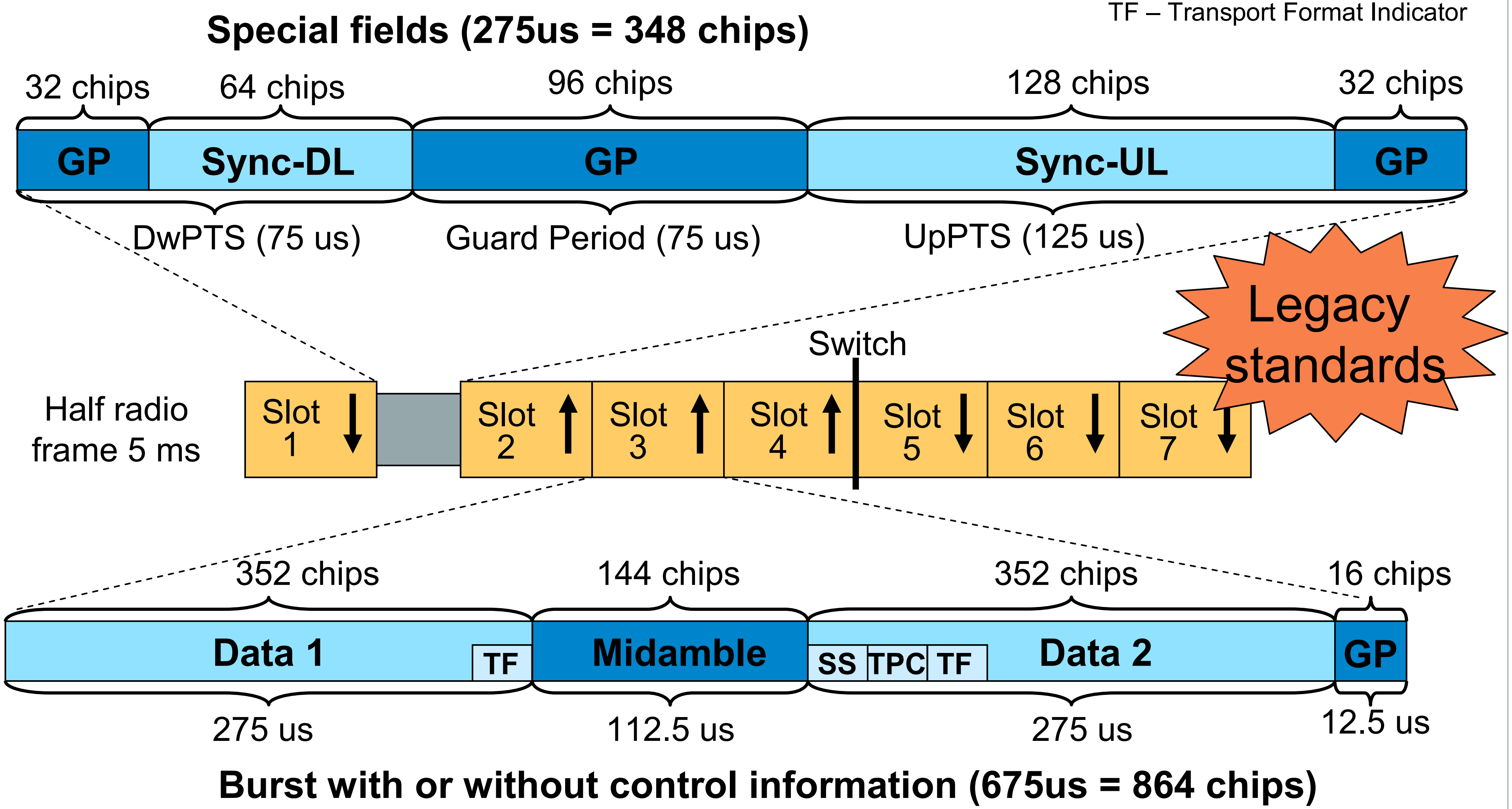
LTE TDD: frame structure type 2



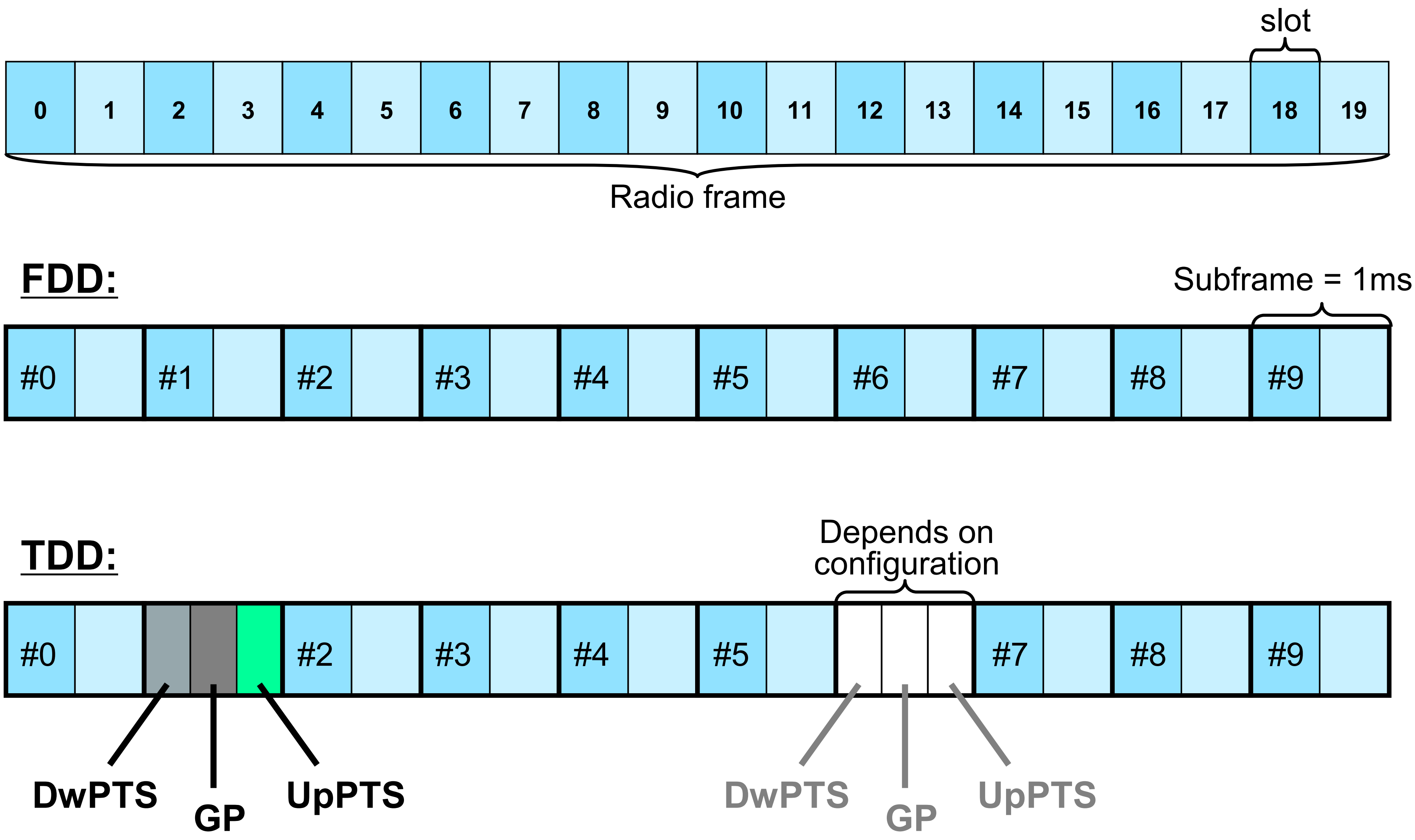
DwPTS = PDCCH, P-Sync, Reference symbol, User Data
GP = main Guard Period for TDD operation
UpPTS = PRACH, sounding reference signal

TD-SCDMA/ UTRA-LCR-TDD Frame Structure

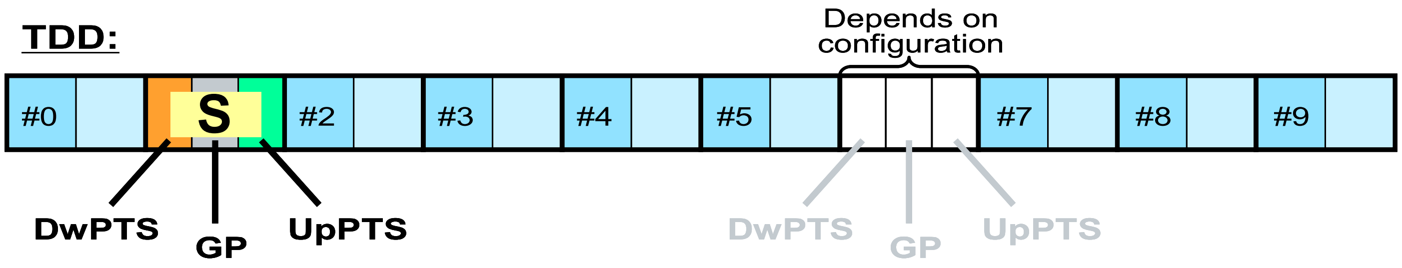
SS – Synchronization Shift
(SS space in uplink unused)
TPC – Transmit Power Control
TF – Transport Format Indicator



TDD versus FDD Frame



TDD Uplink-Downlink Switch-Points



Uplink-downlink configuration	Downlink-to-Uplink Switch-point periodicity	Subframe number									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

D = Subframe is reserved for downlink transmissions

U = Subframe is reserved for uplink transmissions

S = Special subframe containing the three fields DwPTS, GP and UpPTS

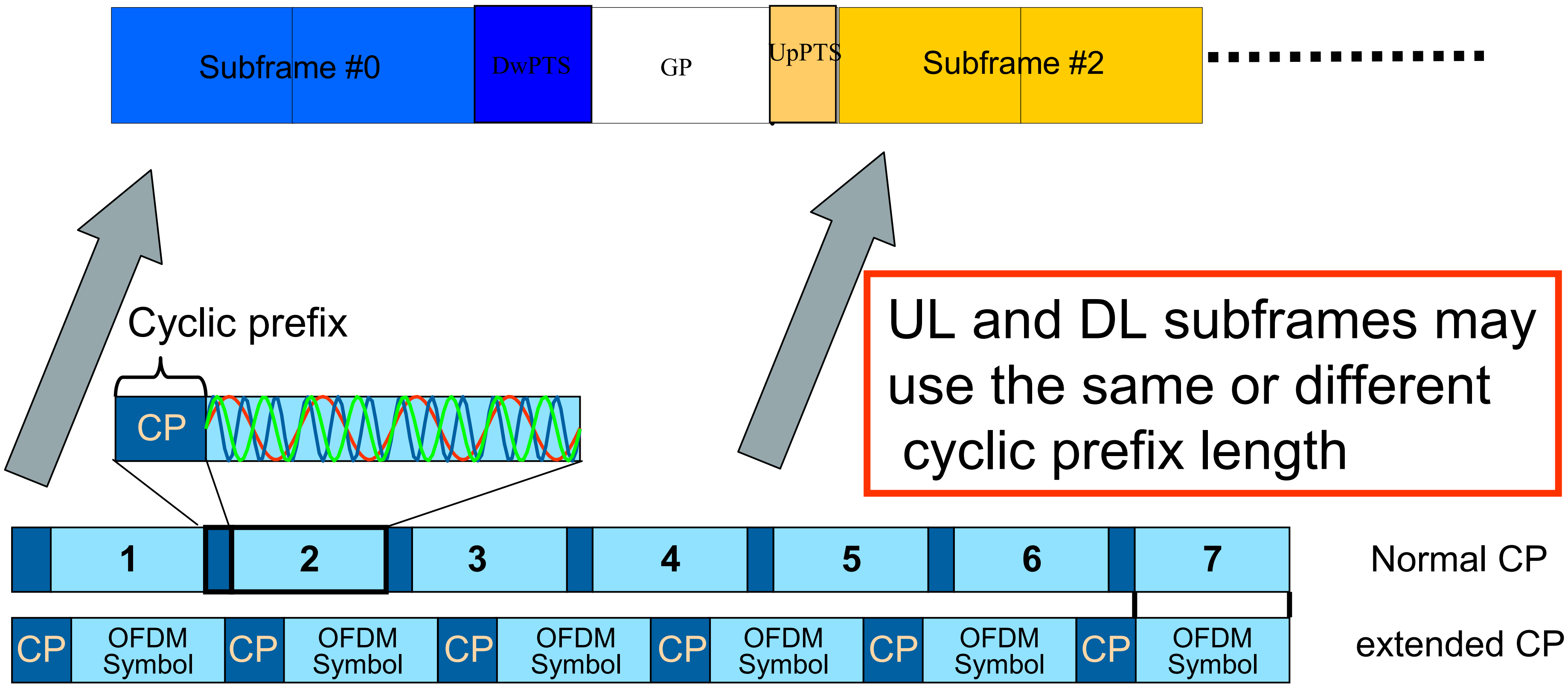
TDD Uplink-Downlink configuration: data rate

Uplink-downlink configuration	Subframe number										Peak data rate (Mbit/sec)	
	0	1	2	3	4	5	6	7	8	9	Downlink	Uplink
0	D	S	U	U	U	D	S	U	U	U	51.5	29.4
1	D	S	U	U	D	D	S	U	U	D	81.4	19.6
2	D	S	U	D	D	D	S	U	D	D	111.6	9.8
3	D	S	U	U	U	D	D	D	D	D	101	14.7
4	D	S	U	U	D	D	D	D	D	D	116.1	9.8
5	D	S	U	D	D	D	D	D	D	D	131.6	4.9
6	D	S	U	U	U	D	S	U	U	D	66.3	24.5

First requirements

- D = Subframe is reserved for downlink transmissions
- U = Subframe is reserved for uplink transmissions
- S = Special subframe containing the three fields DwPTS, GP and UpPTS

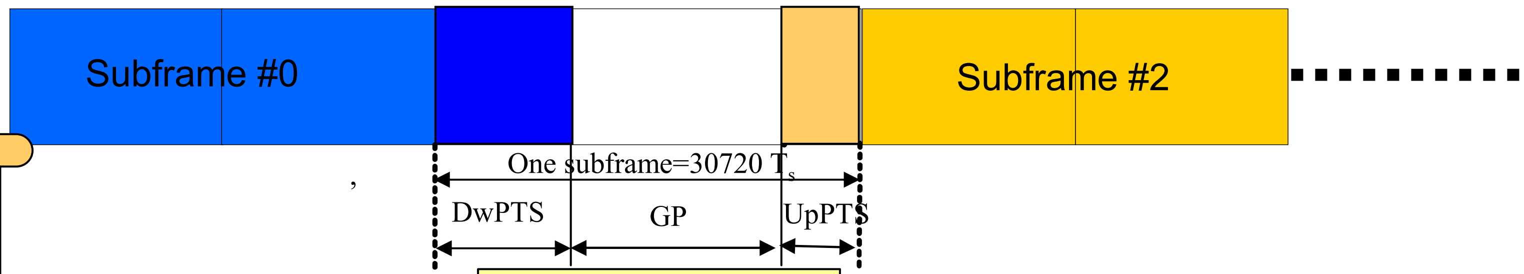
LTE TDD: cyclic prefix used in UL and DL



UL and DL subframes may use the same or different cyclic prefix length

LTE TDD: special subframe configurations

How does the special subframe look like?



SysInfo informs about configuration

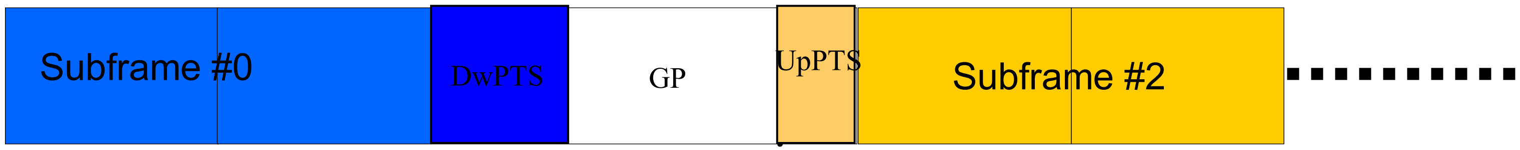
Timing given by:

Special subframe configuration	Normal cyclic prefix in downlink: DwPTS	Normal cyclic prefix in downlink: UpPTS, Normal cyclic prefix in uplink	Normal cyclic prefix in downlink: UpPTS, Extended cyclic prefix in uplink	Extended cyclic prefix in downlink: DwPTS	Extended cyclic prefix in downlink: UpPTS, Normal cyclic prefix in uplink	Extended cyclic prefix in downlink: UpPTS, Extended cyclic prefix in uplink
0	$6592 \cdot T_s$	$2192 \cdot T_s$	$2560 \cdot T_s$	$7680 \cdot T_s$	$2192 \cdot T_s$	$2560 \cdot T_s$
1	$19760 \cdot T_s$			$20480 \cdot T_s$		
2	$21952 \cdot T_s$			$23040 \cdot T_s$		
3	$24144 \cdot T_s$			$25600 \cdot T_s$		
4	$26336 \cdot T_s$			$7680 \cdot T_s$	$4384 \cdot T_s$	$5120 \cdot T_s$
5	$6592 \cdot T_s$	$4384 \cdot T_s$	$5120 \cdot T_s$	$20480 \cdot T_s$		
6	$19760 \cdot T_s$			$23040 \cdot T_s$		
7	$21952 \cdot T_s$			-	-	-
8	$24144 \cdot T_s$			-	-	-

Table from TS 36.211

LTE TDD: special subframe configurations

Special subframe configuration = maximum cell size



Timing given by:

Example for timing

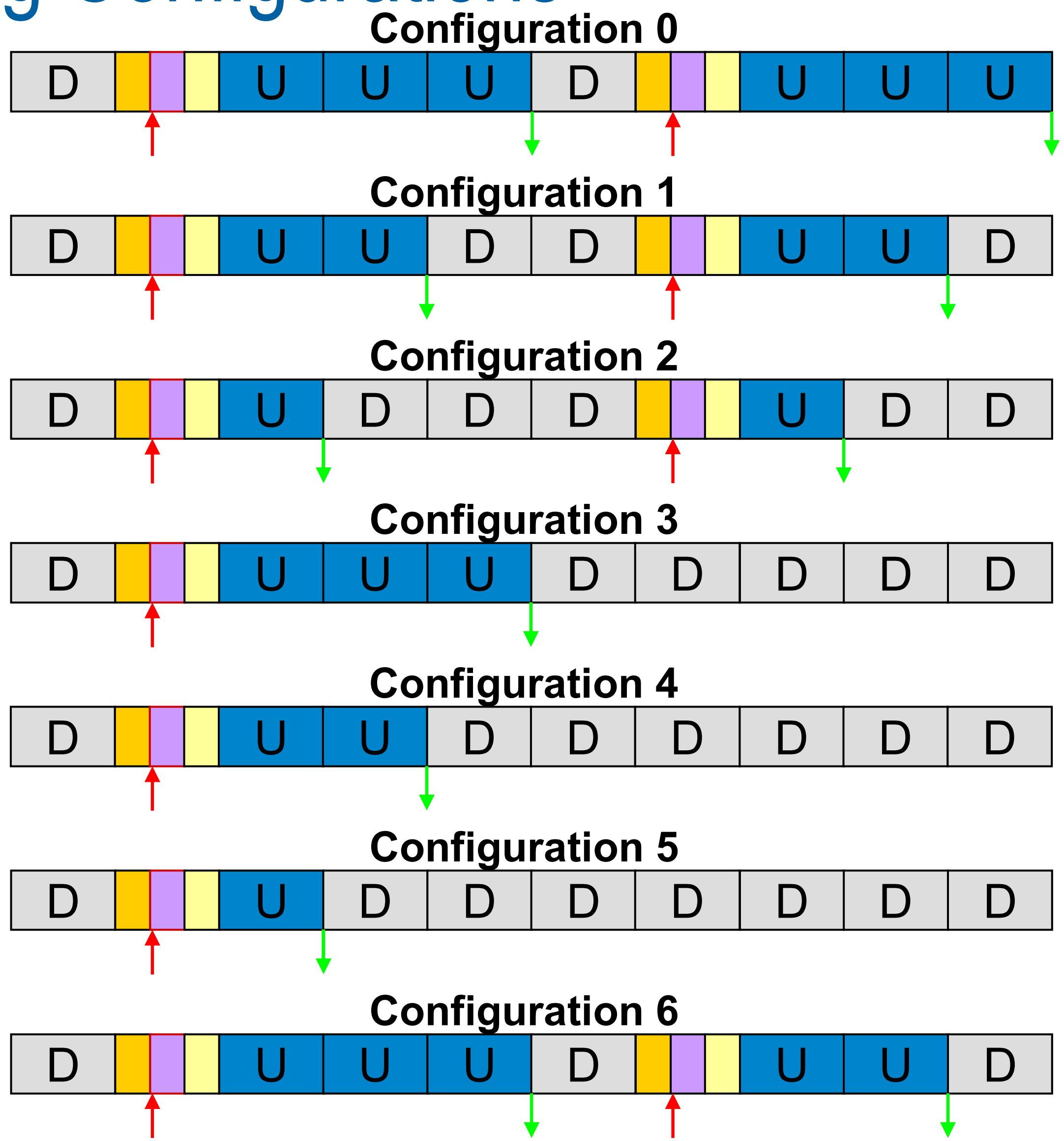
Number basis = 2192*T_s

Special subframe configuration	Normal Cyclic prefix in DL and UL			Max Cell size
	DwPTS	Guard Period	UpPTS	
0	3	10	1	100 km
1	9	4	1	40 km
2	10	6	1	30 km
3	11	2	1	20 km
4	12	1	1	10 km
5*	3	9	2	90 km
6	9	3	2	30 km
7*	10	2	2	20 km
8	11	1	2	10 km

*: first requirements

Detailed TDD Framing Configurations

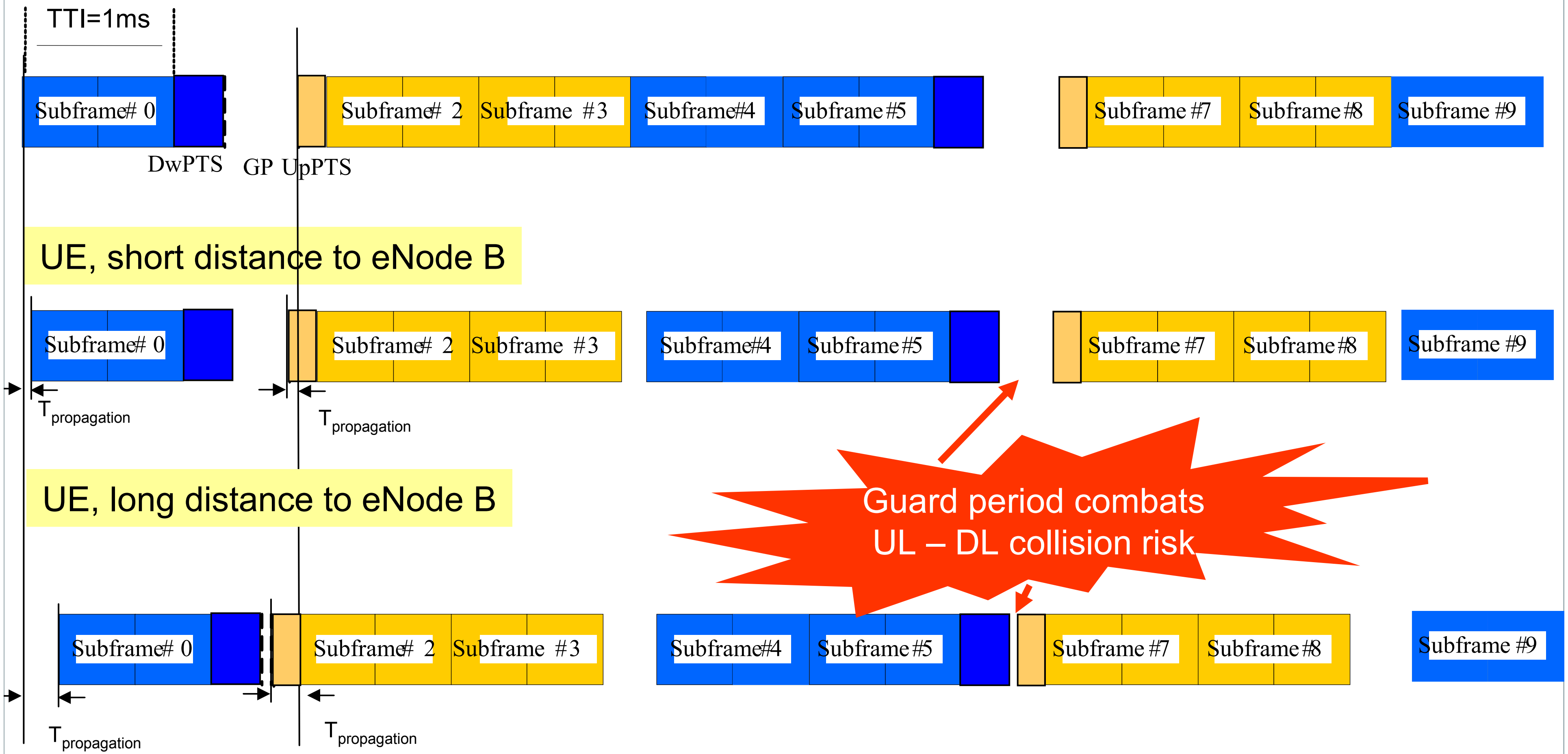
- **Configuration 0,1,2**
  - 5ms DL-to-UL switch period
  - Two identical half radio frames
- **Configuration 3,4,5**
  - 10ms DL-to-UL switch period
- **Configuration 6**
  - 10ms periodicity but two DL-to-UL switches
  - Switch point position differs in half-frames



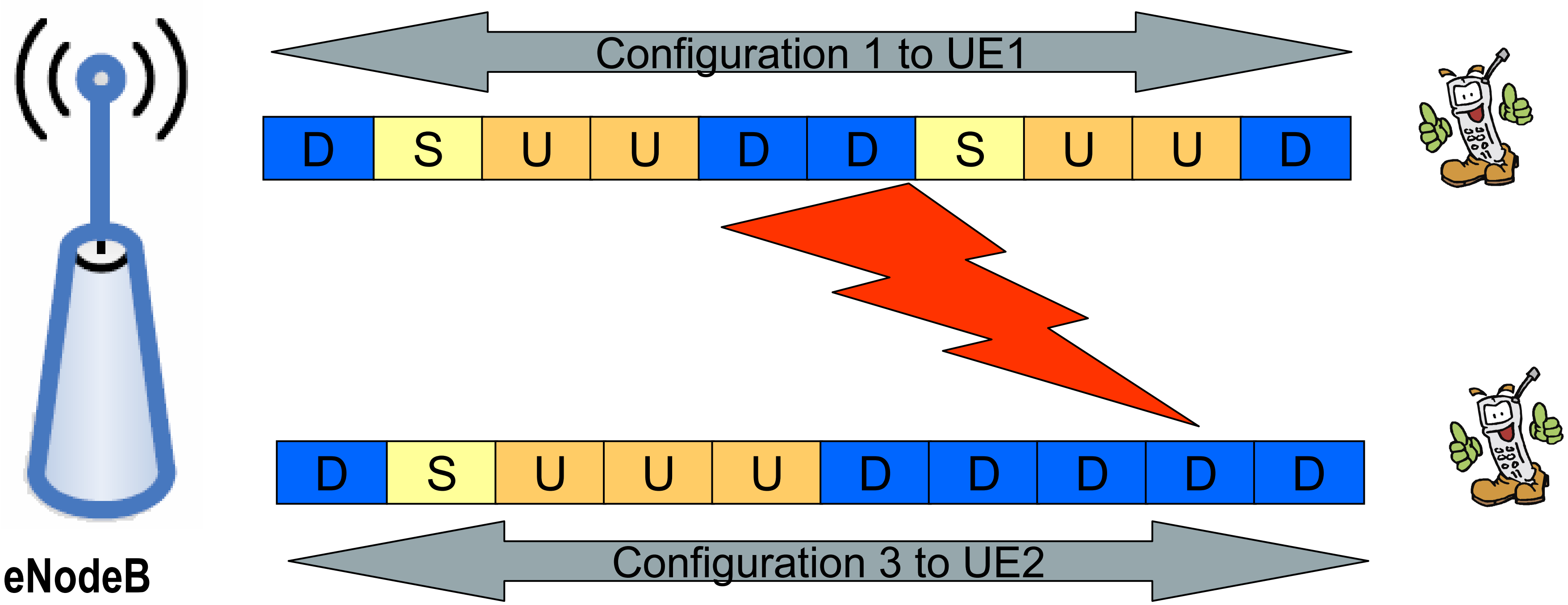
LTE TDD: timing advance and guard period

eNode B

In TDD there is a guard period needed between Transition DL-> UL, because of timing advance

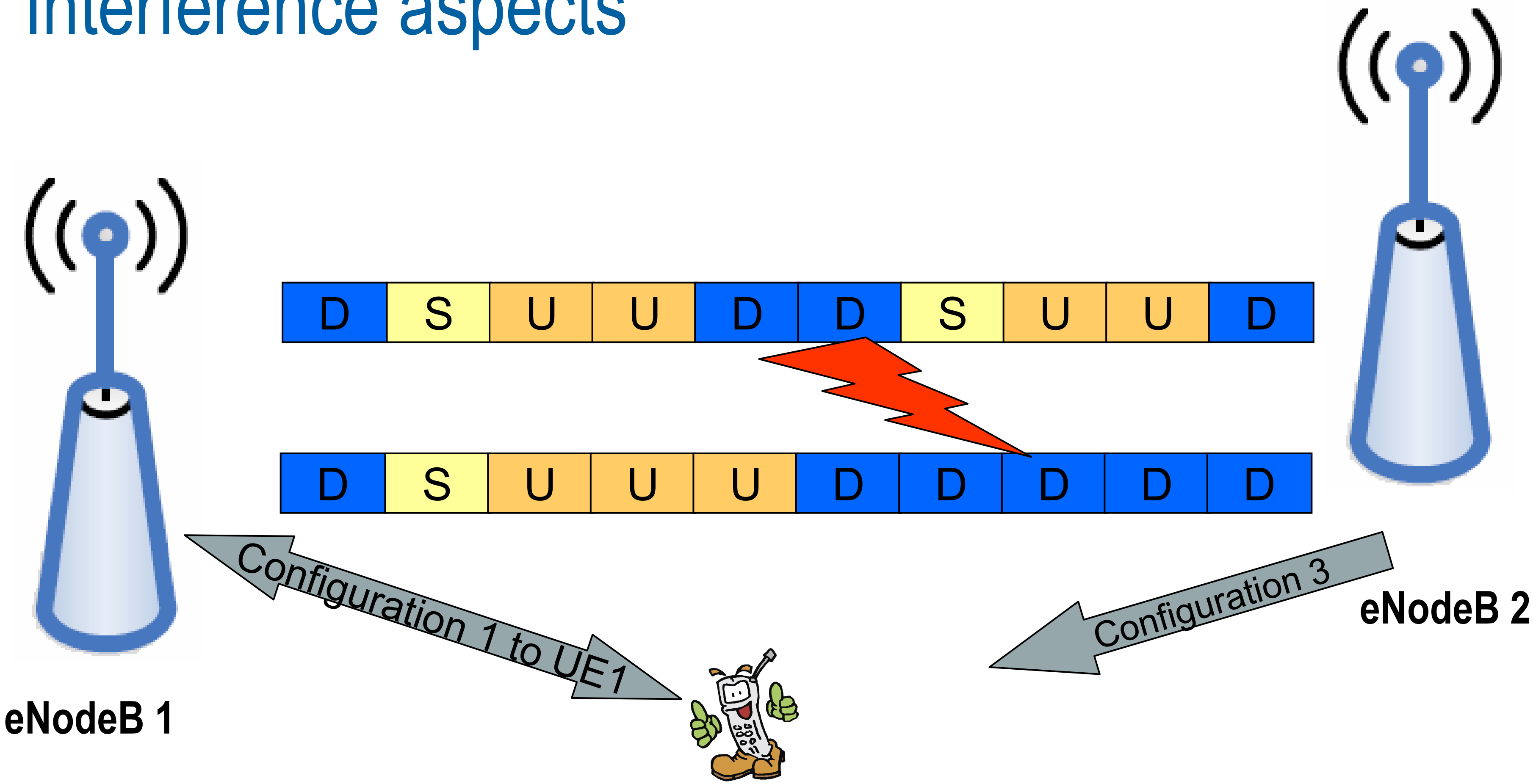


Interference aspects



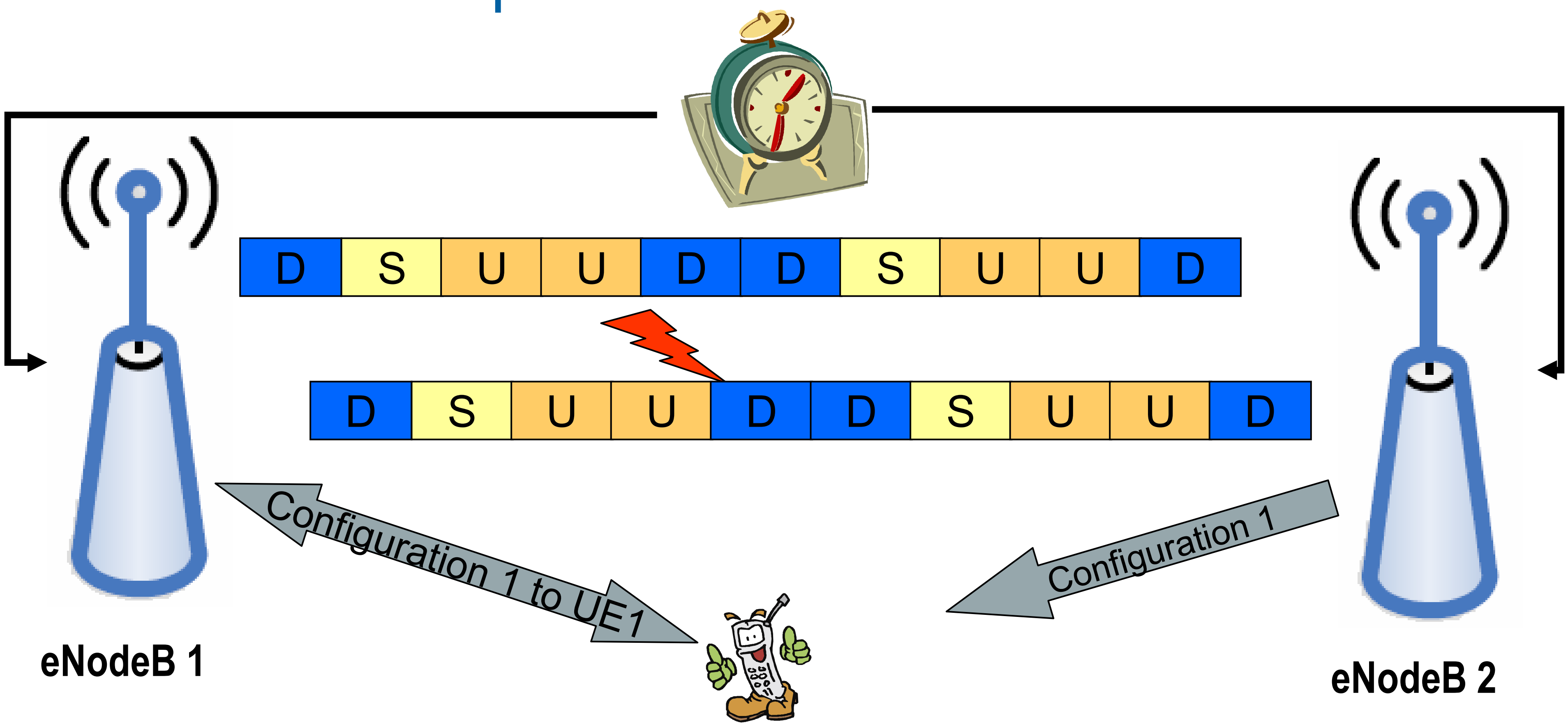
The UL/DL configuration can not vary dynamically between the UEs within a node B

Interference aspects



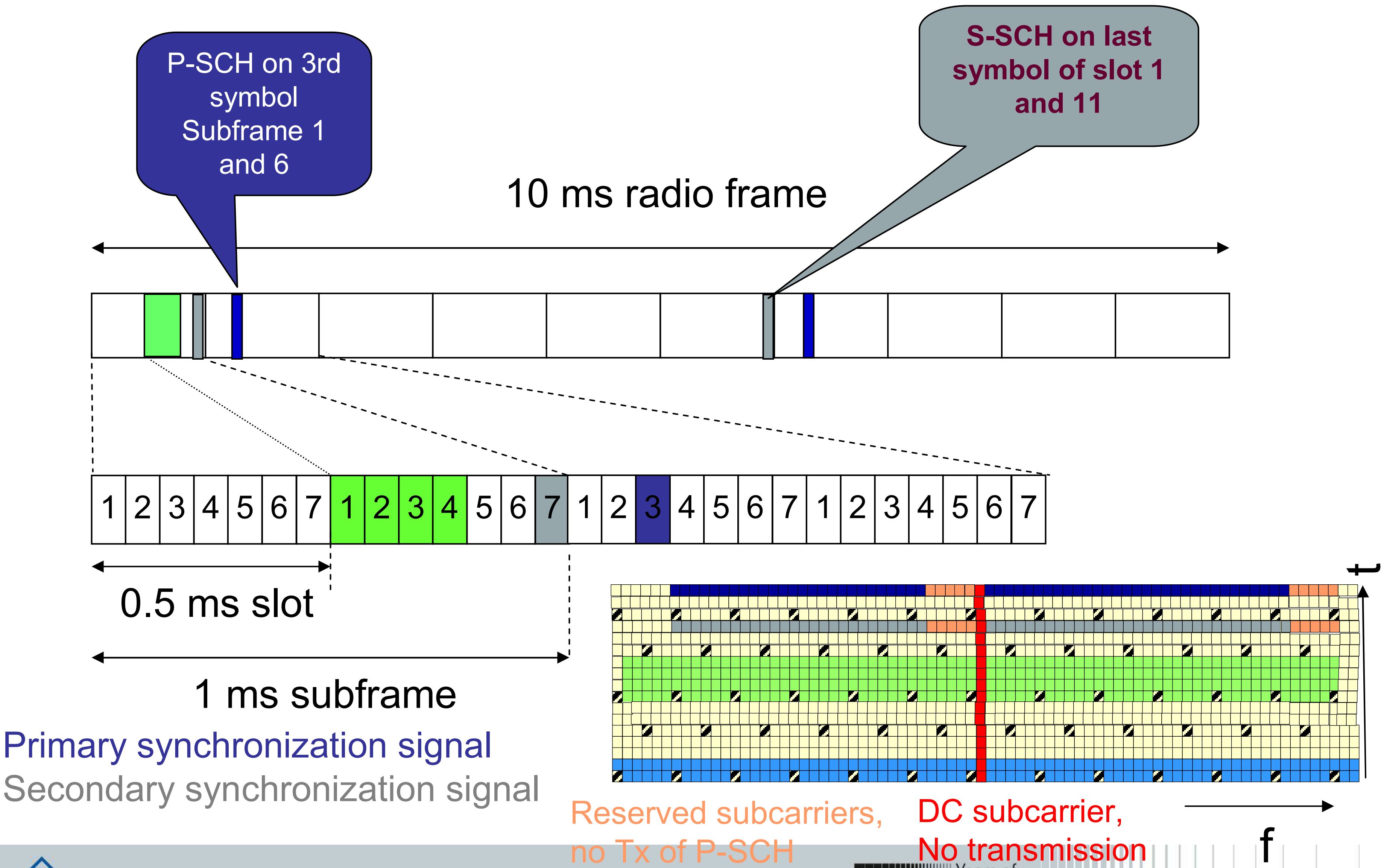
Neighbour cells should have the same UL/DL configurations

Interference aspects



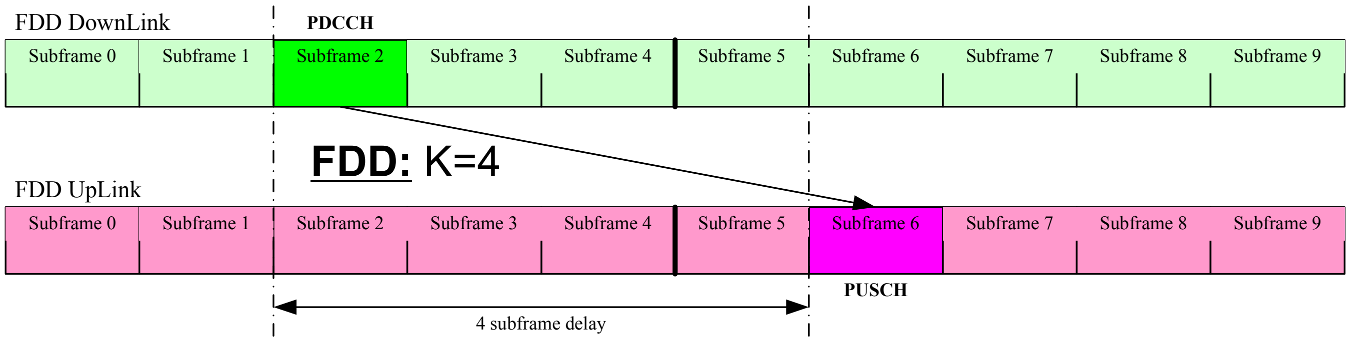
Neighbour cells should have the same Frame timing. Synchronisation required

LTE TDD: P-SCH and S-SCH position



PUSCH and PDCCH Timing Relation

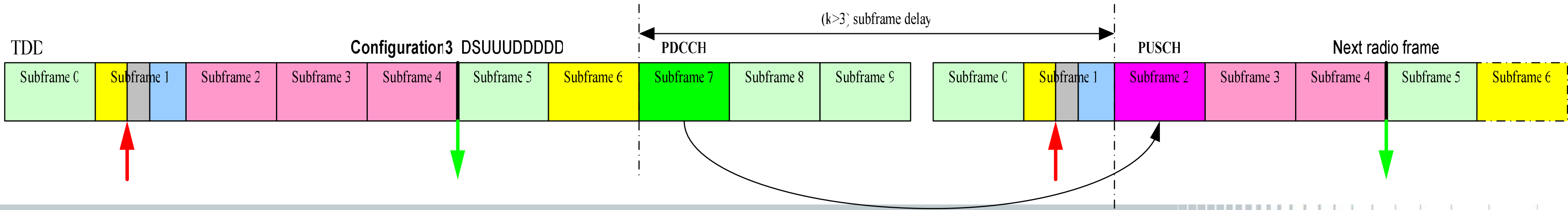
Upon detection of a PDCCH with DCI format 0 and/or a PHICH transmission in sub-frame n intended for the UE, PUSCH is sent in subframe n+K



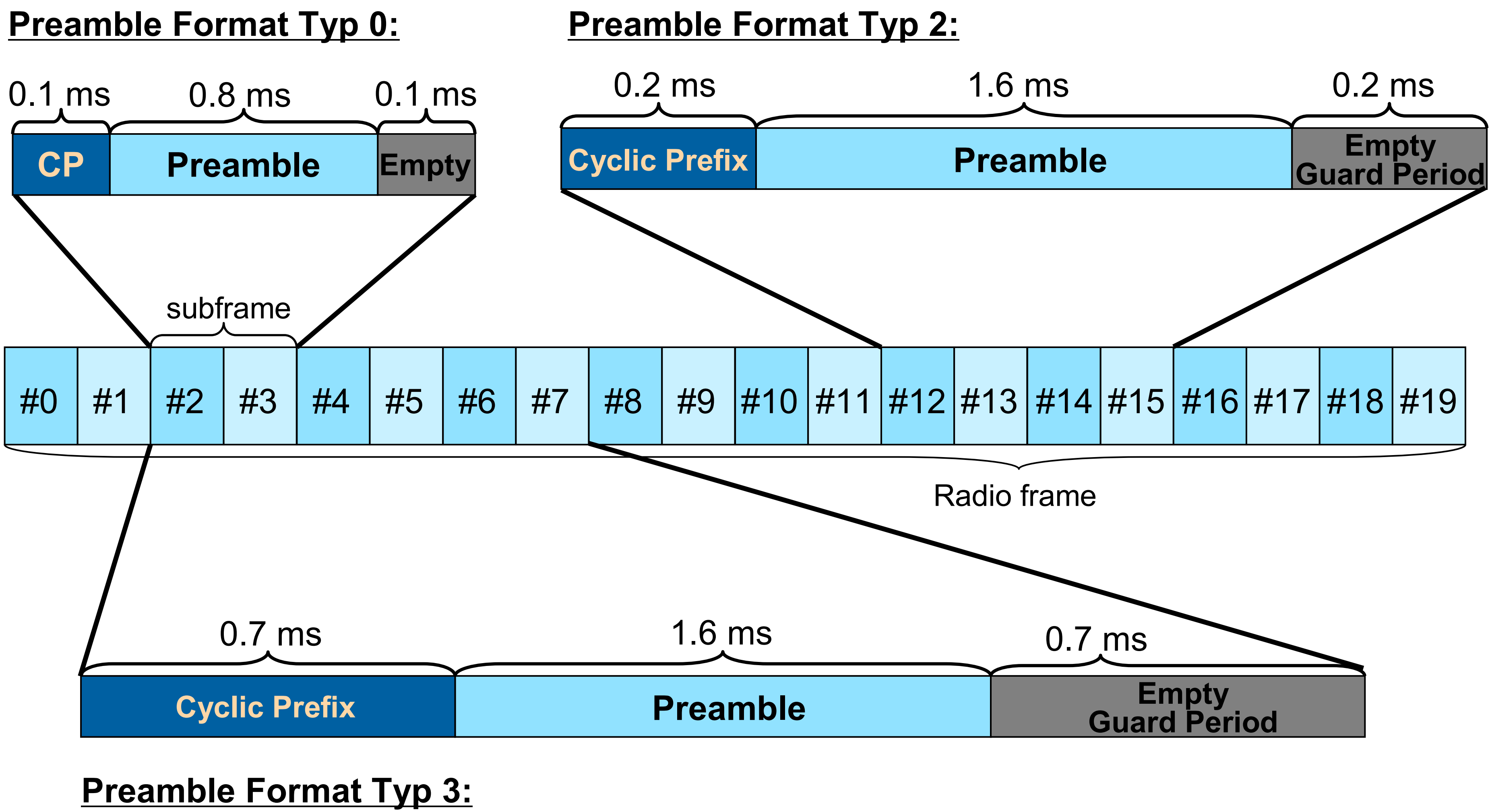
TDD: PUSCH timing relation depends on TDD frame configuration

TDD UL/DL Configuration	Delay K for DL subframe number *n*									
	0	1	2	3	4	5	6	7	8	9
0	4(*)	6(*)				4(*)	6(*)			
1		6			4		6			4
2				4					4	
3	4								4	4
4									4	4
5									4	
6	7	7				7	7			5

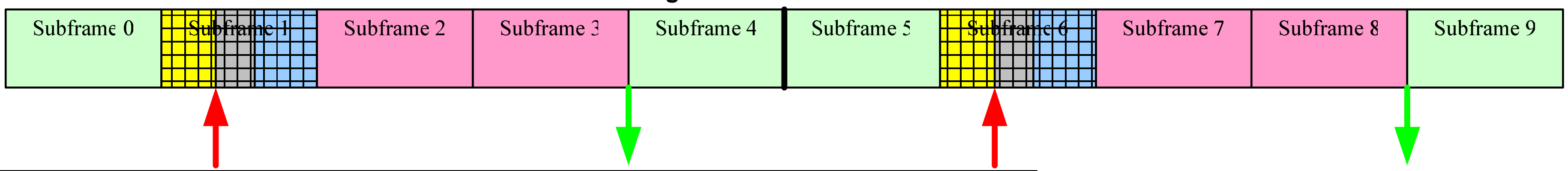
(*): 7 depending on „UL Index" signaled in DCI format 0



PRACH Formats



TDD PRACH Configurations



PRACH conf. Index	Preamble Format	Density Per 10 ms (D_{RA})	Version (r_{RA})	PRACH conf. Index	Preamble Format	Density Per 10 ms (D_{RA})	Version (r_{RA})
0	0	0.5	0	32	2	0.5	2
1	0	0.5	1	33	2	1	0
2	0	0.5	2	34	2	1	1
3	0	1	0	35	2	2	0
4	0	1	1	36	2	3	0
5	0	1	2	37	2	4	0
6	0	2	0	38	2		
7	0	2	1	39	2		
8	0	2	2	40	3		
9	0	3	0	41	3		
10	0	3	1	42	3		
11	0	3	2	43	3		
12	0	4	0	44	3		
13	0	4	1	45	3		
14	0	4	2	46	3		
15	0	5	0	47	3		
16	0	5	1	48	4		
17	0	5	2	49	4		
18	0	6	0	50	4		
19	0	6	1	51	4		
20	1	0.5	0	52	4		
21	1	0.5	1	53	4		
22	1	0.5	2	54	4		
23	1	1	0	55	4		
24	1	1	1	56	4		
25	1	2	0	57	4		
26	1	3	0				
27	1	4	0				
28	1	5	0				
29	1	6	0				
30	2	0.5	0				
31	2	0.5	1				

PRACH configuration indicies for preamble formats 0 to 4

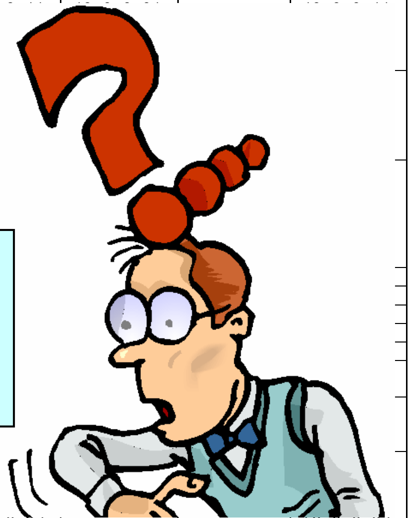
PRACH Index	Preamble Format	Density per 10 ms	Version
0	0	0.5	0
1	0	0.5	1
2	0	0.5	2
3	0	1	0
4	0	1	1
⋮	⋮	⋮	⋮
57	4	6	0

TDD PRACH Mapping Configurations

PRACH conf. Index (See Table 5.7.1-3)	UL/DL configuration (See Table 4.2-2)						
	0	1	2	3	4	5	6
0	(0,1,0,2)	(0,1,0,1)	(0,1,0,0)	(0,1,0,2)	(0,1,0,1)	(0,1,0,0)	(0,1,0,2)
1	(0,2,0,2)	(0,2,0,1)	(0,2,0,0)	(0,2,0,2)	(0,2,0,1)	(0,2,0,0)	(0,2,0,2)
2	(0,1,1,2)	(0,1,1,1)	(0,1,1,0)	(0,1,0,1)	(0,1,0,0)	N/A	(0,1,1,1)
3	(0,0,0,2)	(0,0,0,1)	(0,0,0,0)	(0,0,0,2)	(0,0,0,1)	(0,0,0,0)	(0,0,0,2)
4	(0,0,1,2)	(0,0,1,1)	(0,0,1,0)	(0,0,0,1)	(0,0,0,0)	N/A	(0,0,1,1)
5	(0,0,0,1)	(0,0,0,0)	N/A	(0,0,0,0)	N/A	N/A	(0,0,0,1)
6	(0,0,0,2) (0,0,1,2)	(0,0,0,1) (0,0,1,1)	(0,0,0,0) (0,0,1,0)	(0,0,0,2) (0,0,0,1)	(0,0,0,1) (0,0,0,0)	(0,0,0,0) (1,0,0,0)	(0,0,0,2) (0,0,1,1)
7	(0,0,0,1) (0,0,1,1)	(0,0,0,0) (0,0,1,0)	N/A	(0,0,0,0) (0,0,0,2)	N/A	N/A	(0,0,0,1) (0,0,1,0)
8	(0,0,0,0) (0,0,1,0)	N/A	N/A	(0,0,0,1) (0,0,0,0)	N/A	N/A	(0,0,0,0) (0,0,1,1)
9	(0,0,0,2) (0,0,1,2) (0,0,0,1)	(0,0,0,1) (0,0,1,1) (0,0,0,0)	(0,0,0,0) (0,0,1,0) (1,0,0,0)	(0,0,0,2) (0,0,0,1) (0,0,0,0)	(0,0,0,1) (0,0,0,0) (1,0,0,1)	(0,0,0,0) (1,0,0,0) (2,0,0,0)	(0,0,0,2) (0,0,1,1) (0,0,0,1)
10	(0,0,1,1) (0,0,0,0) (0,0,1,0)	(0,0,1,0) (0,0,0,1) (0,0,1,1)	(0,0,1,0) (0,0,0,0) (1,0,1,0)	N/A	(0,0,0,0) (0,0,0,1) (1,0,0,0)	N/A	(0,0,1,0) (0,0,0,0) (0,0,0,2)
11	N/A	(0,0,0,0) (0,0, (0,0,	N/A	N/A	N/A	N/A	(0,0,1,1)
12	(0,0,0,2) (0,0,1,2) (0,0,0,1) (0,0,1,1)	(0,0, (0,0, (0,0, (0,0,					
13	(0,0,0,0) (0,0,1,0) (0,0,0,2) (0,0,1,2)	N/					
14	(0,0,0,1) (0,0,1,1) (0,0,0,0) (0,0,1,0)	N/		(0,0,0,1) (1,0,0,0)			(0,0,0,2) (0,0,1,1)
15	(0,0,0,2) (0,0,1,2) (0,0,0,1) (0,0,1,1) (0,0,0,0)	(0,0,0,1) (0,0,1,1) (0,0,0,0) (0,0,1,0) (1,0,0,1)	(0,0,0,0) (0,0,1,0) (1,0,0,0) (1,0,1,0) (2,0,0,0)	(0,0,0,2) (0,0,0,1) (0,0,0,0) (1,0,0,2) (1,0,0,1)	(0,0,0,1) (0,0,0,0) (1,0,0,1) (1,0,0,0 (2,0,0,1)	(0,0,0,0) (1,0,0,0) (2,0,0,0) (3,0,0,0) (4,0,0,0)	(0,0,0,2) (0,0,1,1) (0,0,0,1) (0,0,1,0) (0,0,0,0)
16	(0,0,1,0) (0,0,0,2) (0,0,1,2) (0,0,0,1) (0,0,1,1)	(0,0,1,1) (0,0,0,0) (0,0,1,0) (0,0,0,1) (1,0,1,1)	(0,0,1,0) (0,0,0,0) (1,0,1,0 (1,0,0,0) (2,0,1,0)	(0,0,0,0) (0,0,0,2) (0,0,0,1) (1,0,0,0) (1,0,0,2)	(0,0,0,0) (0,0,0,1) (1,0,0,0) (1,0,0,1) (2,0,0,0)	N/A	N/A
17	(0,0,0,0) (0,0,1,0) (0,0,0,2) (0,0,1,2) (0,0,0,1)	(0,0,0,0) (0,0,1,0) (0,0,0,1) (0,0,1,1) (1,0,0,0)	N/A	(0,0,0,1) (0,0,0,0) (0,0,0,2) (1,0,0,1) (1,0,0,0)	N/A	N/A	N/A
18	(0,0,0,2) (0,0,1,2) (0,0,0,1) (0,0,1,1) (0,0,0,0) (0,0,1,0)	(0,0,0,1) (0,0,1,1) (0,0,0,0) (0,0,1,0) (1,0,0,1) (1,0,1,1)	(0,0,0,0) (0,0,1,0) (1,0,0,0) (1,0,1,0) (2,0,0,0) (2,0,1,0)	(0,0,0,2) (0,0,0,1) (0,0,0,0) (1,0,0,2) (1,0,0,1) (1,0,0,0)	(0,0,0,1) (0,0,0,0) (1,0,0,1) (1,0,0,0) (2,0,0,1) (2,0,0,0)	(0,0,0,0) (1,0,0,0) (2,0,0,0) (3,0,0,0) (4,0,0,0) (5,0,0,0)	(0,0,0,2) (0,0,1,1) (0,0,0,1) (0,0,1,0) (0,0,0,0) (1,0,0,2)
19	N/A	(0,0,0,0) (0,0,1,0) (0,0,0,1) (0,0,1,1) (1,0,0,0) (1,0,1,0)	N/A	N/A	N/A	N/A	(0,0,1,1) (0,0,0,0) (0,0,1,0) (0,0,0,0) (0,0,0,2) (1,0,1,1)
20 / 30	(0,1,0,1)	(0,1,0,0)	N/A	(0,1,0,1)	(0,1,0,0)	N/A	(0,1,0,1)
21 / 31	(0,2,0,1)	(0,2,0,0)	N/A	(0,2,0,1)	(0,2,0,0)	N/A	(0,2,0,1)

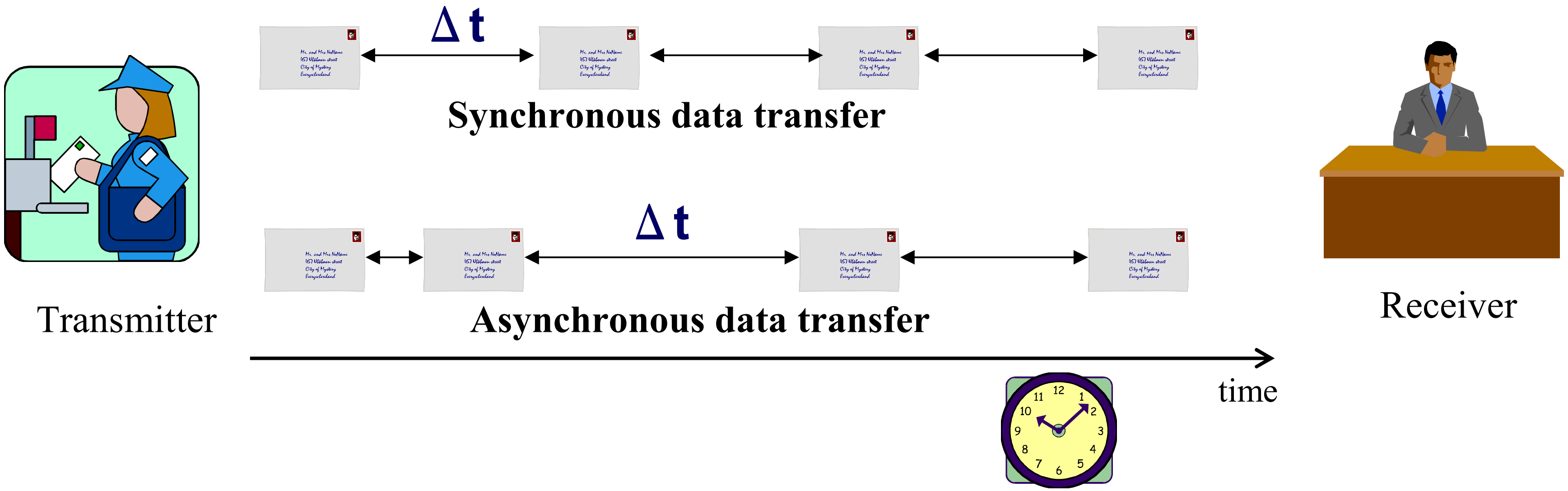
22 / 32	(0,1,1,1)	(0,1,1,0)	N/A	N/A	N/A	N/A	(0,1,1,0)
23 / 33	(0,0,0,1)	(0,0,0,0)	N/A	(0,0,0,1)	(0,0,0,0)	N/A	(0,0,0,1)
24 / 34	(0,0,1,1)	(0,0,1,0)	N/A	N/A	N/A	N/A	(0,0,1,0)
25 / 35	(0,0,0,1) (0,0,1,1)	(0,0,0,0) (0,0,1,0)	N/A	(0,0,0,1) (1,0,0,1)	(0,0,0,0) (1,0,0,0)	N/A	(0,0,0,1) (0,0,1,0)
26 / 36	(0,0,0,1) (0,0,1,1) (1,0,0,1)	(0,0,0,0) (0,0,1,0) (1,0,0,0)	N/A	(0,0,0,1) (1,0,0,1) (2,0,0,1)	(0,0,0,0) (1,0,0,0) (2,0,0,0)	N/A	(0,0,0,1) (0,0,1,0) (1,0,0,1)
27 / 37	(0,0,0,1) (0,0,1,1) (1,0,0,1) (1,0,1,1)	(0,0,0,0) (0,0,1,0) (1,0,0,0) (1,0,1,0)	N/A	(0,0 (1,0 (2,0 (3,0			
28 / 38	(0,0,0,1) (0,0,1,1) (1,0,0,1) (1,0,1,1) (2,0,0,1)	(0,0,0,0) (0,0,1,0) (1,0,0,0) (1,0,1,0) (2,0,0,0)	N/A	(0,0 (1,0 (2,0 (3,0 (4,0			
29 /39	(0,0,0,1) (0,0,1,1) (1,0,0,1) (1,0,1,1)	(0,0,0,0) (0,0,1,0) (1,0,0,0) (1,0,1,0)	N/A	(0,0 (1,0 (2,0 (3,0			
	(1,0,0,2)			(2,0			
47	(0,0,0,0) (0,0,1,0) (1,0,0,0) (1,0,1,0)	N/A	N/A	(0,0 (1,0 (2,0 (3,0			
48	(0,1,0,*)	(0,1,0,*)	(0,1,0,*)	(0,1,0,*)	(0,1,0,*)	(0,1,0,*)	(0,1,0,*)
49	(0,2,0,*)	(0,2,0,*)	(0,2,0,*)	(0,2,0,*)	(0,2,0,*)	(0,2,0,*)	(0,2,0,*)
50	(0,1,1,*)	(0,1,1,*)	(0,1,1,*)	N/A	N/A	N/A	(0,1,1,*)
51	(0,0,0,*)	(0,0,0,*)	(0,0,0,*)	(0,0,0,*)	(0,0,0,*)	(0,0,0,*)	(0,0,0,*)
52	(0,0,1,*)	(0,0,1,*)	(0,0,1,*)	N/A	N/A	N/A	(0,0,1,*)
53	(0,0,0,*) (0,0,1,*)	(0,0,0,*) (0,0,1,*)	(0,0,0,*) (0,0,1,*)	(0,0,0,*) (1,0,0,*)	(0,0,0,*) (1,0,0,*)	(0,0,0,*) (1,0,0,*)	(0,0,0,*) (0,0,1,*)
54	(0,0,0,*) (0,0,1,*) (1,0,0,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*)	(0,0,0,*) (1,0,0,*) (2,0,0,*)	(0,0,0,*) (1,0,0,*) (2,0,0,*)	(0,0,0,*) (1,0,0,*) (2,0,0,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*)
55	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*)	(0,0,0,*) (1,0,0,*) (2,0,0,*) (3,0,0,*)	(0,0,0,*) (1,0,0,*) (2,0,0,*) (3,0,0,*)	(0,0,0,*) (1,0,0,*) (2,0,0,*) (3,0,0,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*)
56	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*) (2,0,0,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*) (2,0,0,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*) (2,0,0,*)	(0,0,0,*) (1,0,0,*) (2,0,0,*) (3,0,0,*) (4,0,0,*)	(0,0,0,*) (1,0,0,*) (2,0,0,*) (3,0,0,*) (4,0,0,*)	(0,0,0,*) (1,0,0,*) (2,0,0,*) (3,0,0,*) (4,0,0,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*) (2,0,0,*)
57	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*) (2,0,0,*) (2,0,1,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*) (2,0,0,*) (2,0,1,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*) (2,0,0,*) (2,0,1,*)	(0,0,0,*) (1,0,0,*) (2,0,0,*) (3,0,0,*) (4,0,0,*) (5,0,0,*)	(0,0,0,*) (1,0,0,*) (2,0,0,*) (3,0,0,*) (4,0,0,*) (5,0,0,*)	(0,0,0,*) (1,0,0,*) (2,0,0,*) (3,0,0,*) (4,0,0,*) (5,0,0,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*) (2,0,0,*) (2,0,1,*)

302 applicable configurations



LTE: HARQ protocol

Synchronous data transfer, Δt = const



LTE HARQ protocol

- **Downlink**:
  - Asynchronous adaptive protocol
  - Retransmission of data blocks can occur at any time after the initial transmission
  - To identify, the eNode B assigns a HARQ process identifier

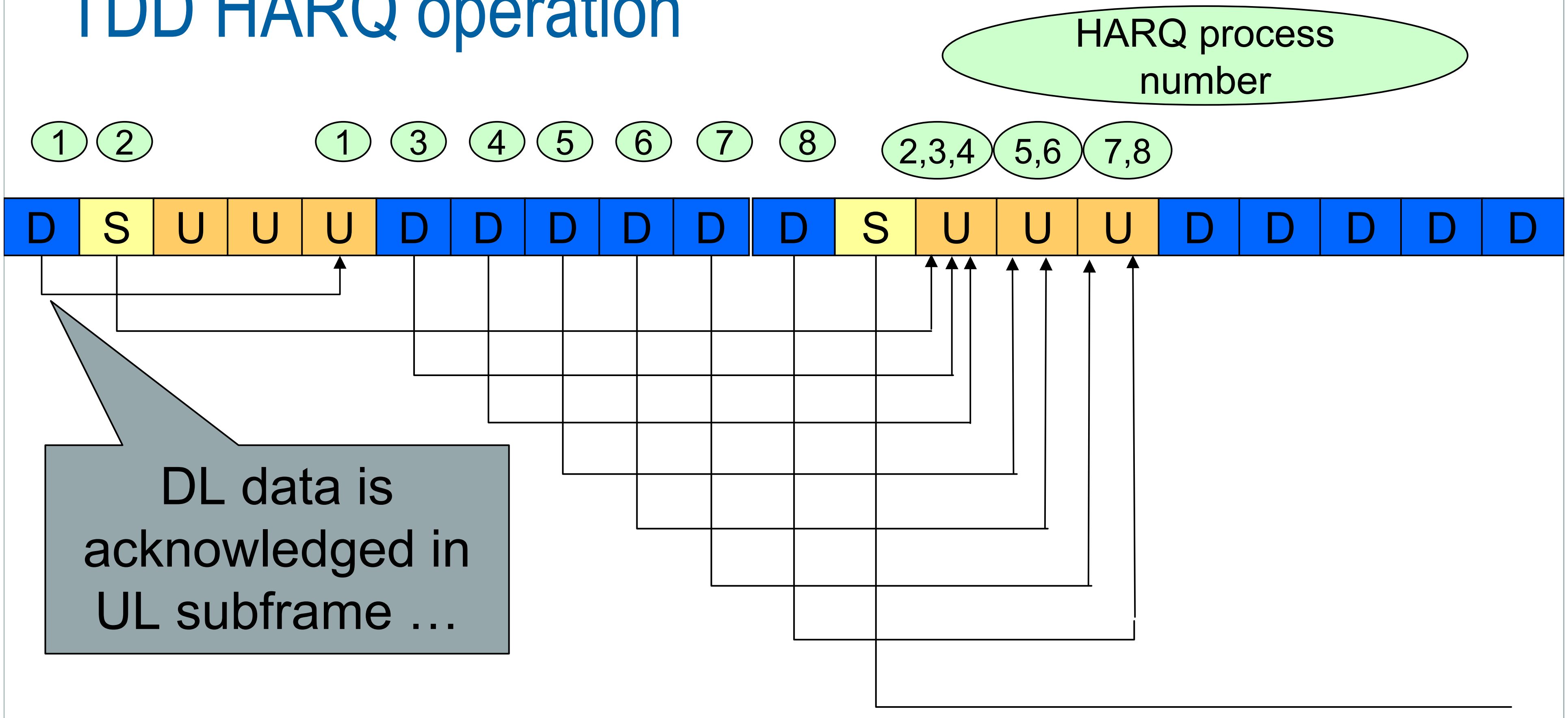
- **Uplink**:
  - Synchronous non-adaptive protocol
  - Retransmission occurs at a predefined time after the initial transmission
  - HARQ process number is not assigned. Process can be derived from timing

LTE TDD: HARQ processes in UL and DL

UL/DL configuration defines the number of HARQ processes, in configuration 2,3,4 and 5 are more than FDD

TDD UL/DL configuration	Maximum number of HARQ processes in Downlink	Maximum number of HARQ processes in Uplink
0	4	**7**
1	7	4
2	10	2
3	9	3
4	12	2
5	15	1
6	6	6

TDD HARQ operation



Uplink subframe may combine acknowledgement of several Downlink data subframes.
-> different DL – UL timing and roundtrip times

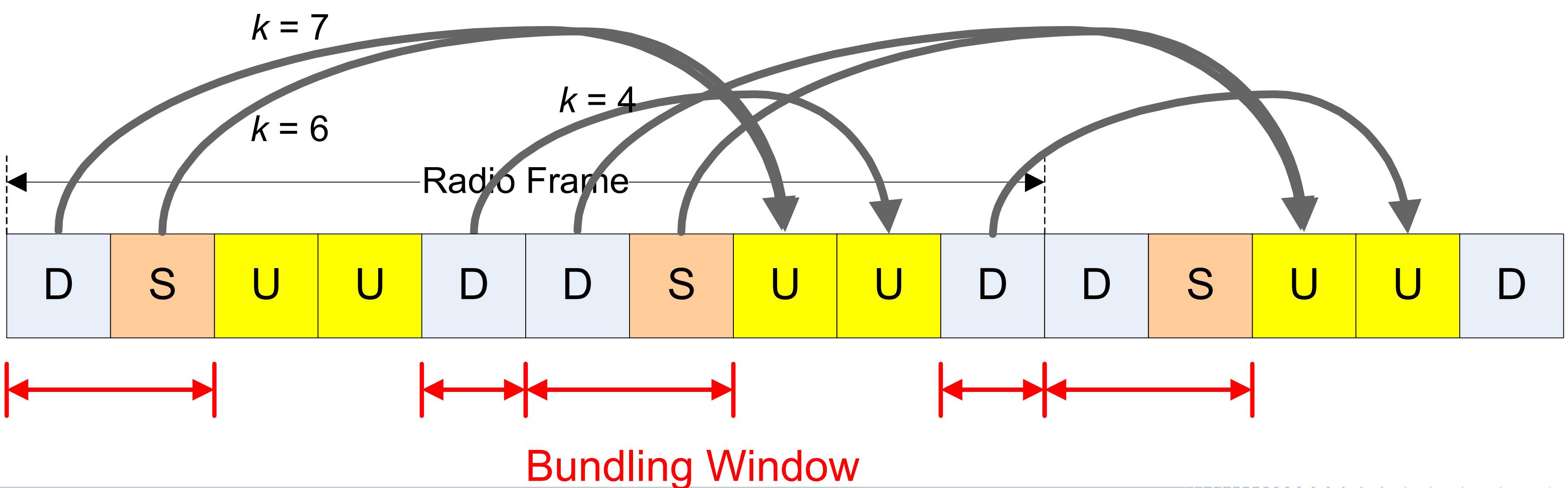
LTE TDD HARQ operation

Acknowledgement of downlink data received in Subframe n is done in Uplink subframe n+k, where k is given by:

UL/DL configuration	Subframe n									
	0	1	2	3	4	5	6	7	8	9
0	4	6	-	-	-	4	6	-	-	
1	7	6	-	-	4	7	6	-	-	4
2	7	6	-	4	8	7	6	-	4	8
3	4	11	-	-	-	7	6	6	5	5
4	12	11	-	-	8	7	7	6	5	4
5	12	11	-	9	8	7	6	5	4	13
6	7	7	-	-	-	7	7	-	-	5

TDD ACK/NAK Bundling

- In TDD a single ACK/NAK response may provide feedback for multiple dynamically and semi-persistently scheduled PDSCH assignments via logical AND of ACK/NAKs
- For frame configurations with more DL subframes (including DwPTS) than UL subframes
- Downlink Assignment Index defined for DCI (formats 1, 1A, 1B, 2) to provide information about the number of dynamically assigned DL subframes in the current bundling window (grows from subframe to subframe in the window when further PDSCH are scheduled)
- DTX is sent instead of ACK/NAK when one or more of the dynamically assigned DL assignments (signaled in DCI) was missed during the current bundling window
- Proposal of RAN1-53b: Number of DL HARQ processes can be increased up to 16 by eNodeB when ACK/NAK bundling is active (considers 4bit TDD HARQ-process DCI field)



Uplink-ACK/NAK Timing

ACK/NAK timing for detected PDSCH transmissions for which an ACK/NAK shall be provided:

FDD: For PDSCH in subframe n-4 the ACK/NACK response is in subframe n

TDD: For PDSCHs in subframe(s) n-k the single or bundled ACK/NACK response is transmitted in subframe n

UL-DL Configuration	Sets of values k									
	0	1	2	3	4	5	6	7	8	9
0	-	-	6	-	4	-	-	6	-	4
1	-	-	7, 6	4	-	-	-	7, 6	4	-
2	-	-	8, 7, 6, 4	-	-	-	-	8, 7, 6, 4	-	-
3	-	-	11, 7, 6	6, 5	5, 4	-	-	-	-	-
4	-	-	12, 11, 8, 7	7, 6, 5, 4	-	-	-	-	-	-
5	-	-	TBD	-	-	-	-	-	-	-
6	-	-	7	7	5	-	-	7	7	-

Downlink-ACK/NAK Timing

- For scheduled PUSCH transmissions in subframe *n*, a UE shall determine the corresponding PHICH resource in subframe *n*+*k*, where *k* is always 4 for FDD and is given in the table below for TDD

TDD UL/DL Configuration	UL subframe index *n*									
	0	1	2	3	4	5	6	7	8	9
0			4	7	6			4	7	6
1			4	6				4	6	
2			6					6		
3			6	6	6					
4			6	6						
5			6							
6			4	6	6			4	7	

LTE Identifiers and System Information

Radio Network Transaction Identifiers, RNTI

C-RNTI
Cell RNTI,
identifies a UE
having a RRC connection
within a cell

SI-RNTI
System Information-
RNTI,
Broadcast of
System information

RA-RNTI
Random Access-
RNTI,
Random Access Response

P-RNTI
Paging-RNTI,
Paging and System
Information change info

TPC-RNTI
Transmit Power Control
RNTI,
For power control, DCI 3,
i.e. multiplexing TPC
commands

E-UTRAN Identities

3GPP TS 36.300 subclause 8

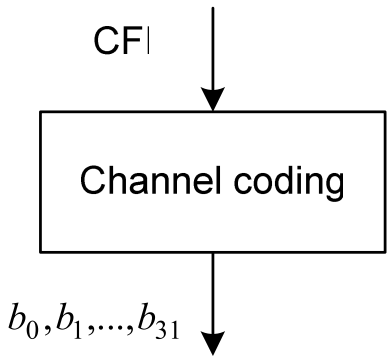
- **UE identities**
  - C-RNTI (Cell Radio Network Temporary Identity)
  - Random value for contention resolution
- **eNodeB identities**
  - ECI – E-UTRAN Cell Identifier
    - 28 Bit eNB Identifier
  - ECGI – E-UTRAN Cell Global Identifier
    - Composition of MCC (Mobile Country Code), MNC (Mobile Network Code) and ECI
  - TAI – Tracking Area Identifier
    - Composition of MCC, MNC and TAC (Tracking Area Code)

Physical Format Indicator Channel, PCFICH

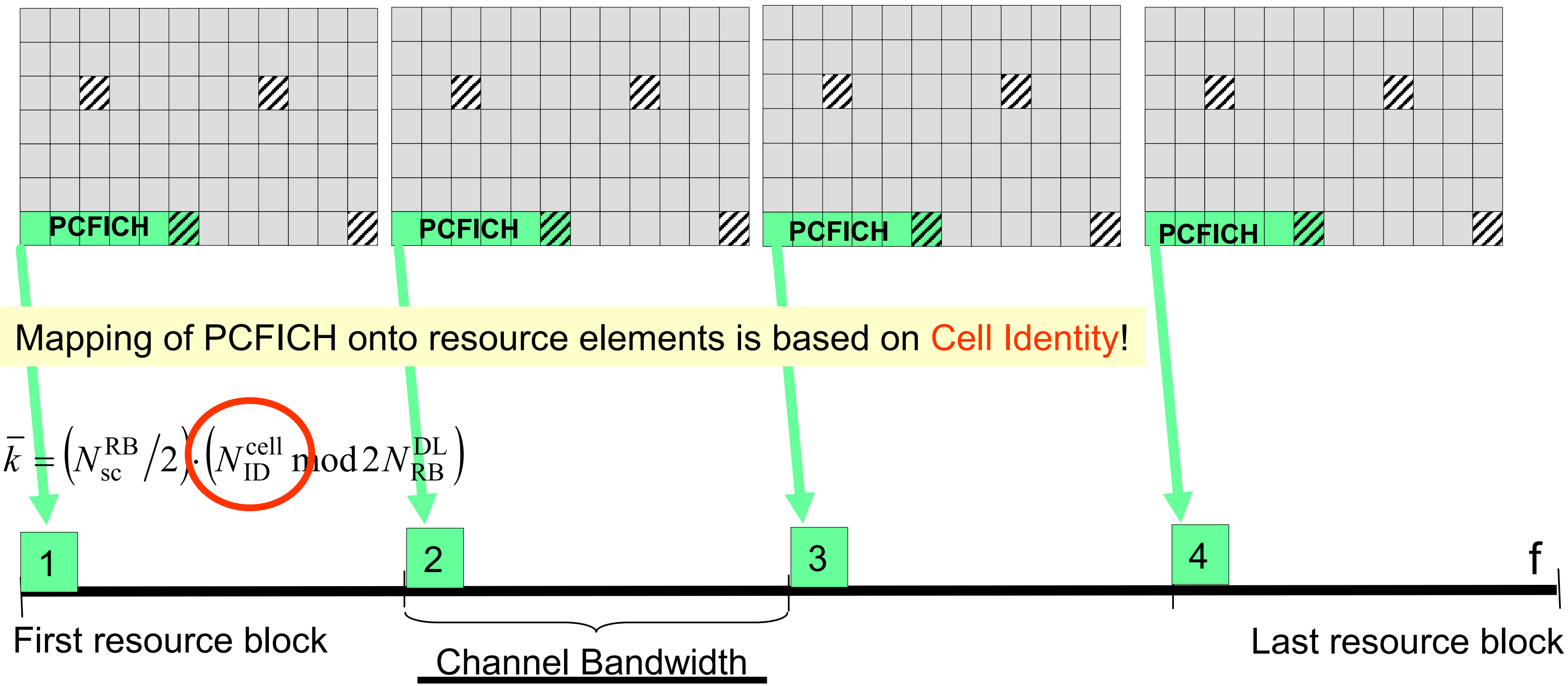
- Indicates how many OFDM symbols are used for PDCCH in that subframe, i.e. the control format indicator, CFI
- Transmitted in every subframe, QPSK modulated
- Coded as 32 bits, transmitted in 4 Resource Element Groups, REG
- Mapping on frequency resource depends on cell identity (see TS36.211 section 6.7.4)

Subframe where PCFICH is sent	Number of OFDM symbols for PDCCH when	
	$N_{RB}^{DL} > 10$	$N_{RB}^{DL} \leq 10$
Subframe 1 and 6 in TDD mode	1, 2	2
Subframe 0 in FDD mode	1, 2, 3	2, 3, 4

Most frequent scenario



PCFICH mapping on physical resource



Mapping of PCFICH onto resource elements is based on Cell Identity!

$$\bar{k} = \left(N_{\mathrm{sc}}^{\mathrm{RB}}/2\right)\cdot\left(N_{\mathrm{ID}}^{\mathrm{cell}} \bmod 2N_{\mathrm{RB}}^{\mathrm{DL}}\right)$$

$z^{(p)}(0)$ is mapped to the resource-element group represented by $k = \bar{k}$

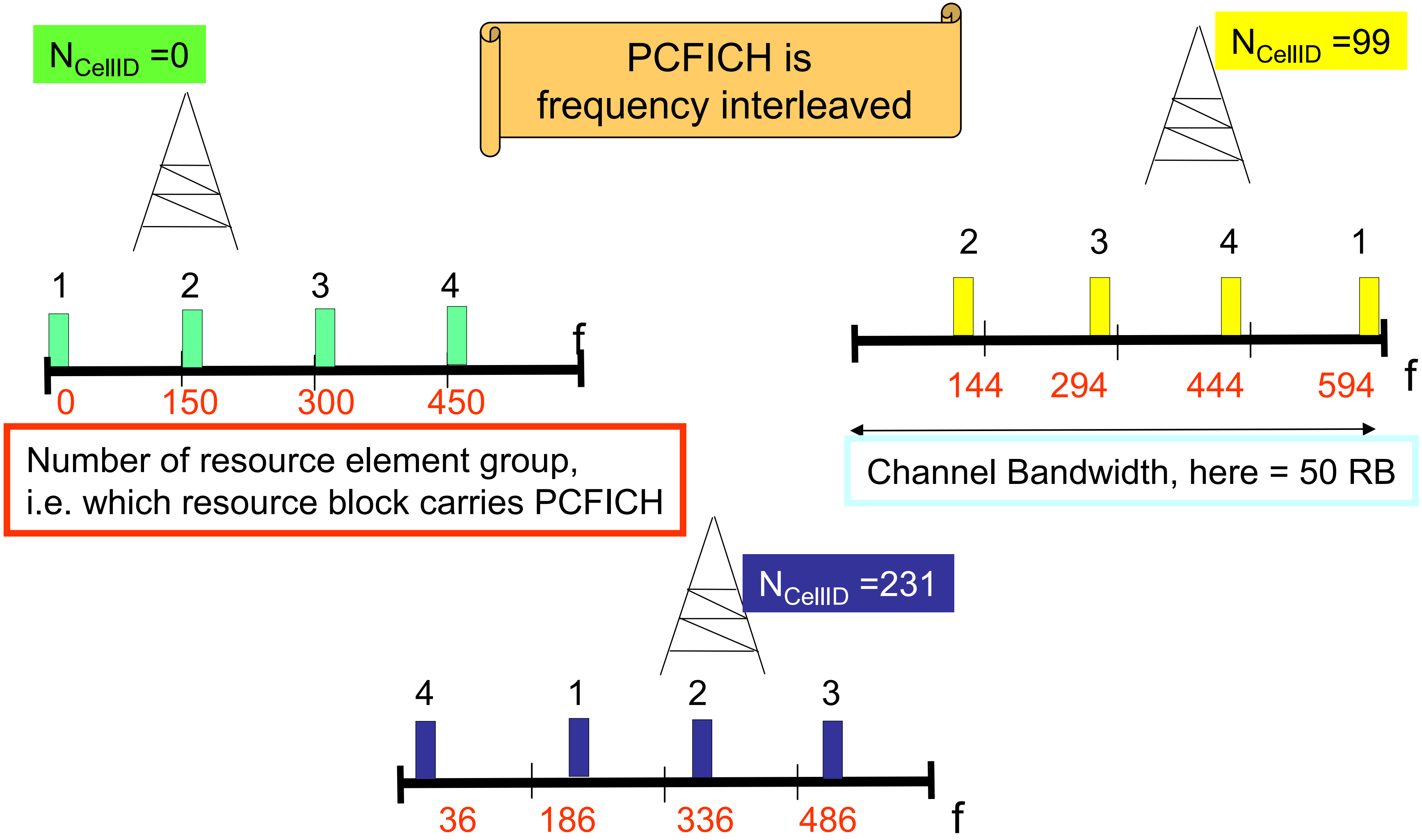
$z^{(p)}(1)$ is mapped to the resource-element group represented by $k = \bar{k} + \lfloor N_{\mathrm{RB}}^{\mathrm{DL}}/2 \rfloor \cdot N_{\mathrm{sc}}^{\mathrm{RB}}/2$

$z^{(p)}(2)$ is mapped to the resource-element group represented by $k = \bar{k} + \lfloor 2N_{\mathrm{RB}}^{\mathrm{DL}}/2 \rfloor \cdot N_{\mathrm{sc}}^{\mathrm{RB}}/2$

$z^{(p)}(3)$ is mapped to the resource-element group represented by $k = \bar{k} + \lfloor 3N_{\mathrm{RB}}^{\mathrm{DL}}/2 \rfloor \cdot N_{\mathrm{sc}}^{\mathrm{RB}}/2$

PCFICH mapping on physical resource

Example: 3 cells with 10 MHz

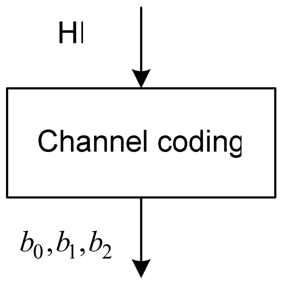


Physical HARQ Indicator Channel, PHICH

- Indicates ACK or NACK of previous uplink data block
- Transmitted in every subframe, BPSK modulated
- Multiple PHICHs on same resource -> separated by orthogonal sequence
- Mapping on frequency resource depends on cell identity (see TS36.211 section 6.7.4)

PHICH is identified by group and sequence identifiers

$$\left(n_{\mathrm{PHICH}}^{\mathrm{group}}, n_{\mathrm{PHICH}}^{\mathrm{seq}}\right)$$



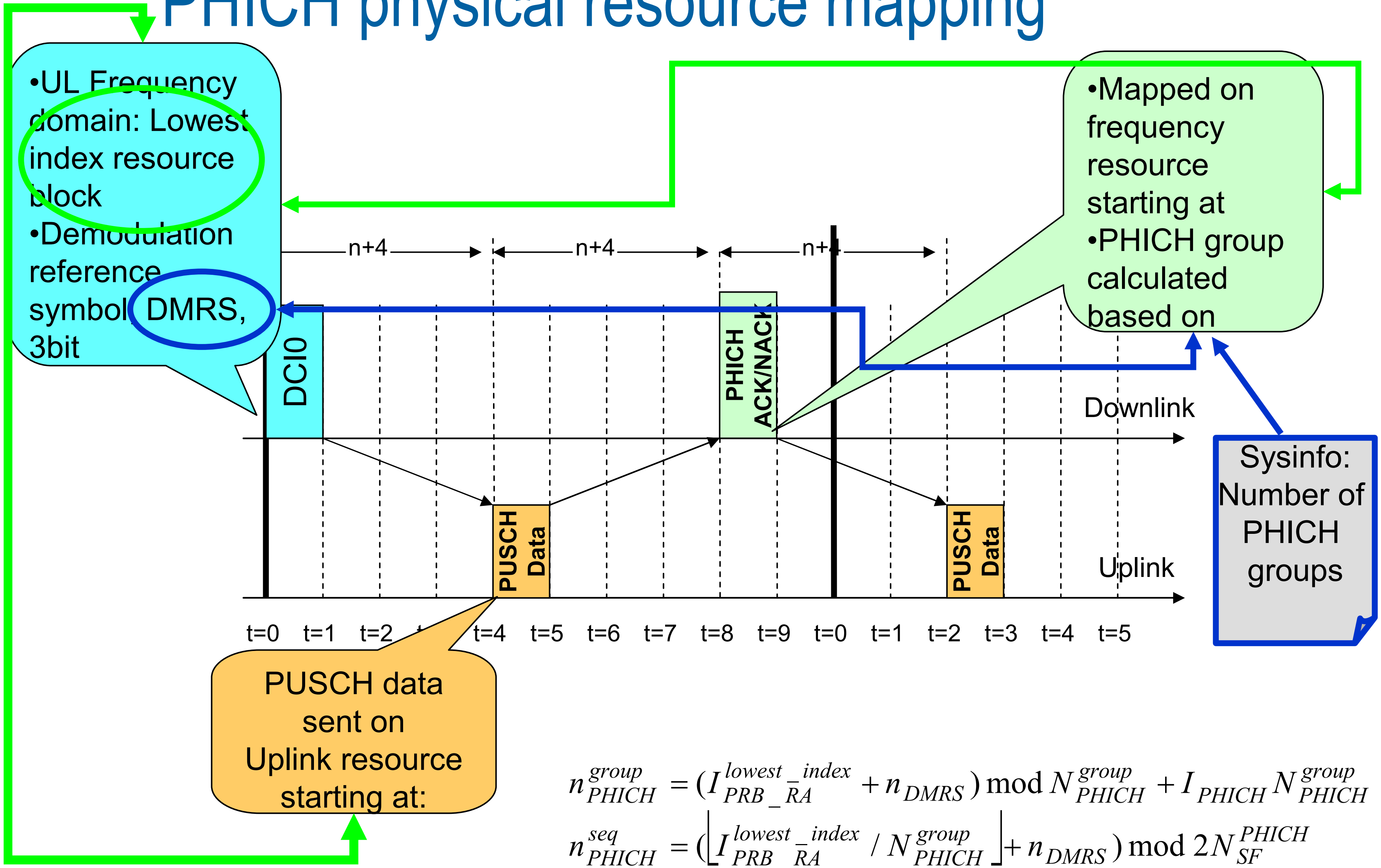
RRC layer configures number of groups:
PHICH-resource (1/6, ½,1 or 2) multiplied with bandwidth

$$N_{\mathrm{PHICH}}^{\mathrm{group}} = \begin{cases} \left\lceil N_g \left(N_{\mathrm{RB}}^{\mathrm{DL}} / 8 \right) \right\rceil & \text{for normal cyclic prefix} \\ 2 \cdot \left\lceil N_g \left(N_{\mathrm{RB}}^{\mathrm{DL}} / 8 \right) \right\rceil & \text{for extended cyclic prefix} \end{cases}$$

Orthogonal sequence, Spreading Factor is 2 or 4

Sequence index $n_{\mathrm{PHICH}}^{\mathrm{seq}}$	Orthogonal sequence: Normal cyclic prefix $N_{\mathrm{SF}}^{\mathrm{PHICH}} = 4$	Orthogonal sequence: Extended cyclic prefix $N_{\mathrm{SF}}^{\mathrm{PHICH}} = 2$
0	$[+1 \ +1 \ +1 \ +1]$	$[+1 \ +1]$
1	$[+1 \ -1 \ +1 \ -1]$	$[+1 \ -1]$
2	$[+1 \ +1 \ -1 \ -1]$	$[+j \ +j]$
3	$[+1 \ -1 \ -1 \ +1]$	$[+j \ -j]$
4	$[+j \ +j \ +j \ +j]$	-
5	$[+j \ -j \ +j \ -j]$	-
6	$[+j \ +j \ -j \ -j]$	-
7	$[+j \ -j \ -j \ +j]$	-

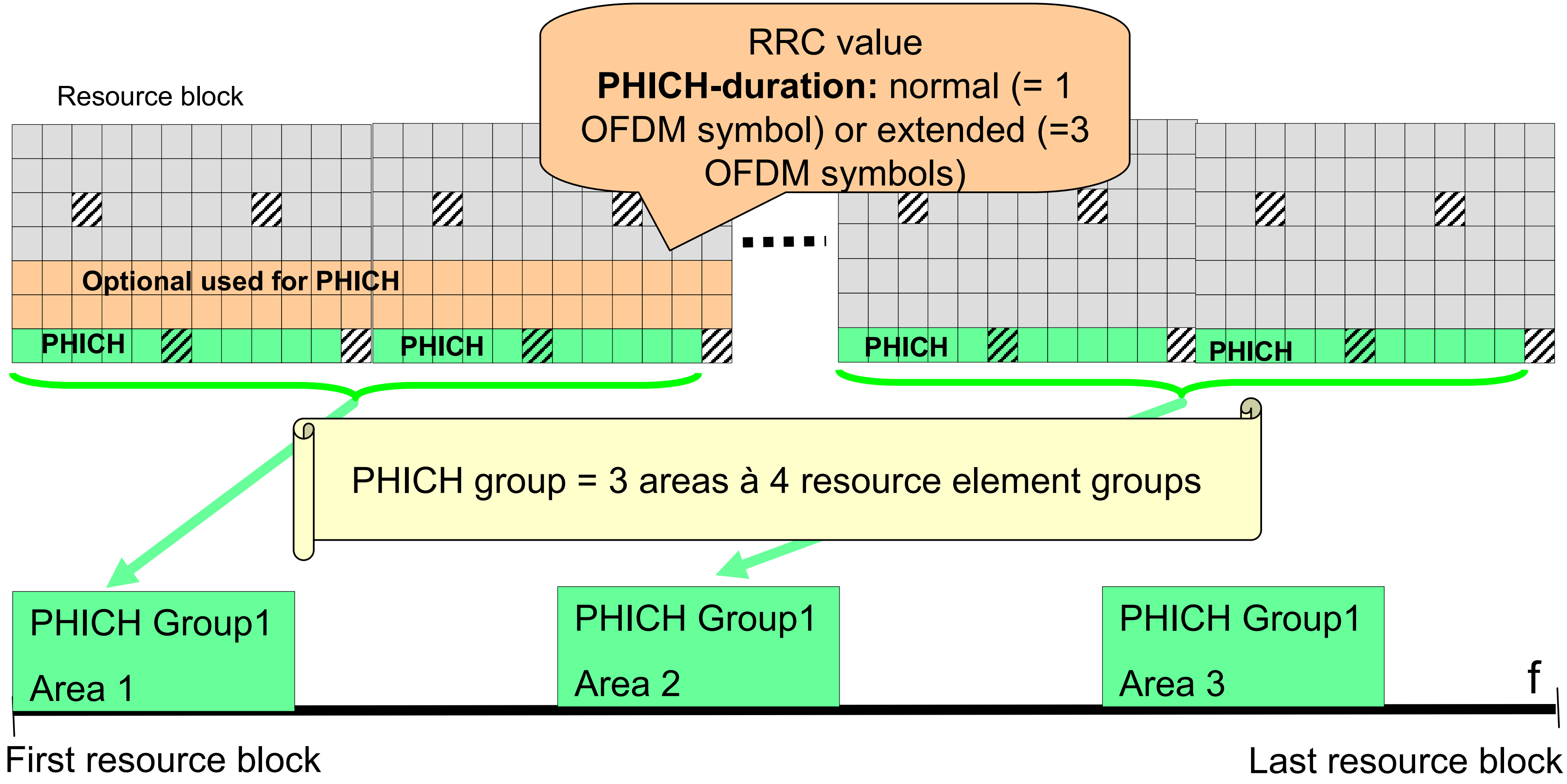
PHICH physical resource mapping



$$n_{PHICH}^{group} = (I_{PRB\_RA}^{lowest\_index} + n_{DMRS}) \bmod N_{PHICH}^{group} + I_{PHICH} N_{PHICH}^{group}$$

$$n_{PHICH}^{seq} = \left(\left\lfloor I_{PRB\_RA}^{lowest\_index} / N_{PHICH}^{group} \right\rfloor + n_{DMRS}\right) \bmod 2N_{SF}^{PHICH}$$

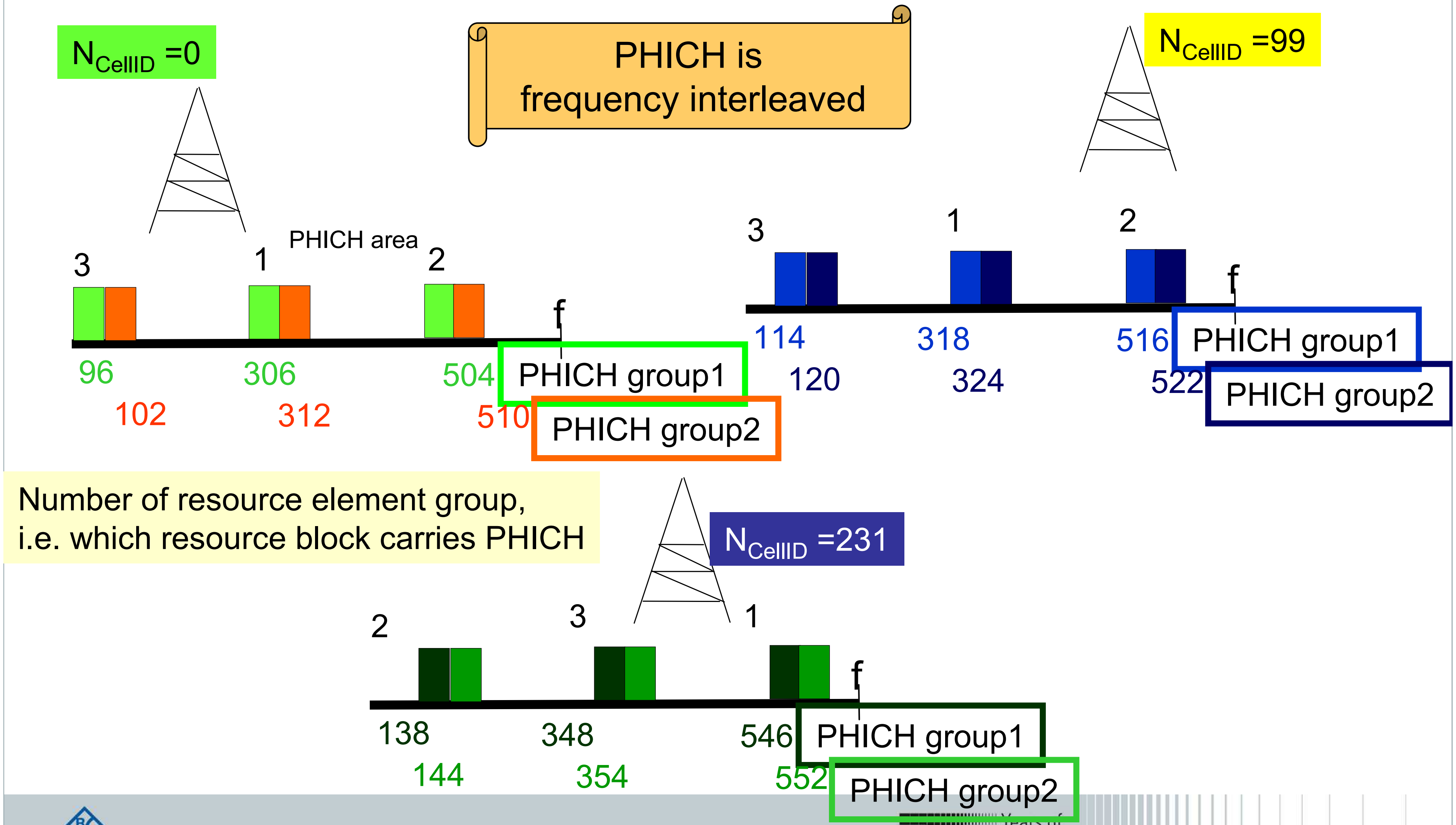
PHICH mapping on physical resource



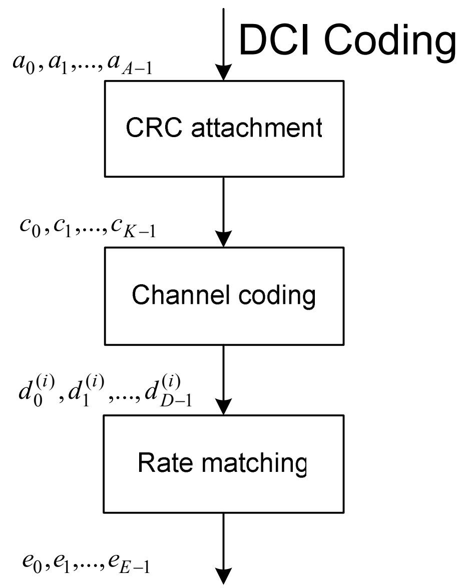
Mapping of PHICH onto resource elements is based on Cell Identity!

PHICH mapping on physical resource

Example: 3 cells with 10 MHz, each cell has 2 PHICH groups configured



Downlink Control Channel (PDCCH)



- Each PDCCH is transmitted via one or several consecutive Control Channel Elements (CCEs). Content of these CCEs is the Downlink Control Information (DCI).
- DCI contains DL or UL scheduling, or UL power control
- CRC is scrambled with UE-specific identity
- UE monitors a set of PDCCH candidates for assigned DCIs in every non-DRX subframe (Each possible DCI format is checked.)

- **DCI Formats 1, 1a, 2**
  - HARQ process number – 3 bits (FDD) , 4 bits (TDD)
    {TDD: 1..7 processes, ..16 for TTI bundling}
  - Downlink Assignment Index DAI – 2 bits (only TDD)
    {number of dynamically assigned subframes in an Uplink-ACK/NAK bundling window}
- **DCI Formats 0**
  - UL Index – 2 bits (only TDD)
    {PUSCH scheduling delay handling for TDD UL/DL frame configuration 0}

PDCCH format	Number of CCEs	Number of Resource-Element Groups	Number of PDCCH bits
0	1	9	72
1	2	18	144
2	4	36	288
3	8	72	576

DCI Format:
0 – PUSCH assignments
1/1a/1c – PDSCH assignment for SIMO
2 – PDSCH assignment for MIMO
3/3a – Uplink power commands

Downlink Control Channel (PDCCH)

- PDCCH carries L1 and L2 control information
- It is QPSK modulated
- Each PDCCH is transmitted via one or several consecutive Control Channel Elements (CCEs). Content of these CCEs is the Downlink Control Information (DCI).
- DCI contains DL or UL scheduling, or UL power control
- CRC is scrambled with UE-specific identity
- UE monitors a set of PDCCH candidates for assigned DCIs in every non-DRX subframe (Each possible DCI format is checked.)

1 PDCCH ⇨ 1,2,4 or 8 CCEs

⇩

1 CCE ⇨ 9 Resource Element Groups REG

⇩

1 REG ⇨ 6 Resource Elements RE in 1st symbol
4 RE in 2nd and 3rd symbol

PDCCH format	Number of CCEs	Number of Resource-Element Groups	Number of PDCCH bits
0	1	9	72
1	2	18	144
2	4	36	288
3	8	72	576

DCI formats

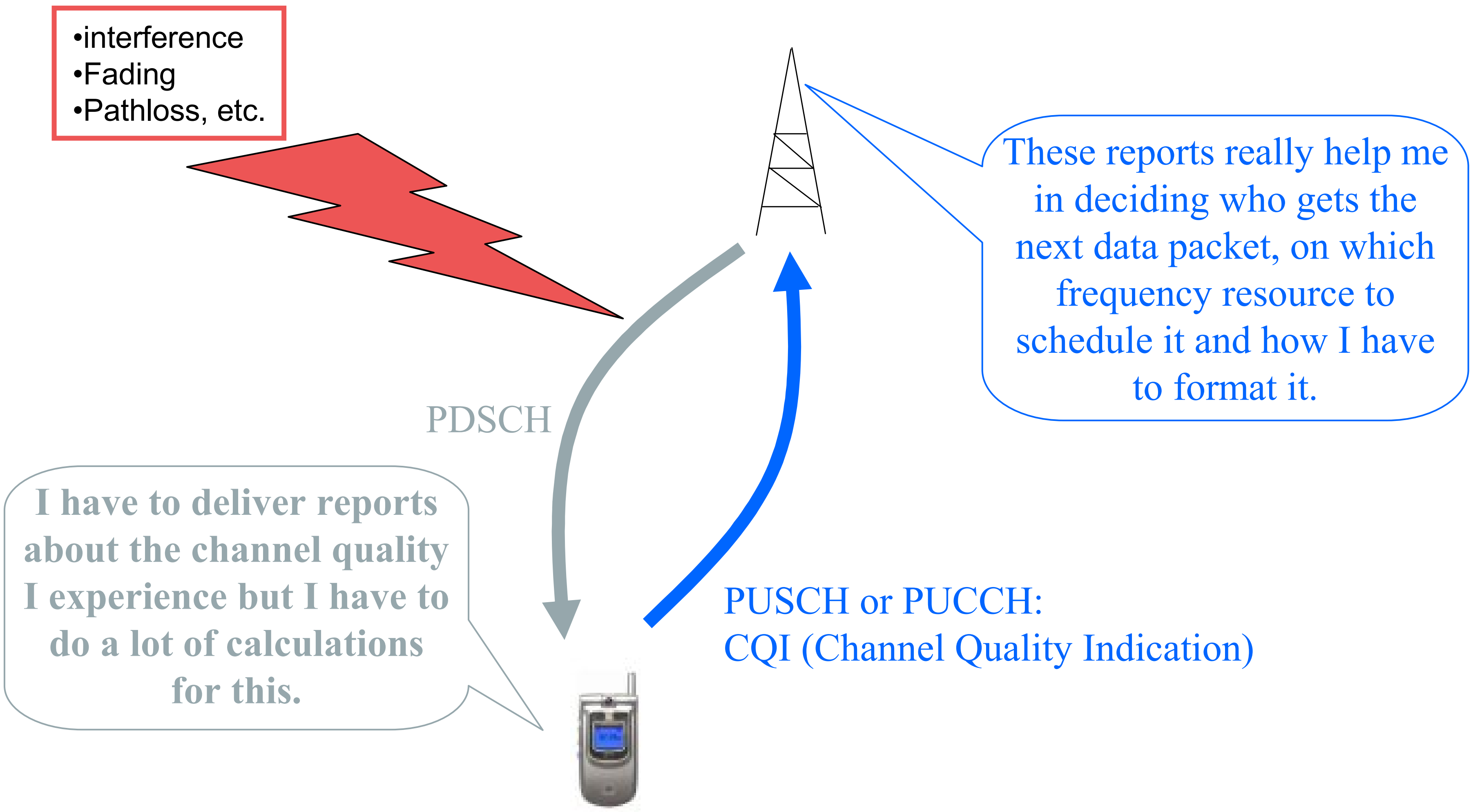
- DCI format 0 is used for the scheduling of PUSCH.
- DCI format 1 is used for the scheduling of one PDSCH codeword.
- DCI format 1A is used for the compact scheduling of one PDSCH codeword and random access procedure initiated by a PDCCH order.
- DCI format 1B is used for the compact scheduling of one PDSCH codeword with precoding information.
- DCI format 1C is used for very compact scheduling of one PDSCH codeword.
- DCI format 1D is used for the compact scheduling of one PDSCH codeword with precoding and power offset information.
- DCI format 2 is used for scheduling PDSCH to UEs configured in closed-loop spatial multiplexing mode.
- DCI format 2A is used for scheduling PDSCH to UEs configured in open-loop spatial multiplexing mode.
- DCI format 3 is used for the transmission of TPC commands for PUCCH and PUSCH with 2-bit power adjustments.
- DCI format 3A is used for the transmission of TPC commands for PUCCH and PUSCH with single bit power adjustments.

Downlink Control Information DCI content

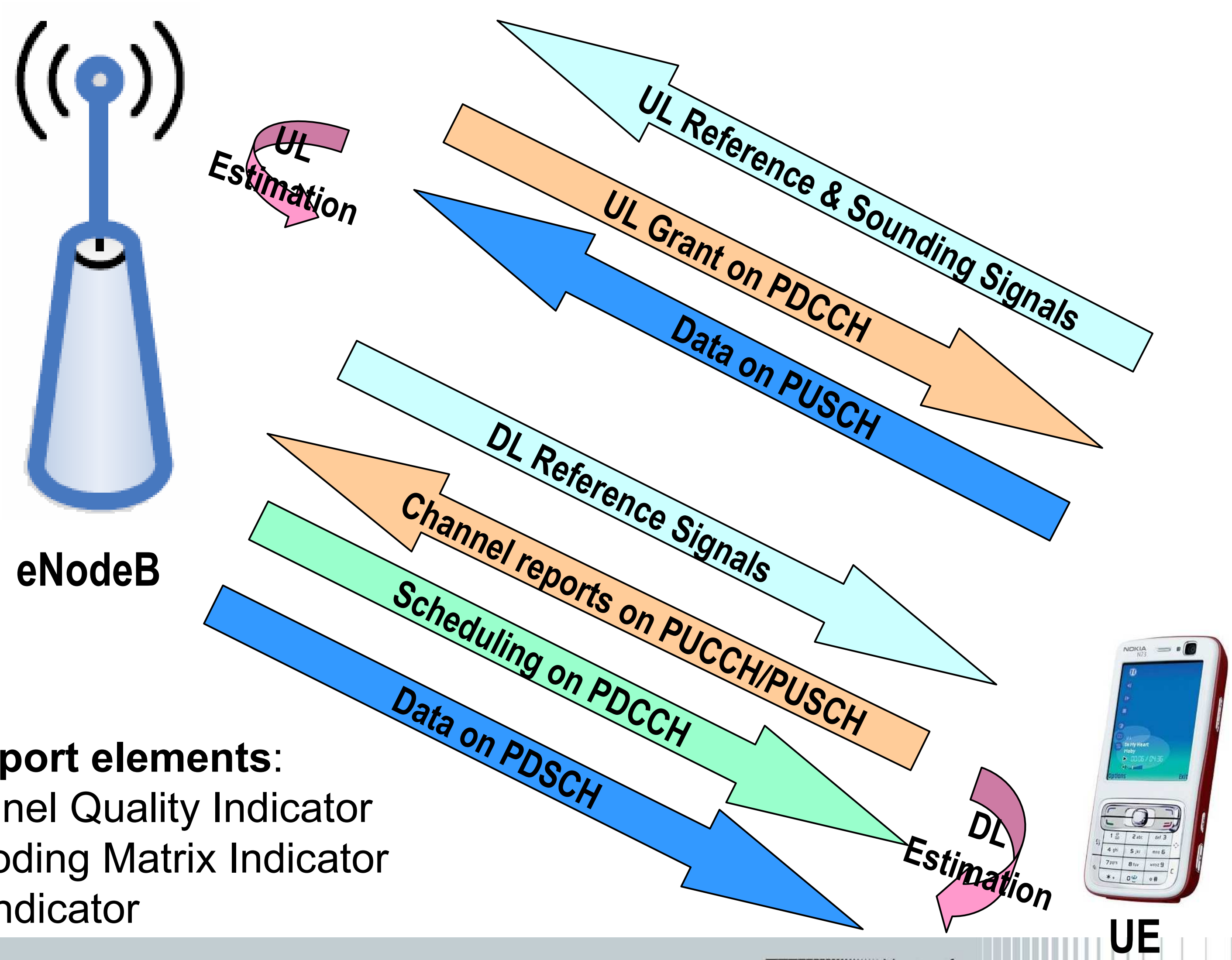
DCI format 0 is used for the scheduling of PUSCH.

- Flag for format0/format1A differentiation
- Hopping flag
- Resource block assignment
- Modulation and coding scheme and redundancy version
- New data indicator
- TPC command for scheduled PUSCH
- Cyclic shift for demodulation reference signals
- UL index (only for TDD)
- Downlink Assignment Index (DAI)   (only for TDD)
- CQI request

Channel Quality Indicator, CQI

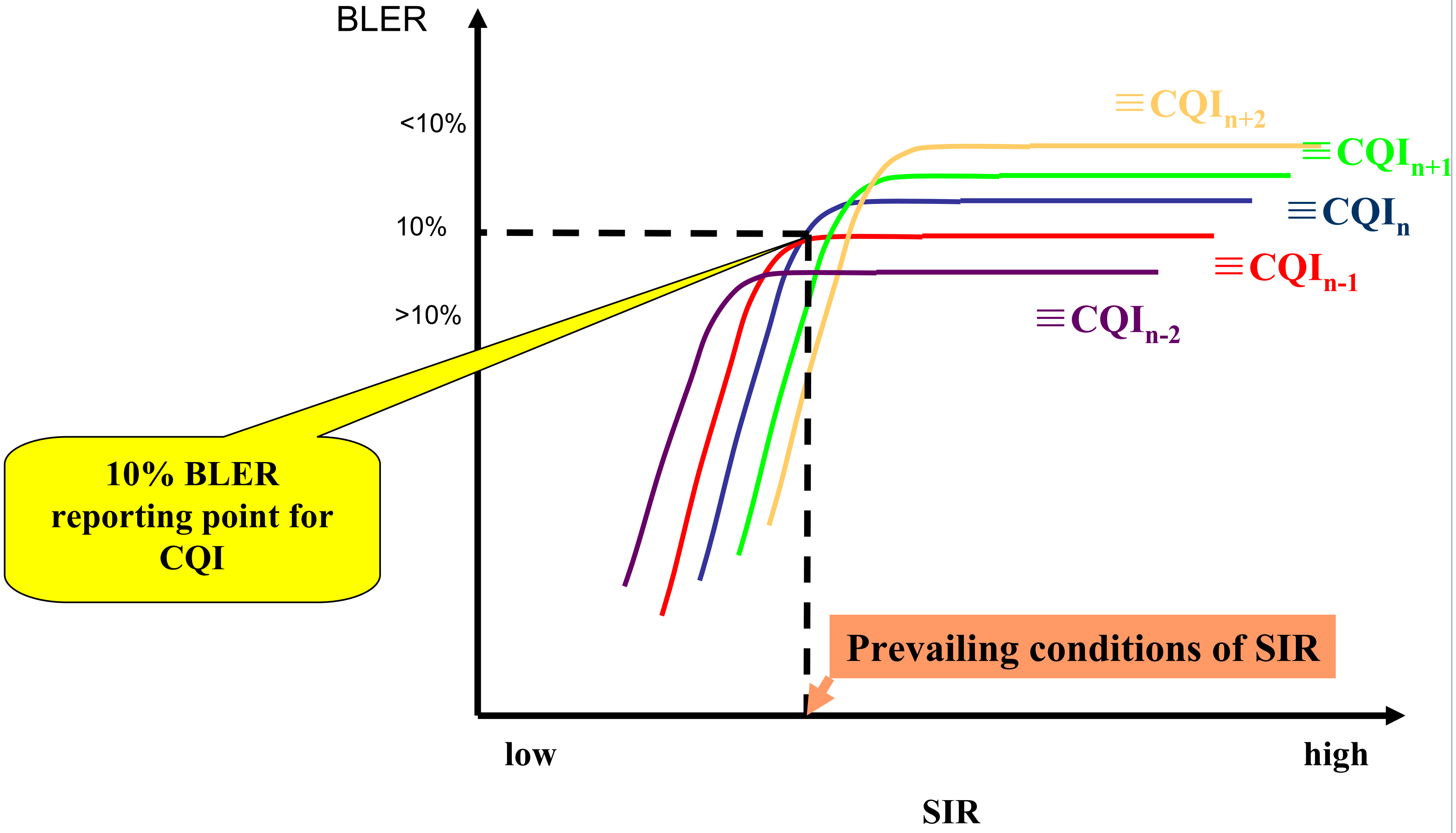


LTE Link Adaptation

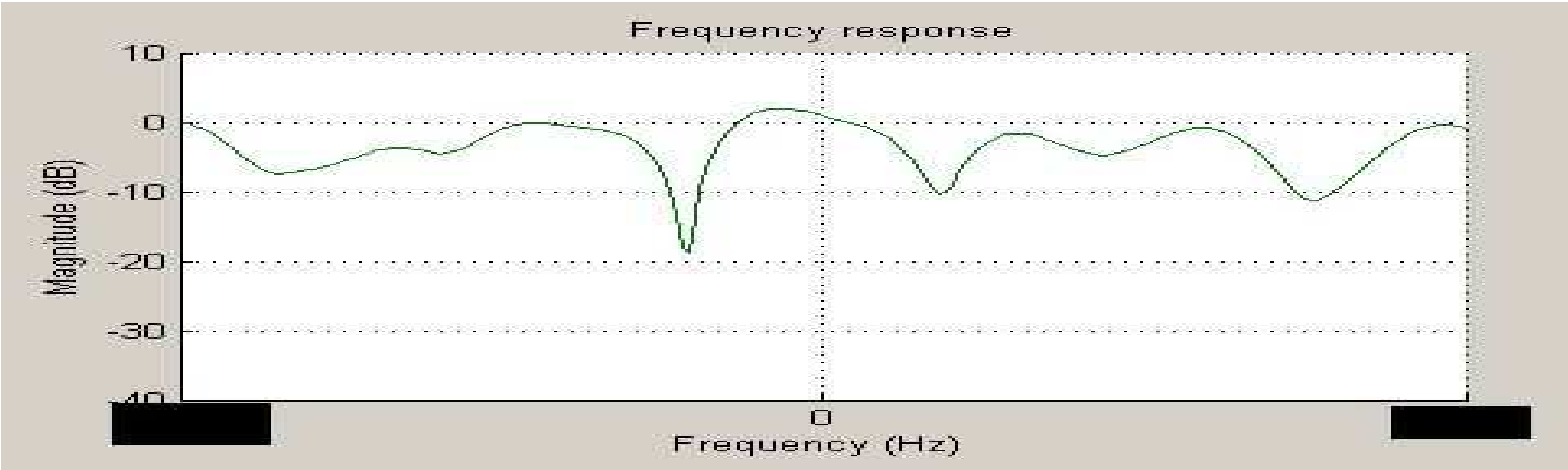


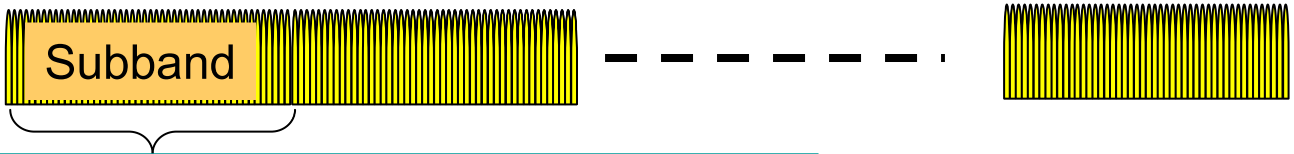
Channel report elements:
CQI – Channel Quality Indicator
PMI – Precoding Matrix Indicator
RI – Rank Indicator

CQI Targeting 10% BLER



CQI reporting – wideband + subbands





CQI per subband are relative to Wideband CQI

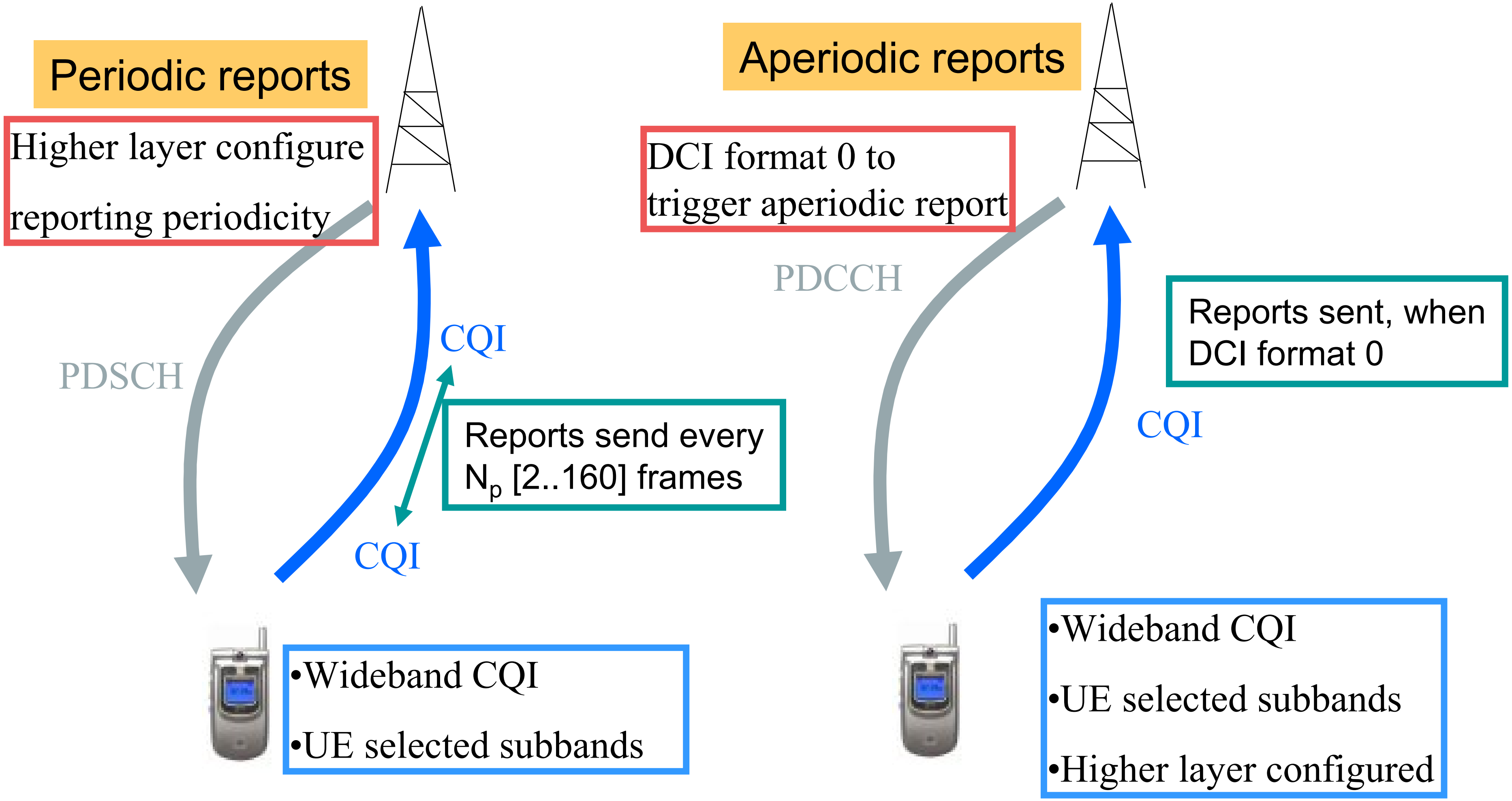
CQI per subband reports can be UE selected or Layer 3 configured

Wideband

CQI reports are subband specific to investigate frequency selectivity

CQI estimation = Σ subbands estimation

CQI reporting: periodic and aperiodic



Channel Quality Reporting

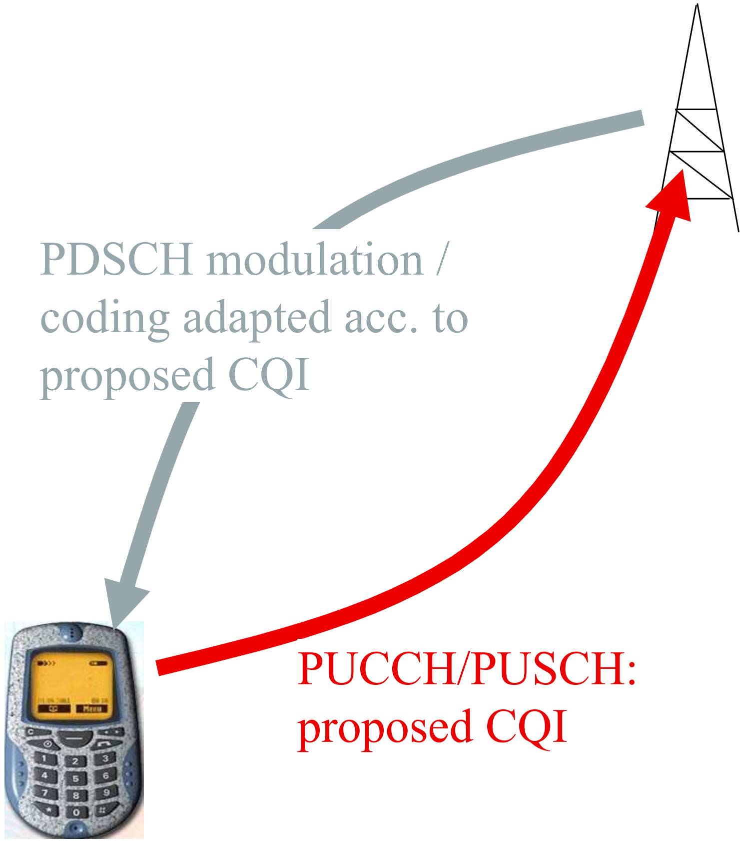
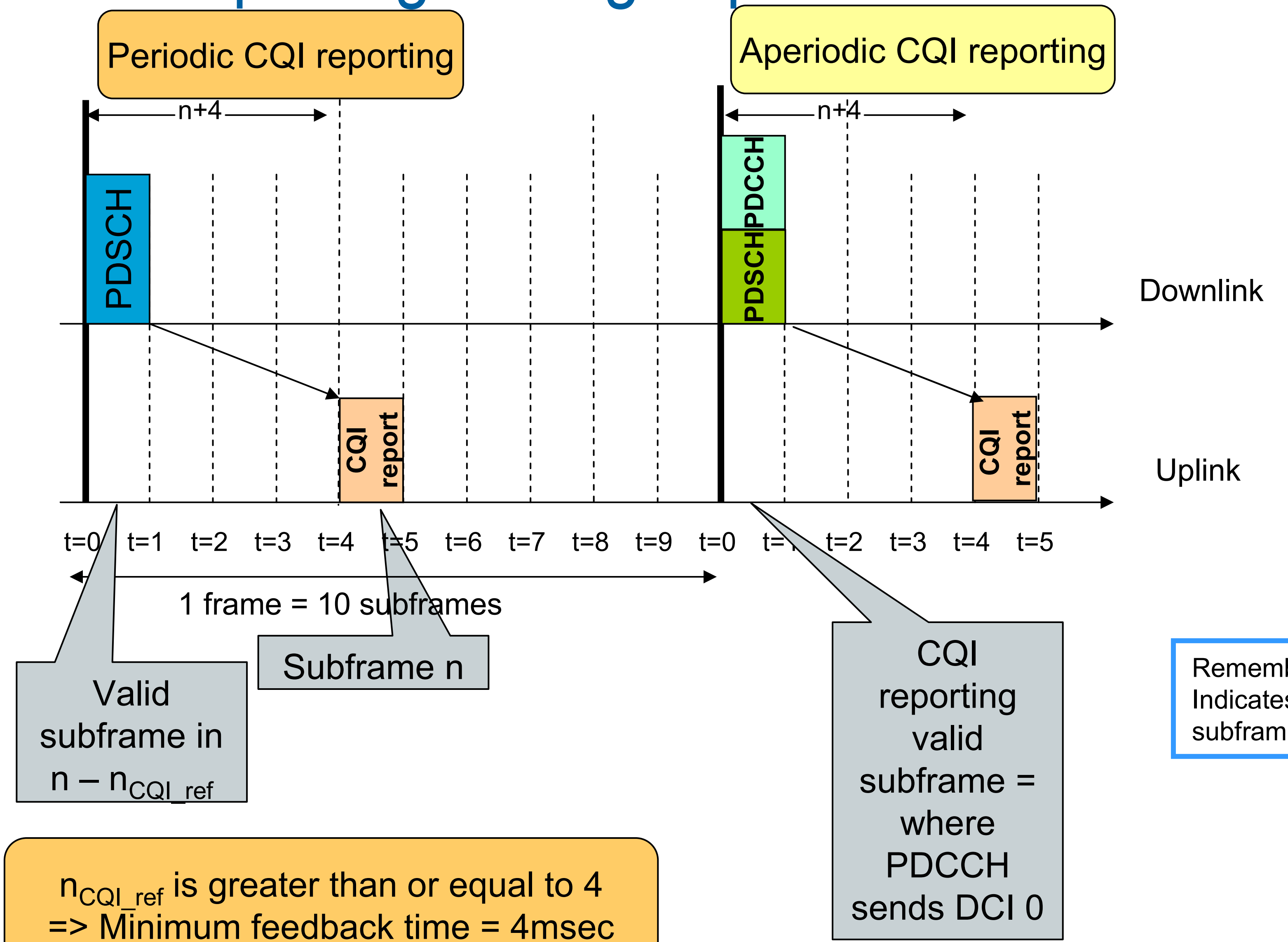


Table according to 3GPP TS 36.213

CQI index	modulation	code rate x 1024	efficiency
0	out of range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

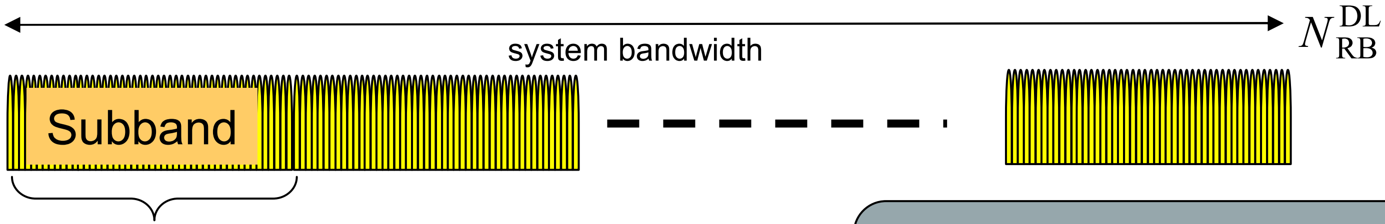
CQI reporting: timing aspects



Remember: DCI format 0
Indicates PU(S/C)CH in
subframe +4

n_{CQI_ref} is greater than or equal to 4
=> Minimum feedback time = 4msec

CQI– higher layer configured reporting



subband = k consecutives resource blocks

Higher layer configured feedback

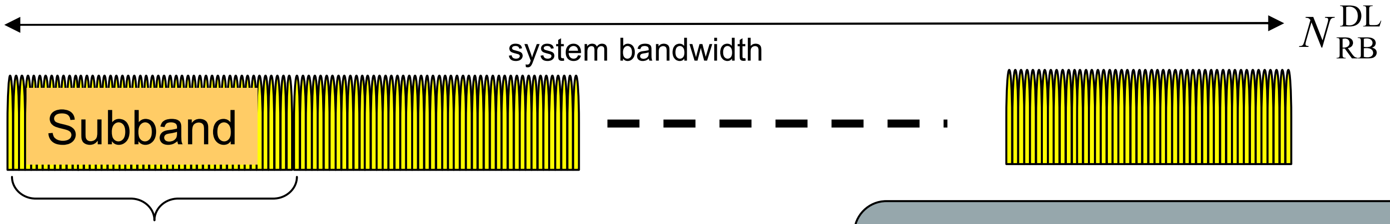
System Bandwidth N_{RB}^{DL}	Subband Size (*k*)
6 - 7	NA
8 - 10	4
11 - 26	4
27 - 63	6
64 - 110	8

Number of subbands is given as:

$$N = \left\lceil N_{RB}^{DL} / k \right\rceil$$

i.e. N = [2 .. 14]

CQI reporting – UE selected



subband = k consecutives resource blocks

UE selected feedback

System Bandwidth N_{RB}^{DL}	Subband Size k (RBs)	*M*
6 – 7	NA	NA
8 – 10	2	1
11 – 26	2	3
27 – 63	3	5
64 – 110	4	6

Number of subbands is given as:

$$N = \lceil N_{RB}^{DL} / k \rceil$$

i.e. N = [2 .. 28]

UE will select M subbands to report to network

CQI reporting modes

	PMI Feedback Type			
CQI Feedback Type		No PMI	Single PMI	Multiple PMI
	Wideband CQI	Mode 1-0	Mode 1-1	Mode 1-2
	UE Selected CQI	Mode 2-0	Mode 2-1	Mode 2-2
	Higher Layer configured CQI	Mode 3-0	Mode 3-1	

Periodic reporting

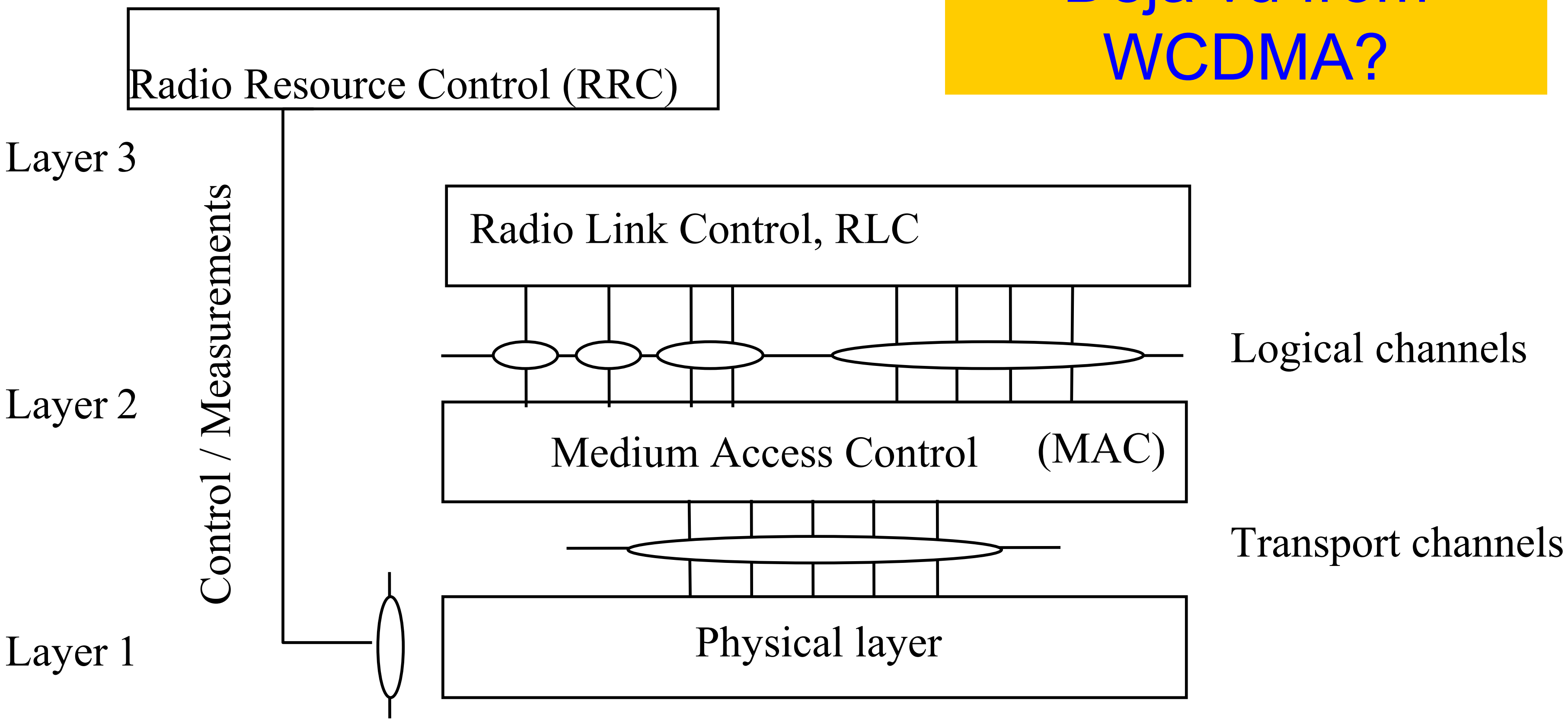
Aperiodic reporting

LTE Protocol Architecture
Reduced complexity

- Reduced number of transport channels
- Shared channels instead of dedicated channels
- Reduction of Medium Access Control (MAC) entities
- Streamlined concepts for broadcast / multicast (MBMS)
- No inter eNodeB soft handover in downlink/uplink
- No compressed mode
- Reduction of RRC states

E-UTRA protocol structure

Déjà vu from WCDMA?



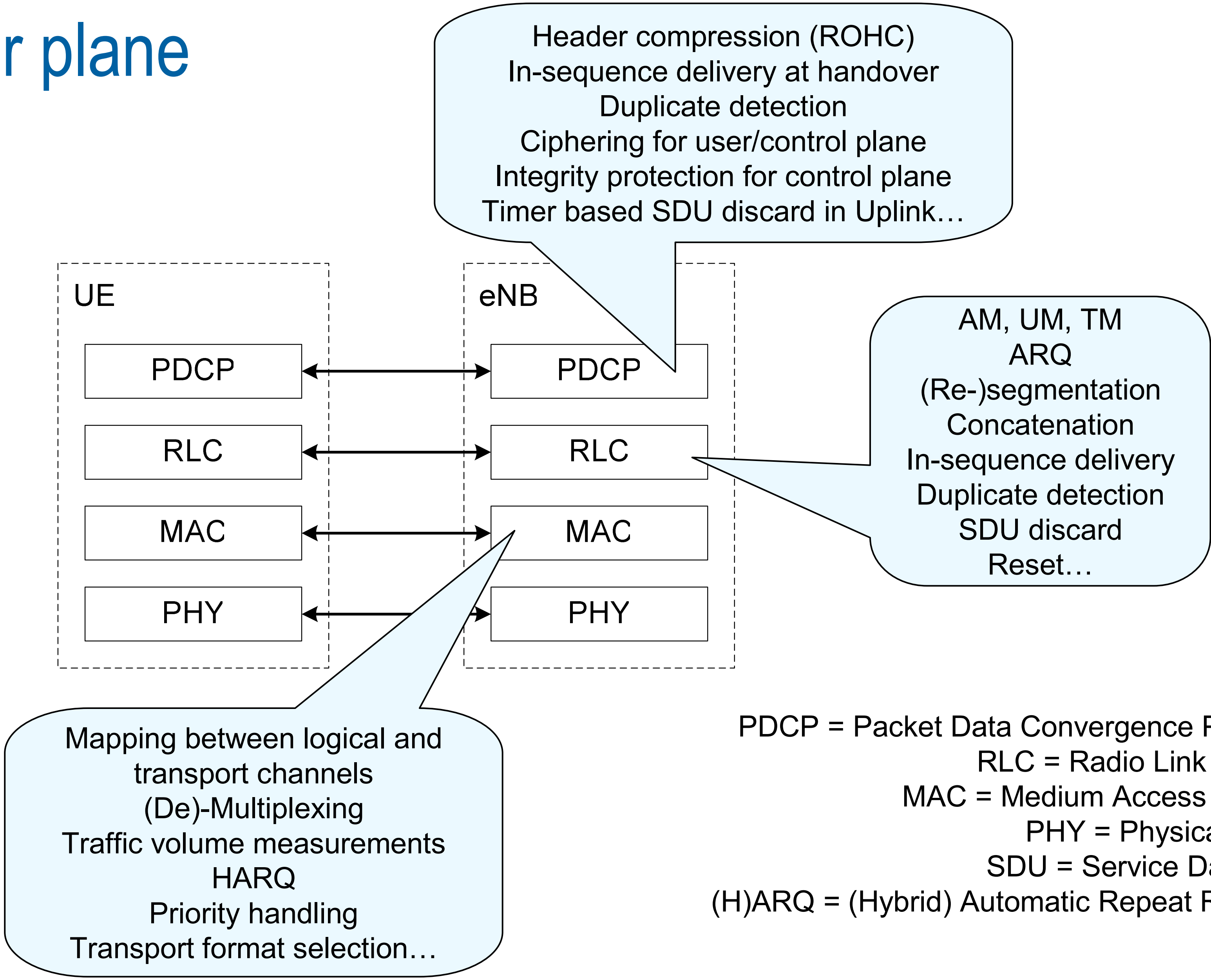
Protocol States (NAS and AS)

- EMM states:
  - EMM-DEREGISTERED
    (UE location not known)
  - EMM-REGISTERED
    (entered by Attach or Tracking Area Update procedure)
- ECM states:
  - ECM-IDLE
    (no NAS signalling connection, UE performs cell (re)selection and PLMN selection)
  - ECM-CONNECTED
    (UE location/cell ID known in MME, UE performs handover)
- RRC states:
  - RRC_IDLE (no RRC context stored in eNodeB)
  - RRC_CONNECTED (UE has E_UTRAN RRC connection and context)

EMM=EPS Mobility Management

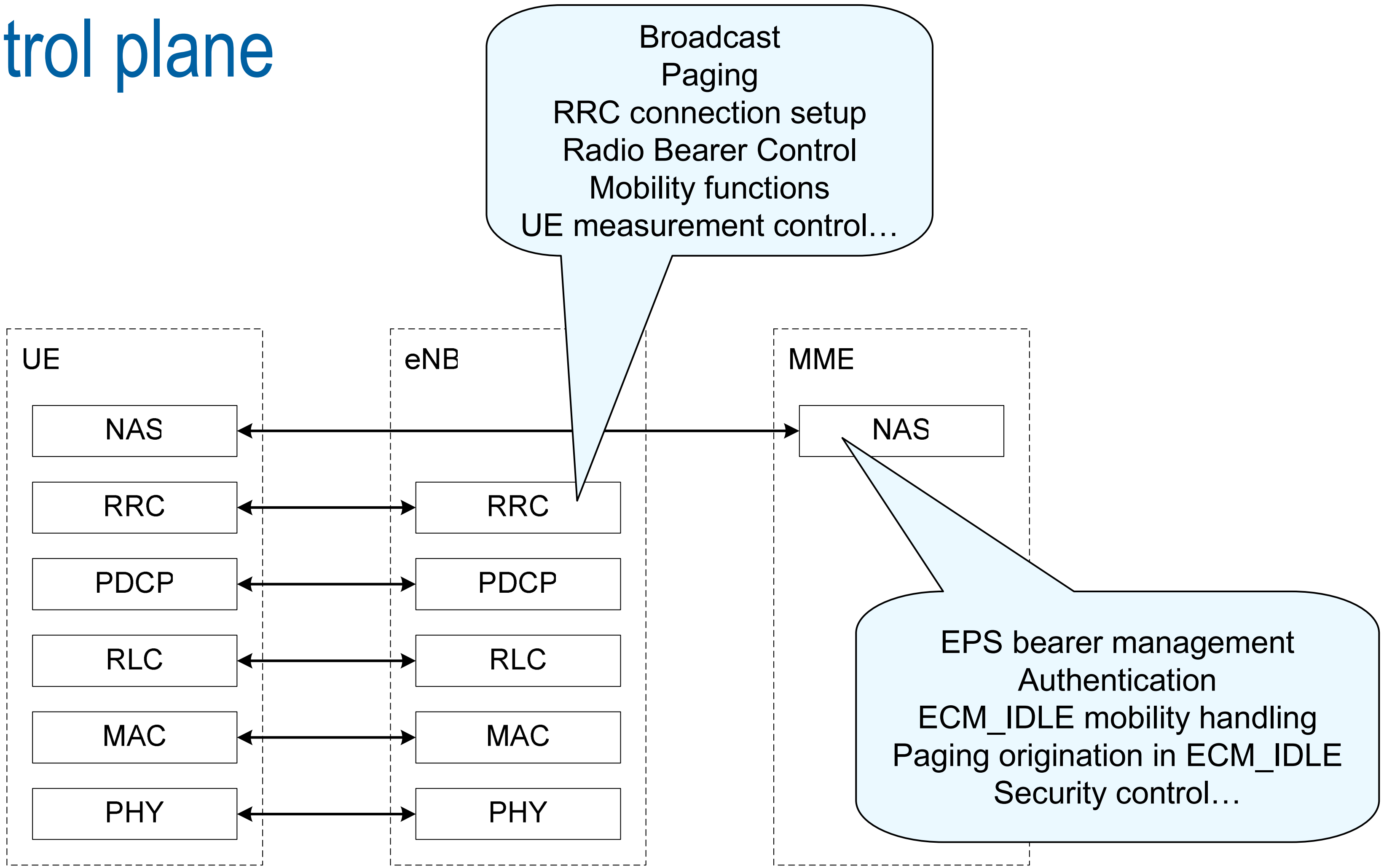
ECM = EPS Connection Management

User plane



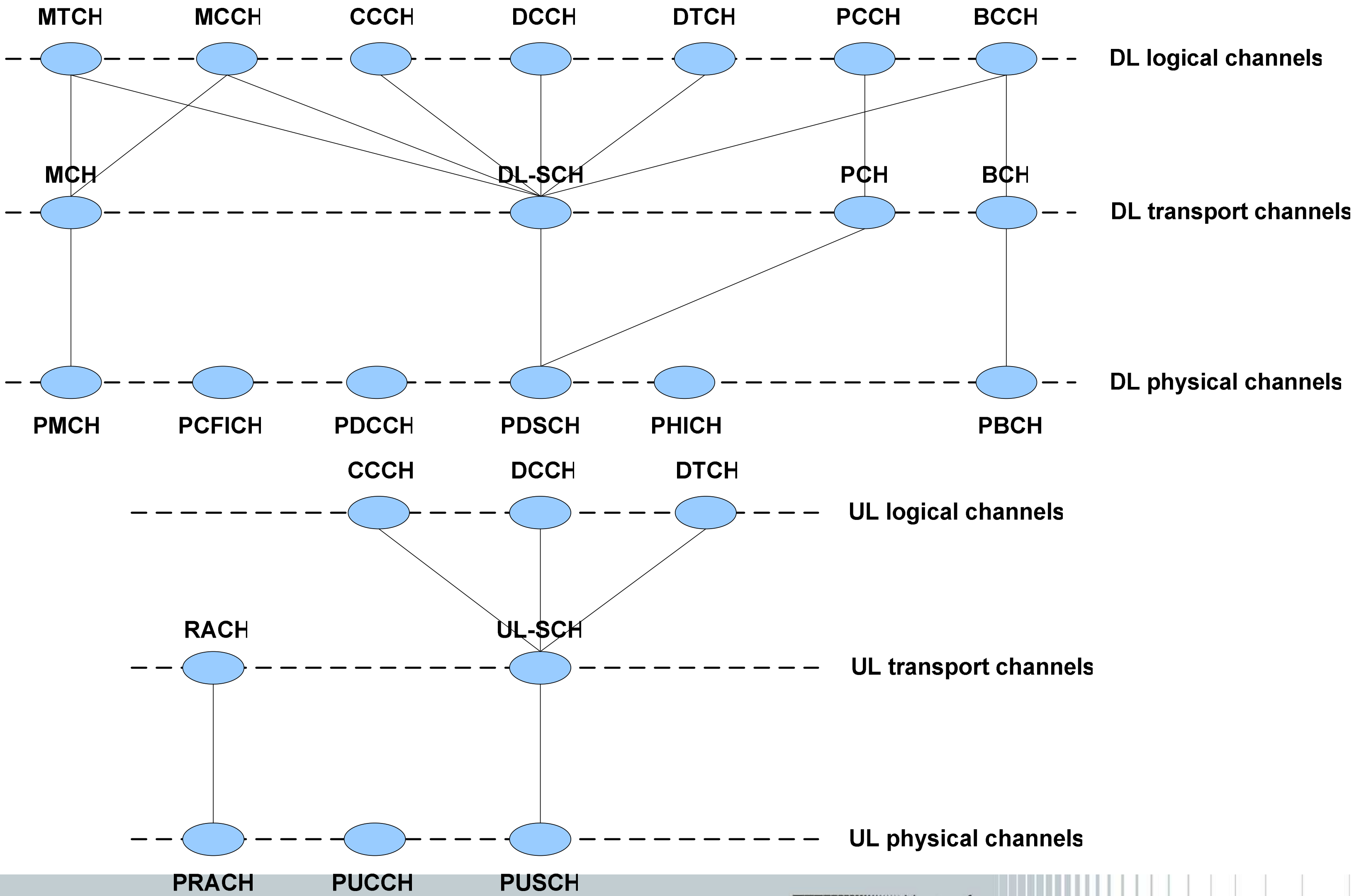
PDCP = Packet Data Convergence Protocol
RLC = Radio Link Control
MAC = Medium Access Control
PHY = Physical Layer
SDU = Service Data Unit
(H)ARQ = (Hybrid) Automatic Repeat Request

Control plane



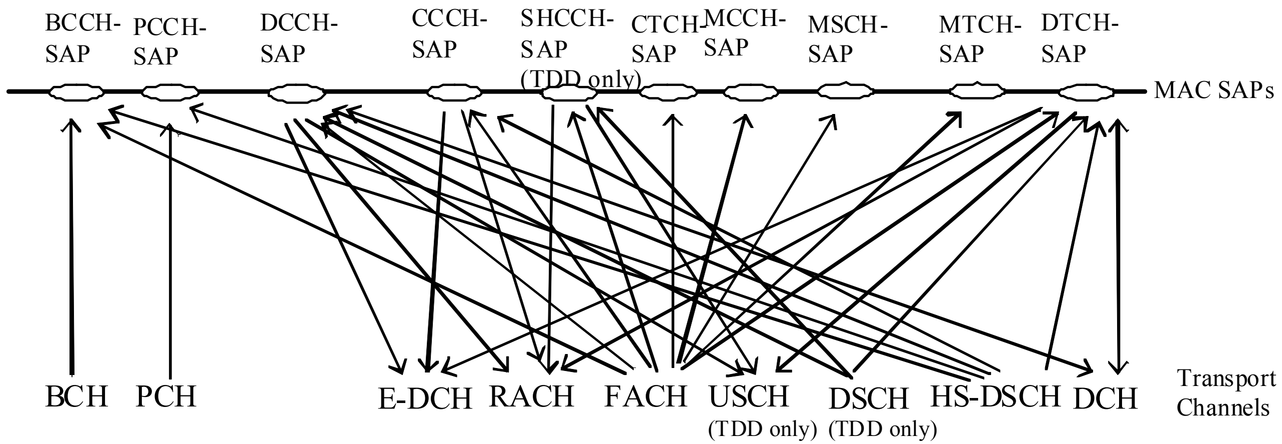
EPS = Evolved packet system
RRC = Radio Resource Control
NAS = Non Access Stratum
ECM = EPS Connection Management

LTE – channels

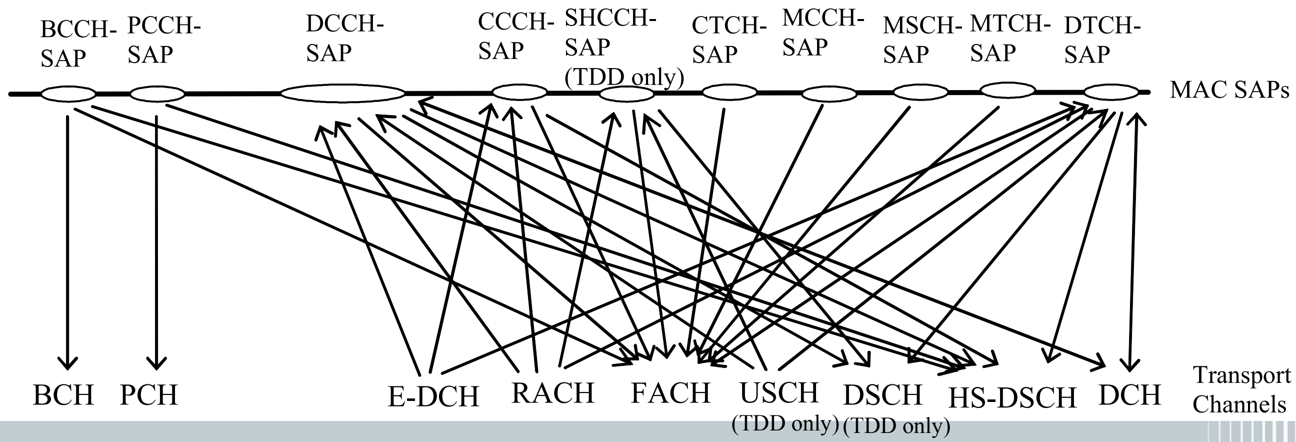


Compare: Logical / Transport channels in UMTS release 7

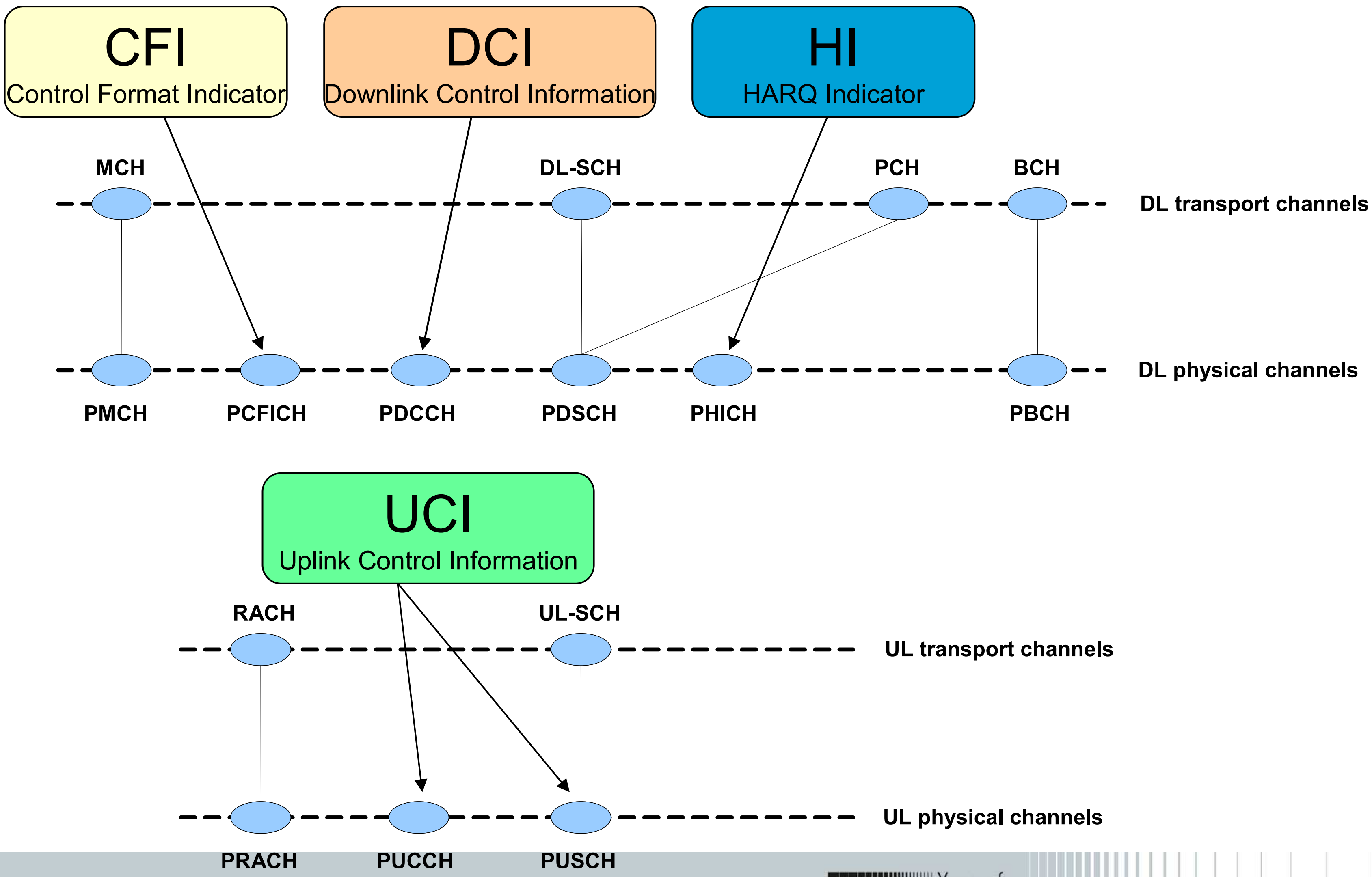
DL:



UL:

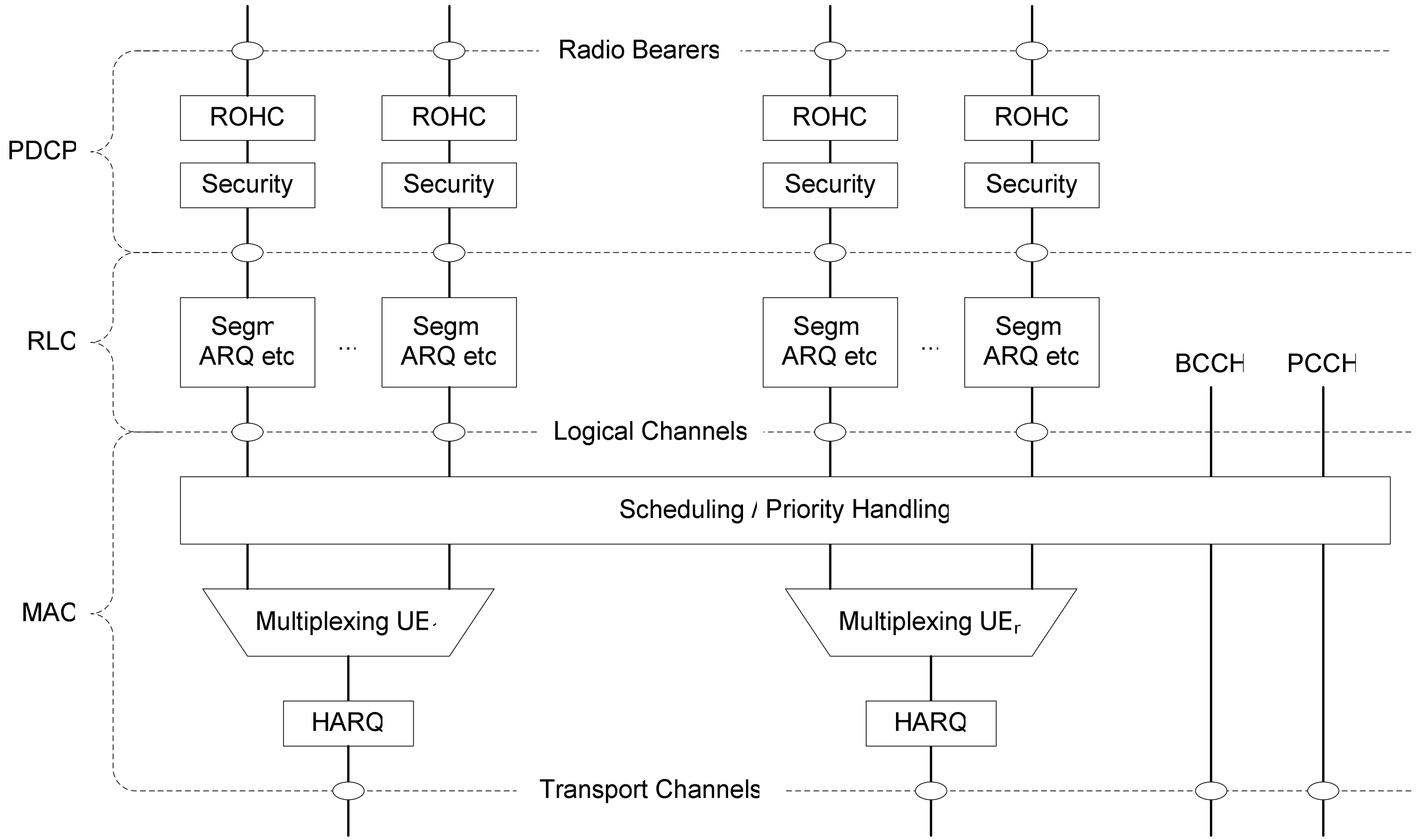


LTE – channels: control information mapping

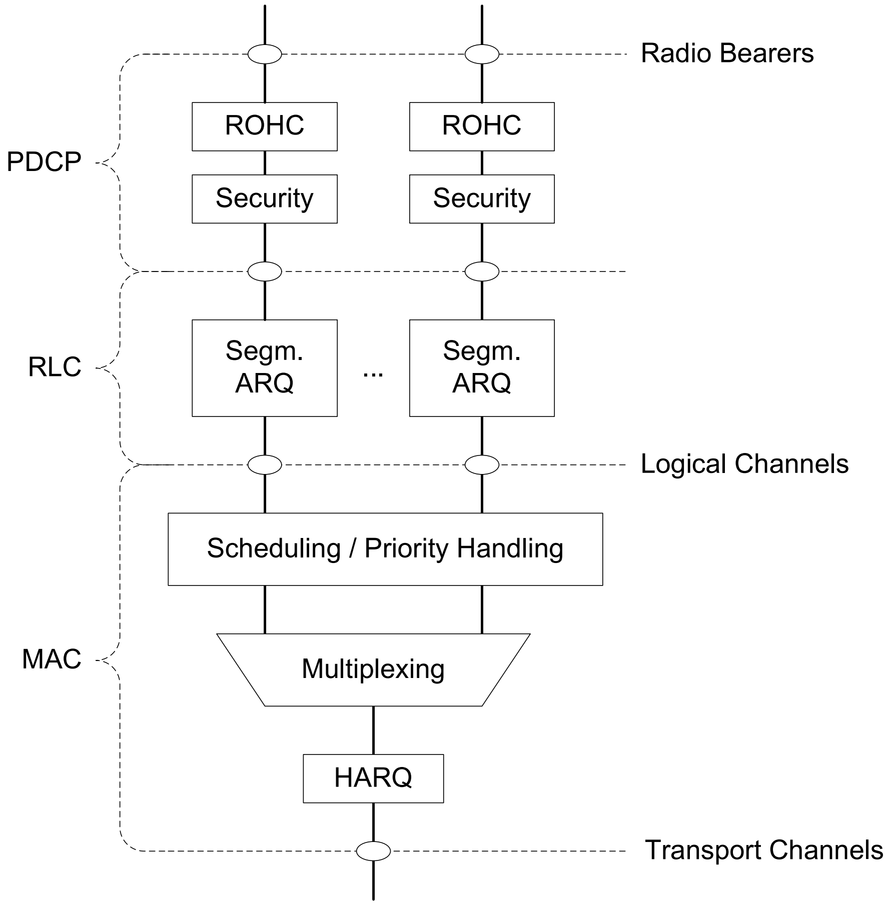


MAC structure

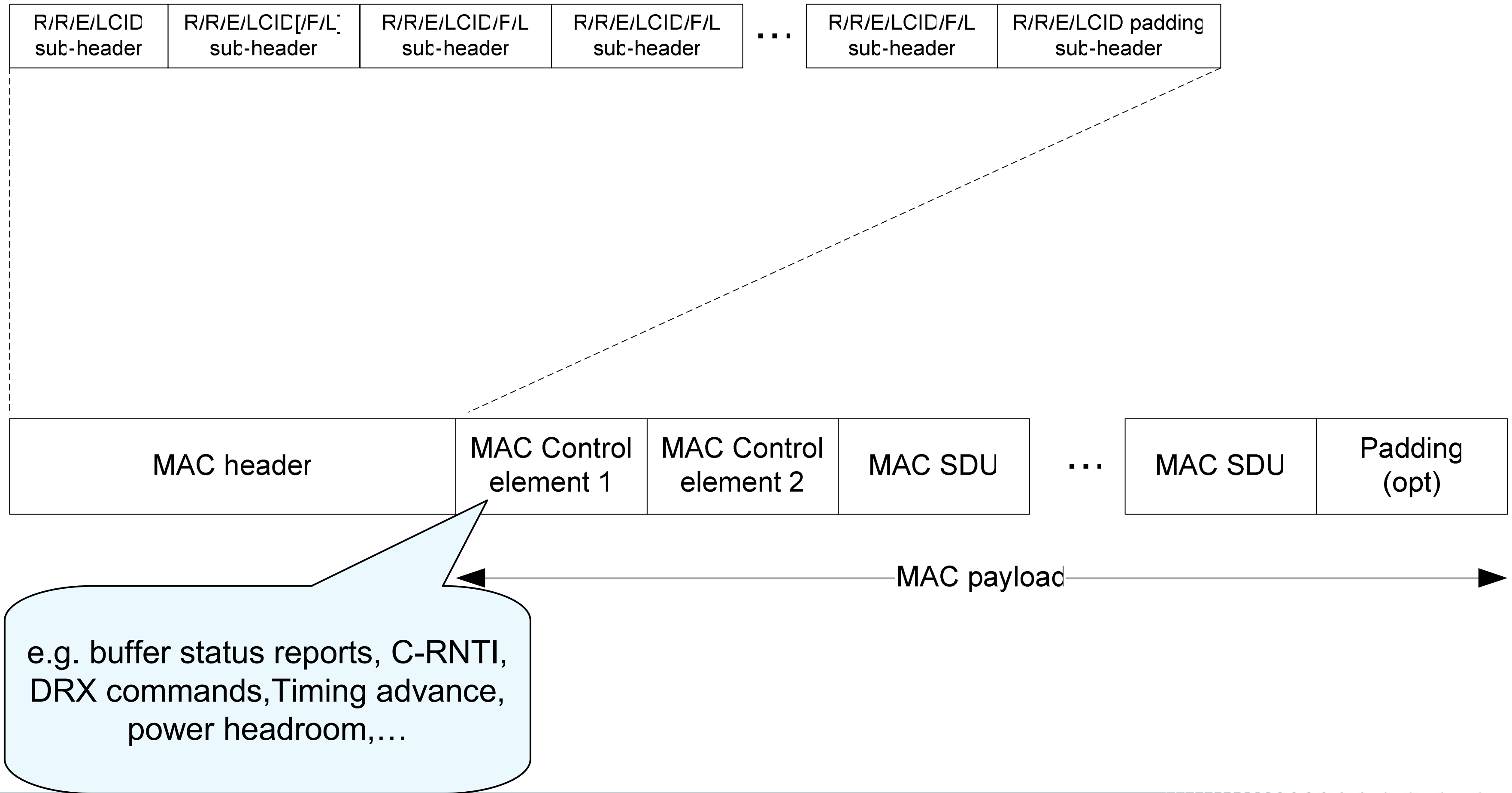
Layer 2 Structure for Downlink



Layer 2 Structure for Uplink

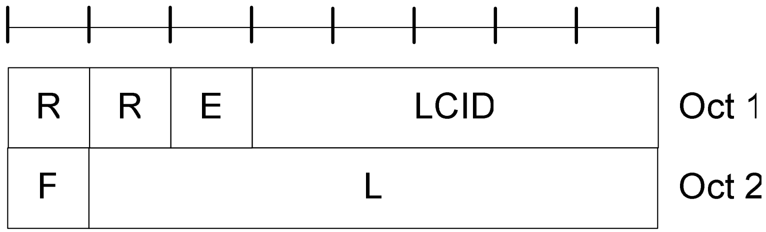


MAC PDU structure

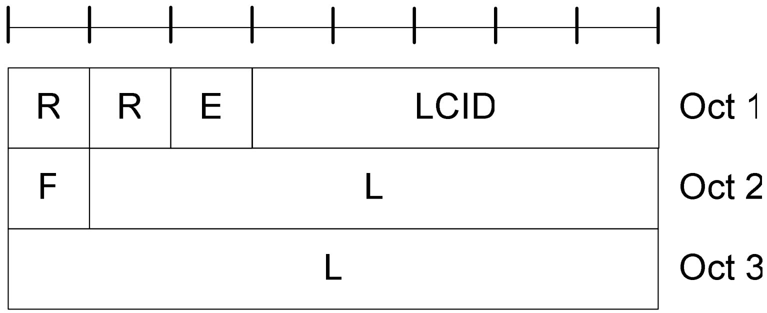


MAC PDU structure

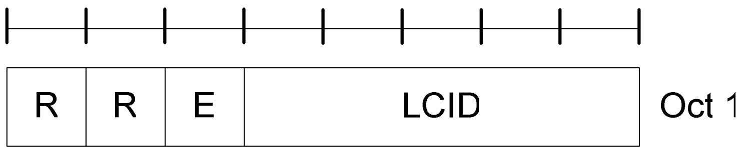
R=reserved
E=Extension field indicating if more fields are present afterwards
F= Format field indicating size of length field
LCID = Logical channel ID of corresponding MAC SDU
L = length field



R/R/E/LCID/F/L sub-header with 7-bits L field



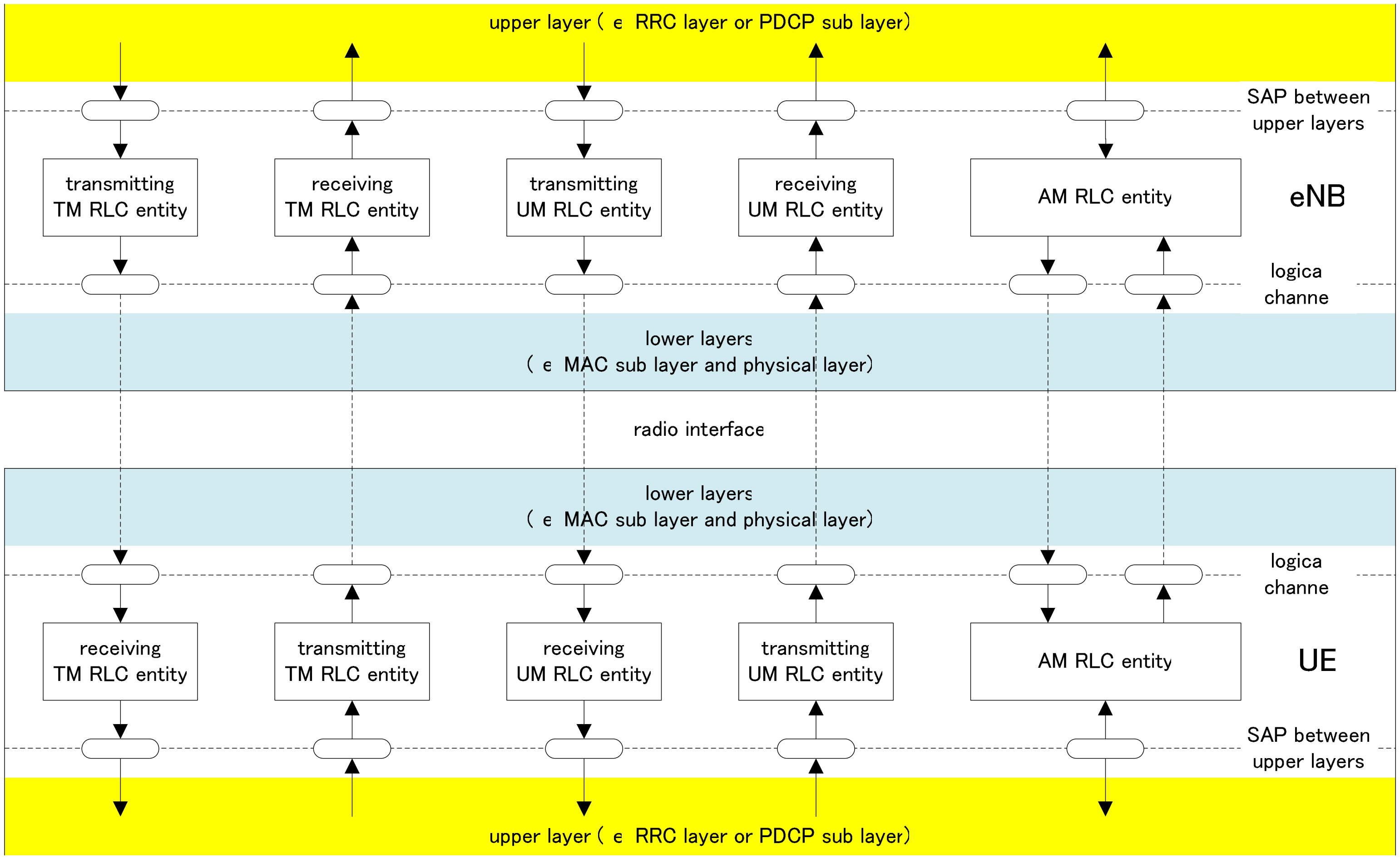
R/R/E/LCID/F/L sub-header with 15-bits L field



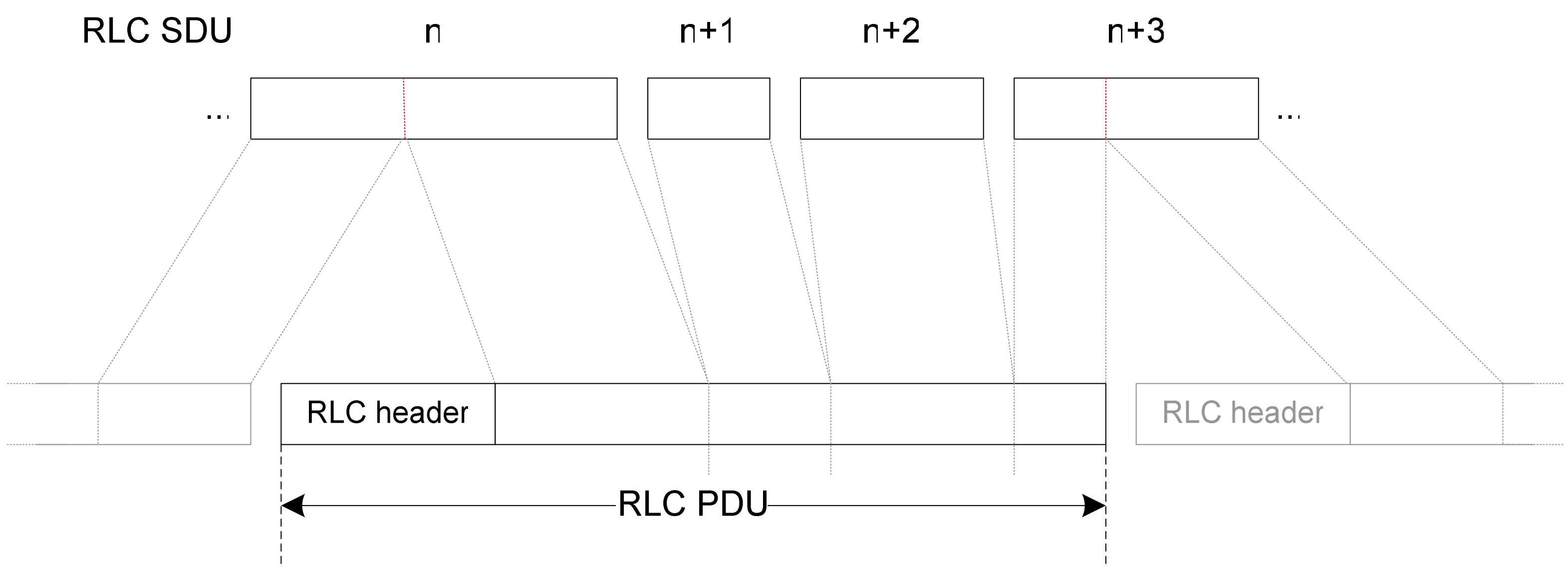
R/R/E/LCID sub-header

RLC structure

RLC model overview



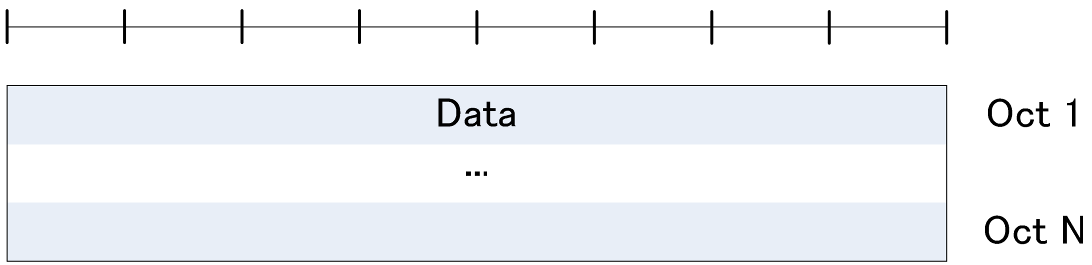
RLC PDU structure



SDU = Service Data Unit
PDU = Packet Data Unit

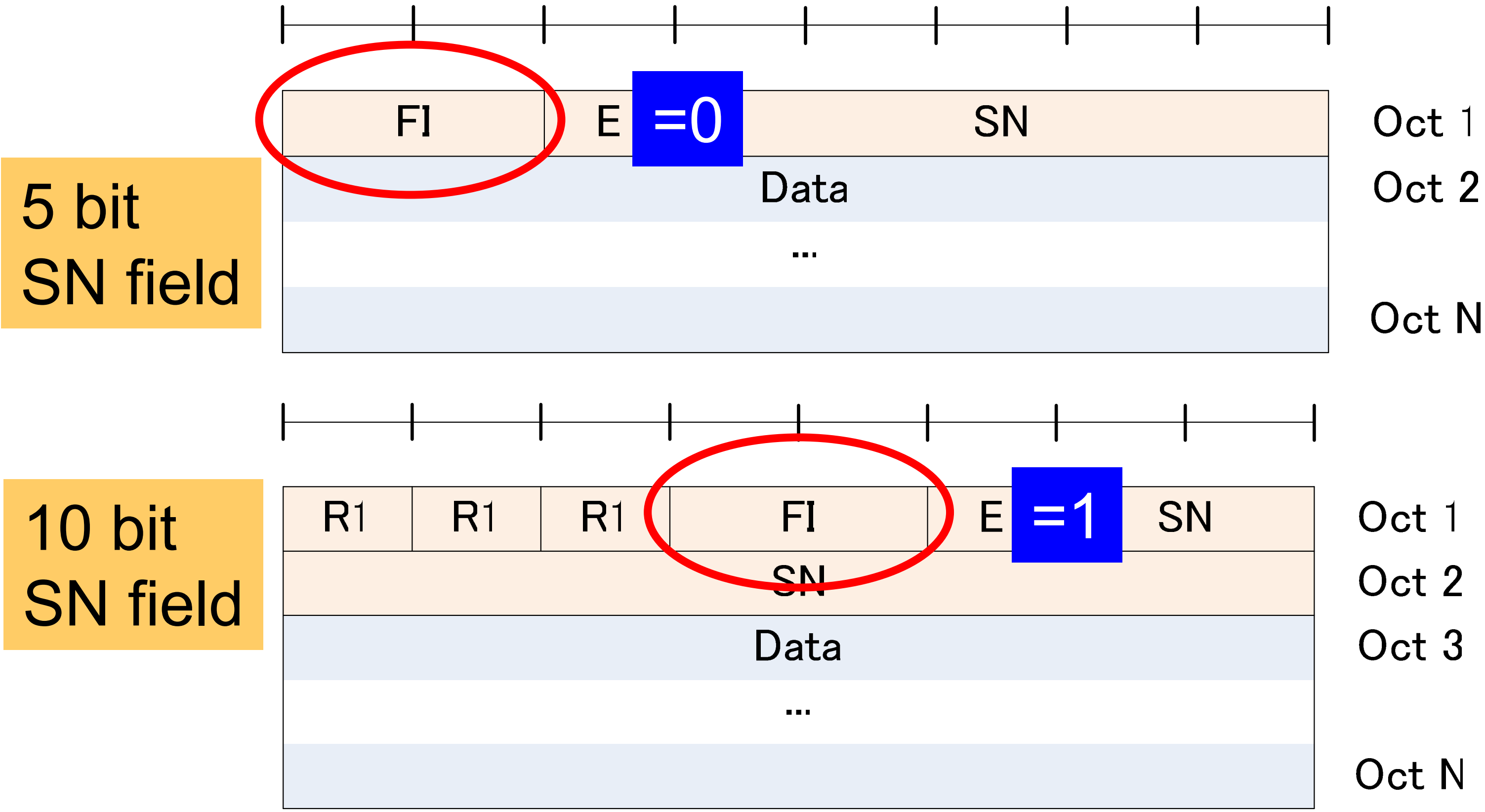
RLC TM PDU

Transparent mode Protocol Data Unit



RLC UM PDU

Unacknowledge mode Protocol Data Unit



FI = Framing Information

R = reserved flag

E = extension flag

SN = sequence number

RLC AM PDU

Acknowledge mode Protocol Data Unit

<table>
<tr><td></td><td>D/C</td><td>RF</td><td>P</td><td colspan="2">FI</td><td>E</td><td colspan="2">SN</td><td>Oct 1</td></tr>
<tr><td></td><td colspan="8">SN</td><td>Oct 2</td></tr>
<tr><td></td><td>E</td><td colspan="7">LI_1</td><td>Oct 3</td></tr>
<tr><td></td><td colspan="4">LI_1</td><td>E</td><td colspan="3">LI_2 (if K>=3)</td><td>Oct 4</td></tr>
<tr><td rowspan="5">Present if K >= 3</td><td colspan="8">LI_2</td><td>Oct 5</td></tr>
<tr><td colspan="8">...</td><td></td></tr>
<tr><td>E</td><td colspan="7">LI_{K-2}</td><td>Oct [2.5+1.5*K-4]</td></tr>
<tr><td colspan="4">LI_{K-2}</td><td>E</td><td colspan="3">LI_{K-1}</td><td>Oct [2.5+1.5*K-3]</td></tr>
<tr><td colspan="8">LI_{K-1}</td><td>Oct [2.5+1.5*K-2]</td></tr>
<tr><td></td><td>E</td><td colspan="7">LI_K</td><td>Oct [2.5+1.5*K-1]</td></tr>
<tr><td></td><td colspan="4">LI_K</td><td colspan="4">Padding</td><td>Oct [2.5+1.5*K]</td></tr>
<tr><td></td><td colspan="8">Data</td><td>Oct [2.5+1.5*K+1]</td></tr>
<tr><td></td><td colspan="8">...</td><td></td></tr>
<tr><td></td><td colspan="8"></td><td>Oct N</td></tr>
</table>

D/C = Data or Control P = Polling bit

RF = Resegmentation flag, PDU or segment

RLC AM segment

Acknowledge mode Protocol Data Unit

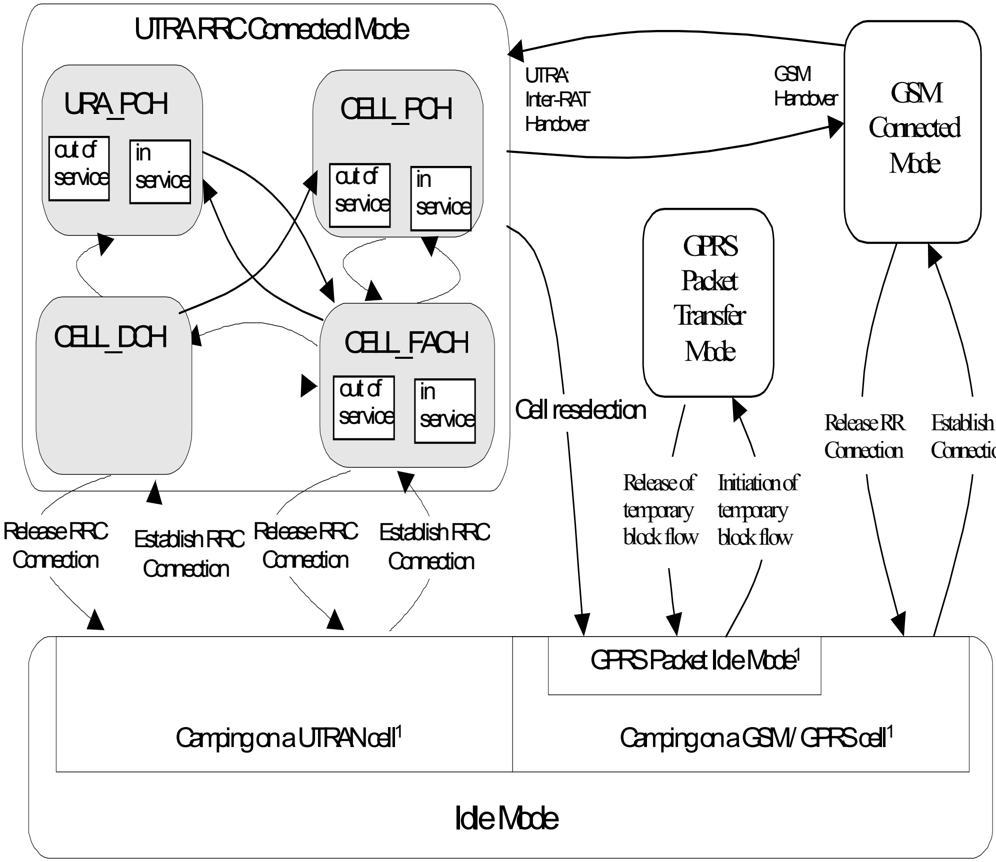
D/C | RF | P | FI | E | SN		Oct 1
SN		Oct 2
LSF | SO		Oct 3
SO		Oct 4
E | LI_1		Oct 5
LI_1 | E | LI_2 (if K>=3)		Oct 6
LI_2	Present if K >= 3	Oct 7
...	Present if K >= 3	
E | LI_{K-2}	Present if K >= 3	Oct [4.5+1.5*K-4]
LI_{K-2} | E | LI_{K-1}	Present if K >= 3	Oct [4.5+1.5*K-3]
LI_{K-1}	Present if K >= 3	Oct [4.5+1.5*K-2]
E | LI_K		Oct [4.5+1.5*K-1]
LI_K | Padding		Oct [4.5+1.5*K]
Data		Oct [4.5+1.5*K+1]
...		
		Oct N

SO = Segment offset, start/end of PDU portion

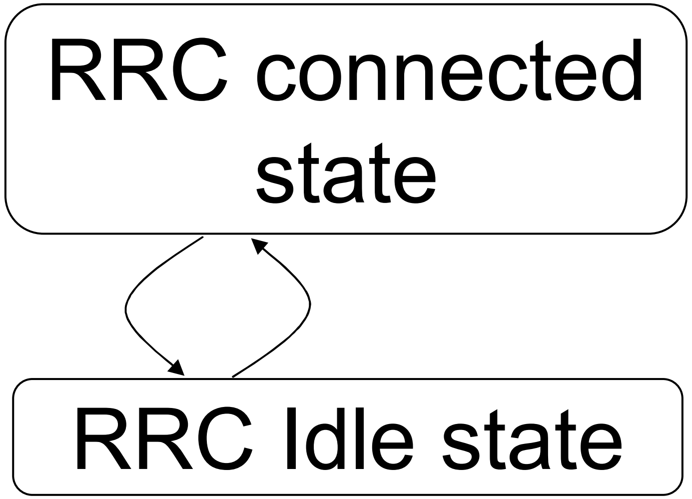
LSF = Last segment flag

RRC procedures

RRC Protocol states WCDMA <-> LTE

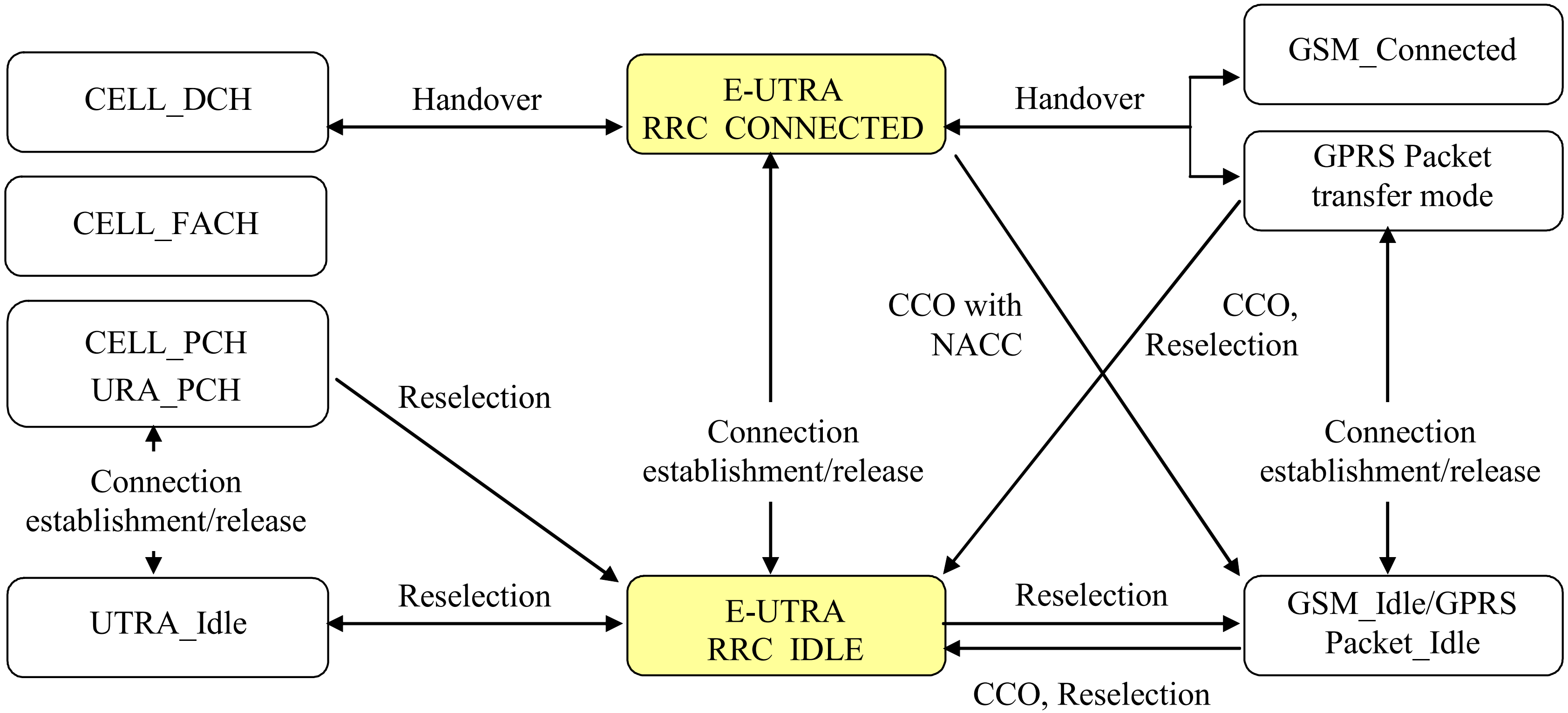


WCDMA protocol states

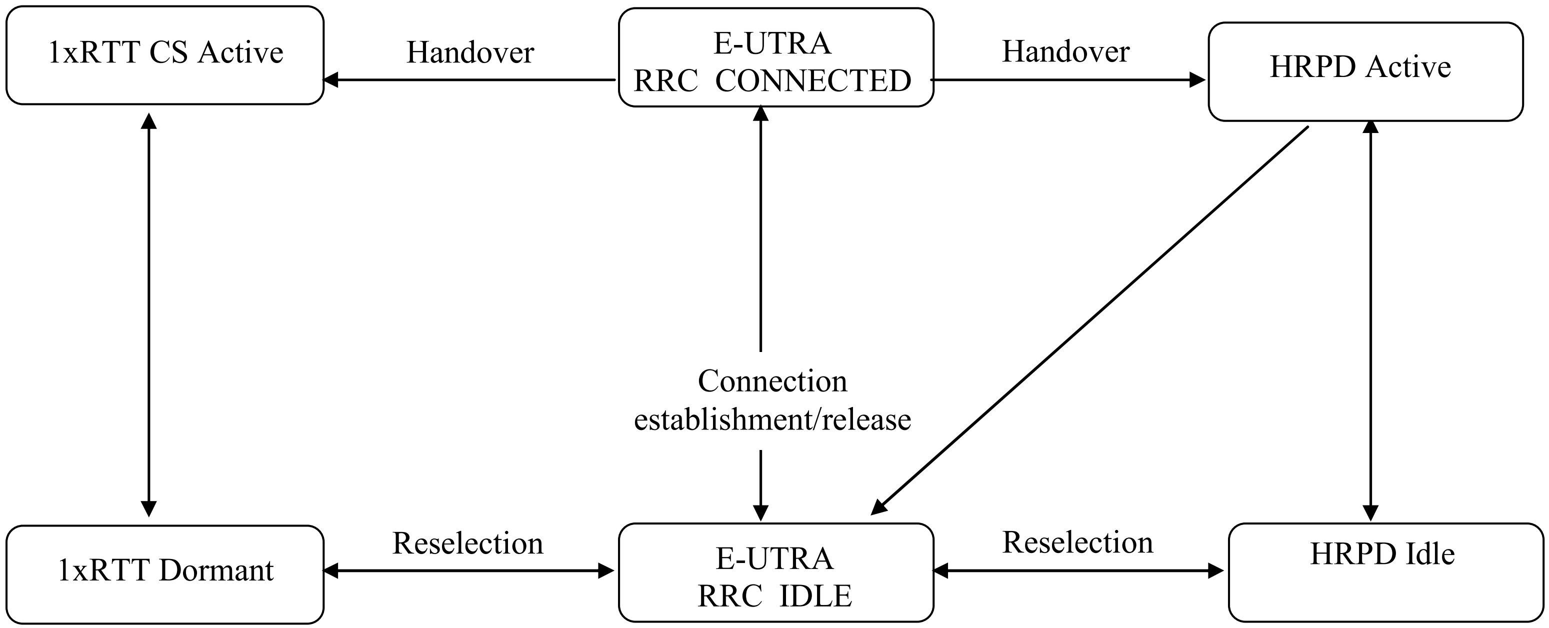


LTE protocol states

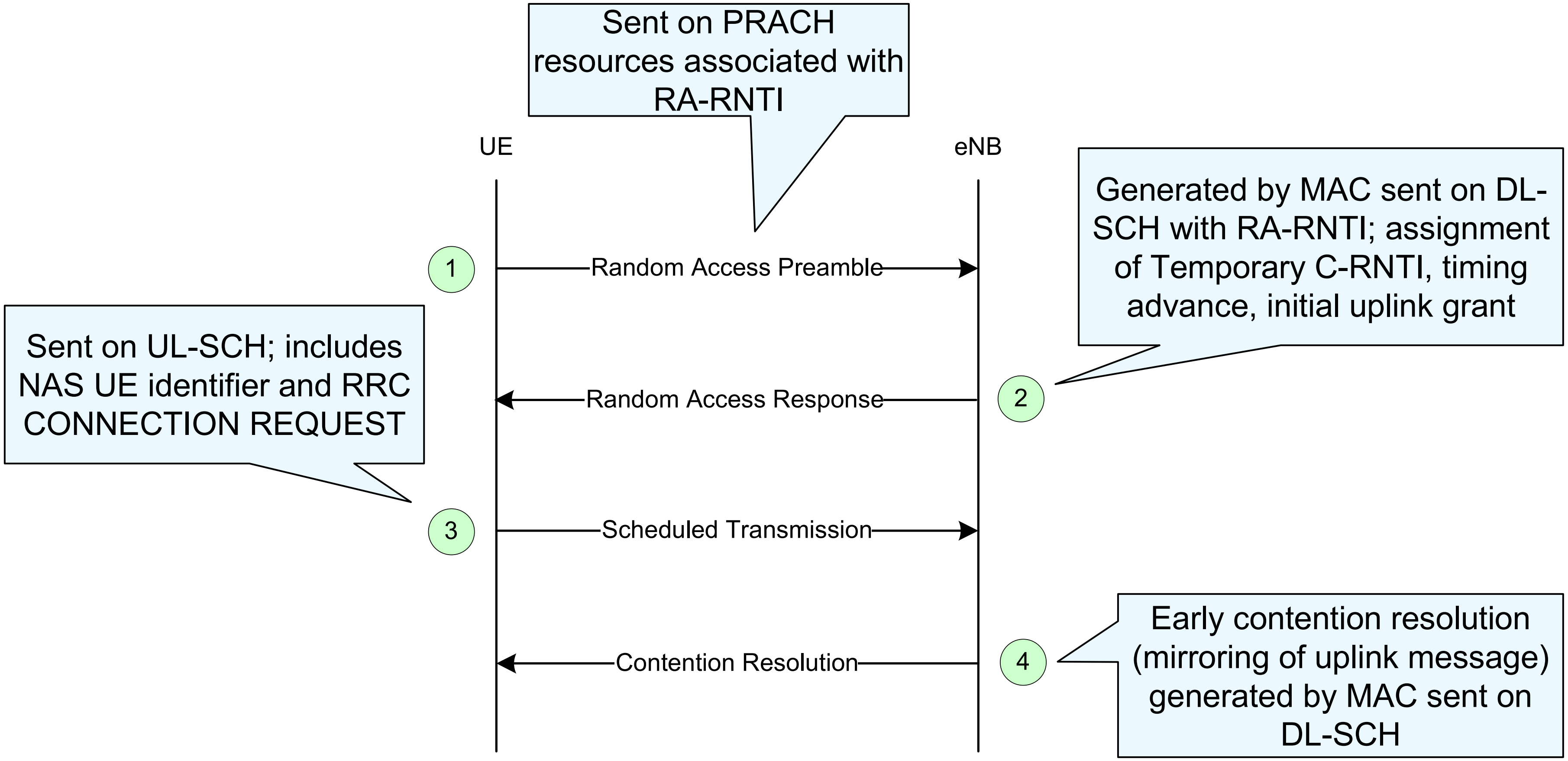
LTE Interworking with 2G/3G
Two RRC states: CONNECTED & IDLE



LTE Interworking with CDMA2000 1xRTT and HRPD (High Rate Packet Data)



Initial access procedure



Paging

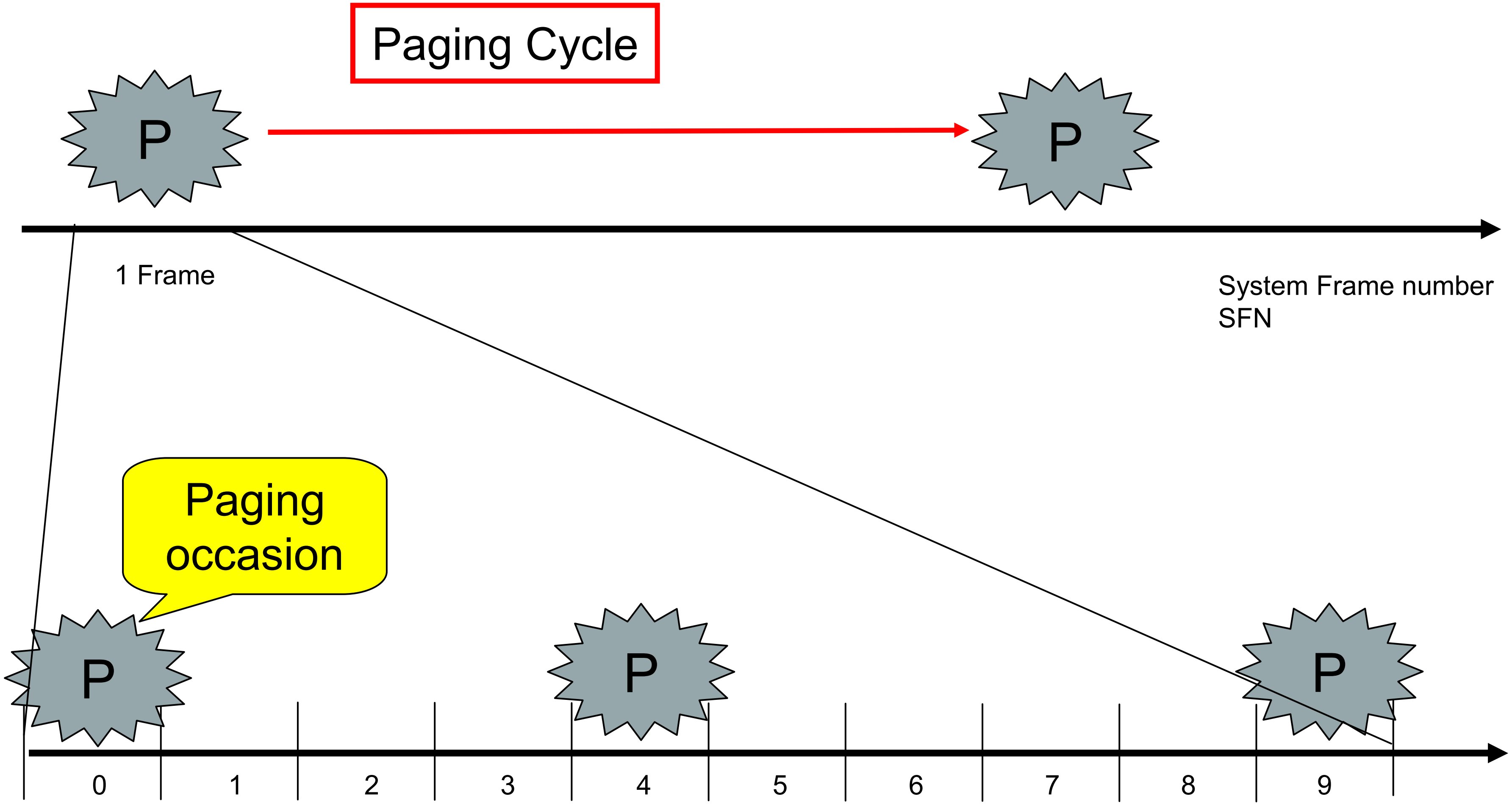
Paging procedure is used to:

•Transmit paging information to a UE

•Inform about System Information Change

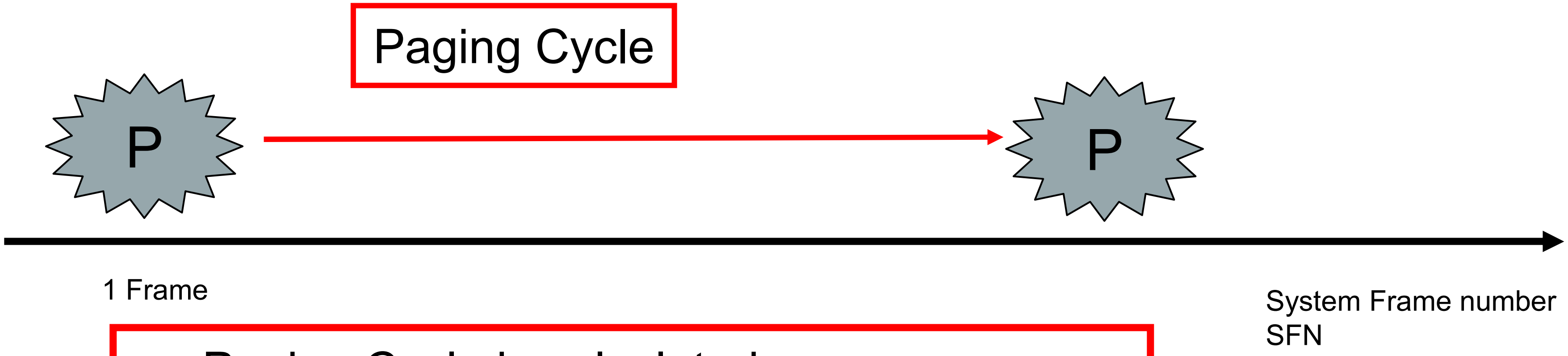
•Send Earthquake and Tsunami Warning

Paging



Paging Frame = Frame in which 1 or more Paging Occasions occur.
Here example: 3 Paging occasions in subframe 0, 4 and 9

Paging



Paging Cycle is calculated as:

SFN mod T= (T div N)*(UE_ID mod N)

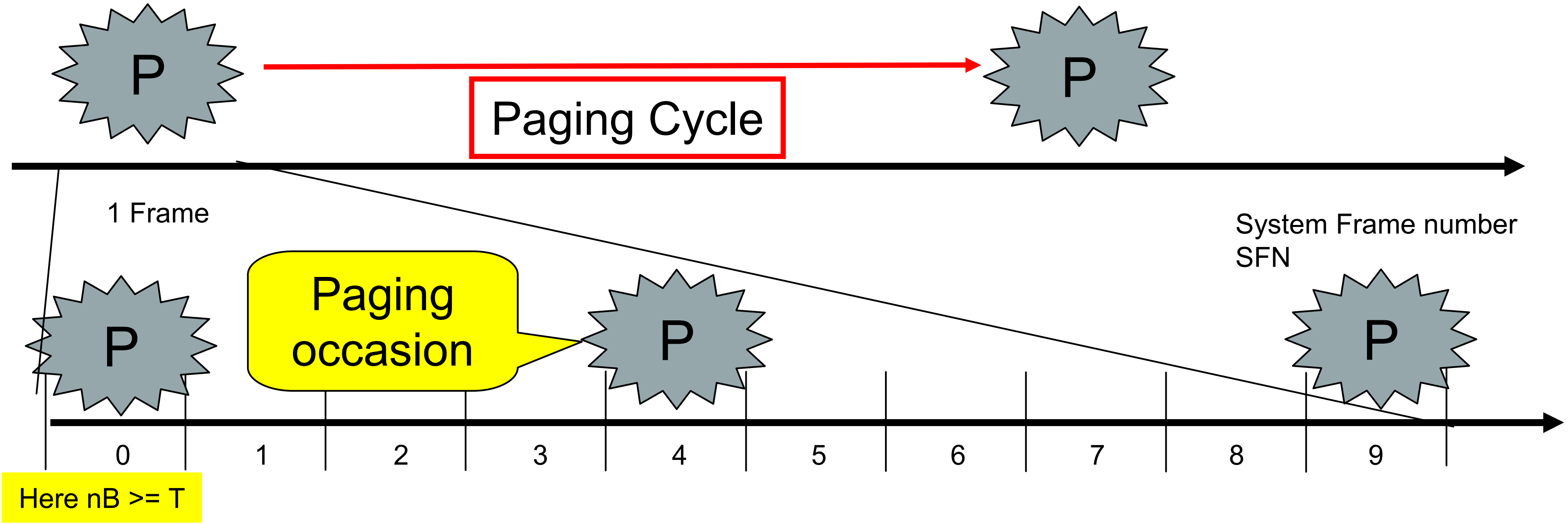
T: DRX cycle of the UE. Values are 32, 64, 128 or 256 Frames
nB: 4T, 2T, T, T/2, T/4, T/8, T/16, T/32.

N: min(T,nB)
Ns: max(1,nB/T)
UE_ID: IMSI mod 1024.

Sysinfo or signaled dedicated to UE

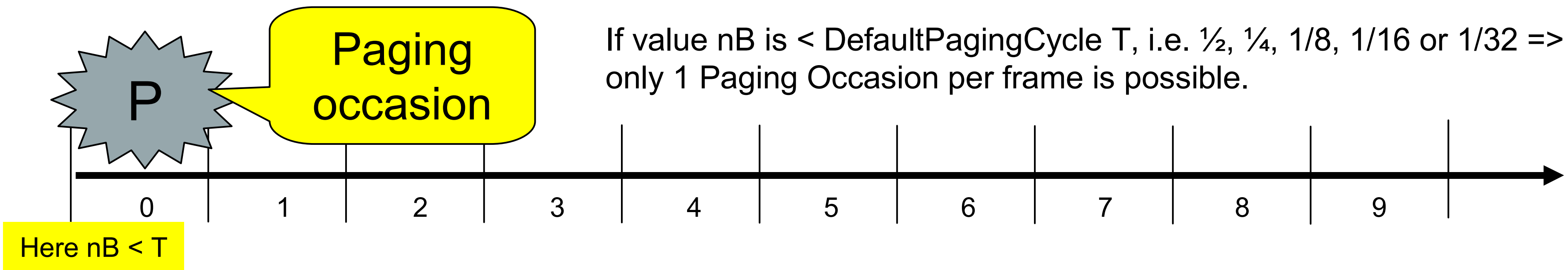
75 Years of Driving Innovation

Paging

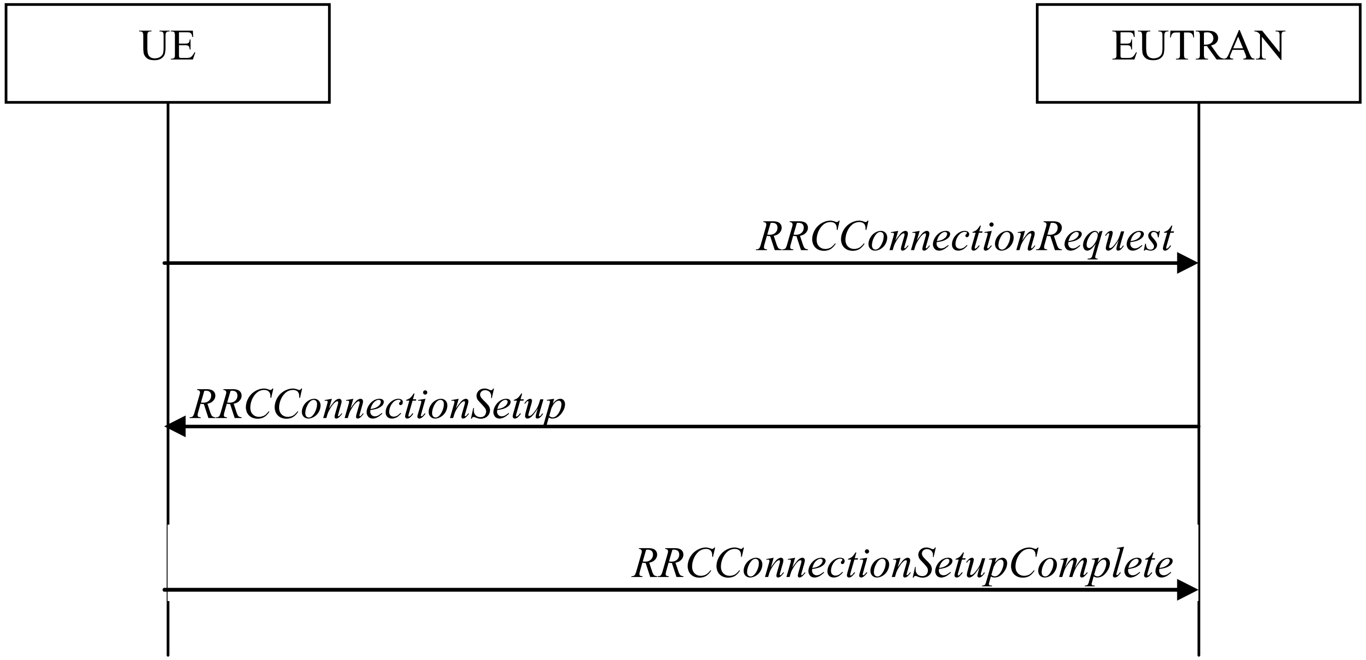


If value nB is >= DefaultPagingCycle T, i.e. 1, 2 or 4 => more Paging Occasions per frame are possible.

If value nB is < DefaultPagingCycle T, i.e. ½, ¼, 1/8, 1/16 or 1/32 => only 1 Paging Occasion per frame is possible.

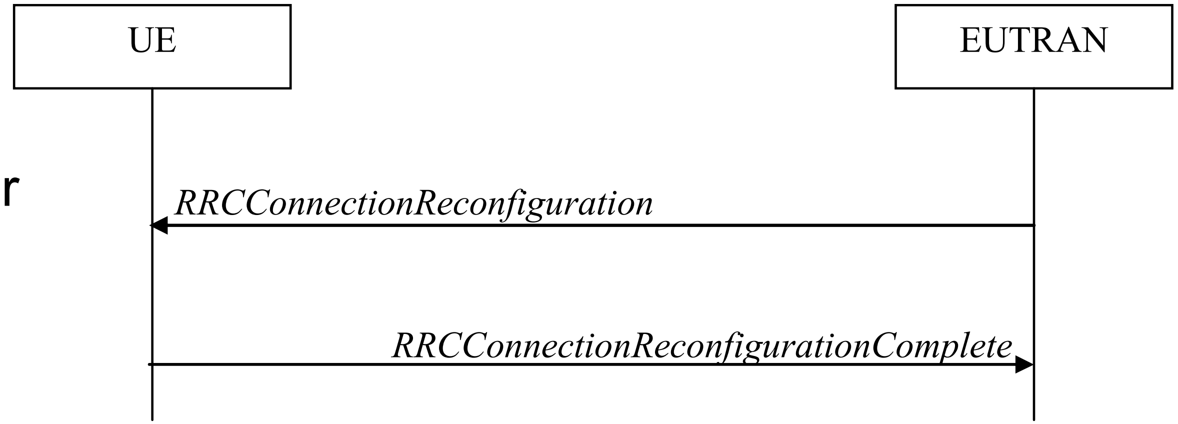


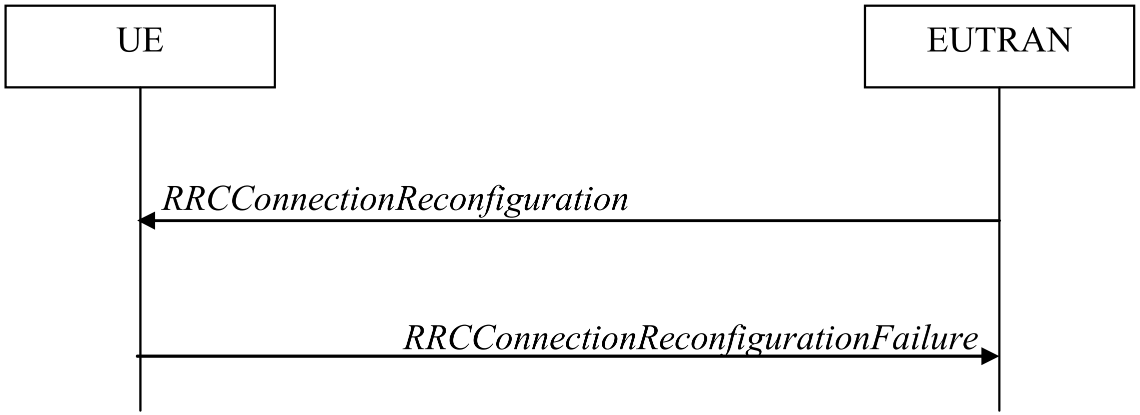
RRC Connection Establishment



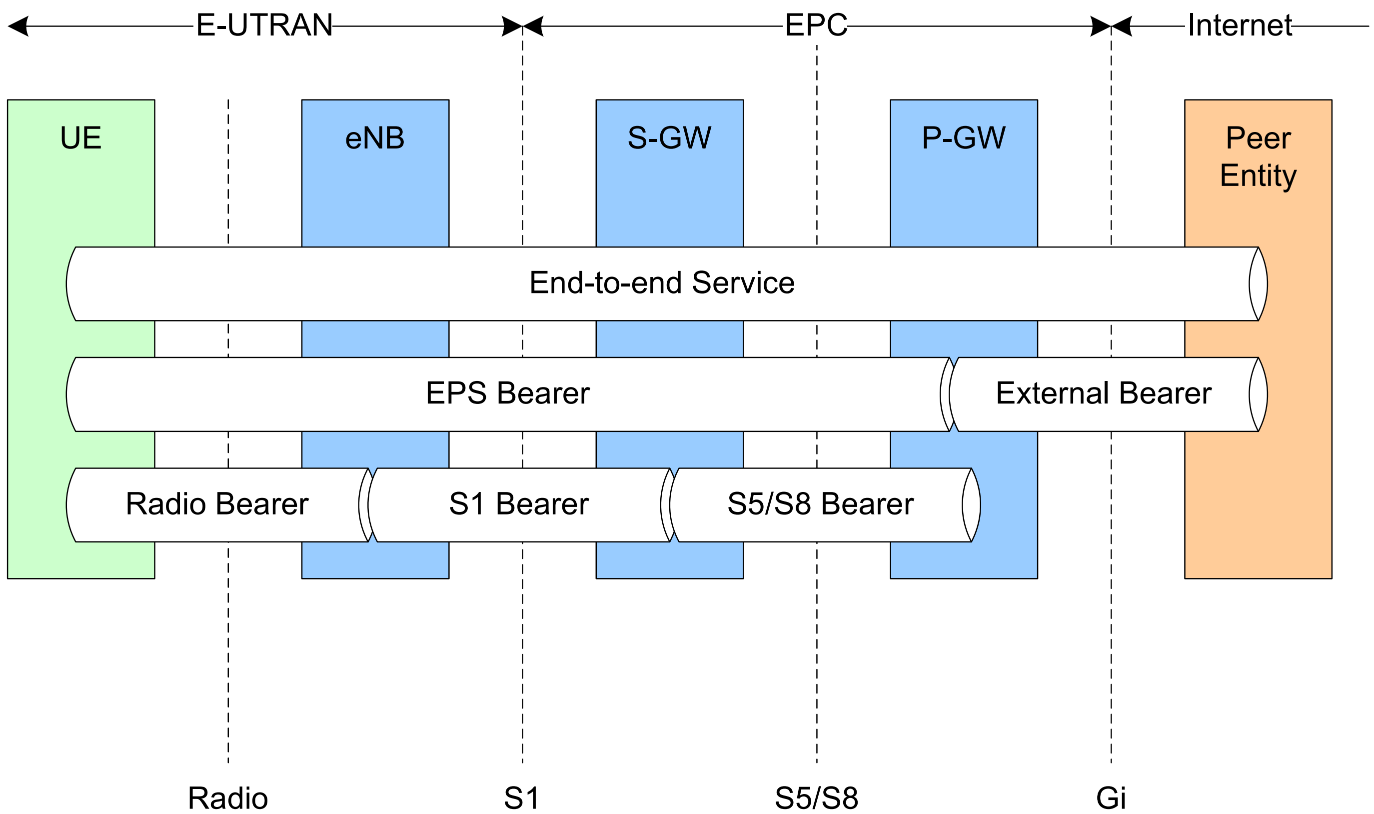
RRC Connection Reconfiguration

Also used for handover

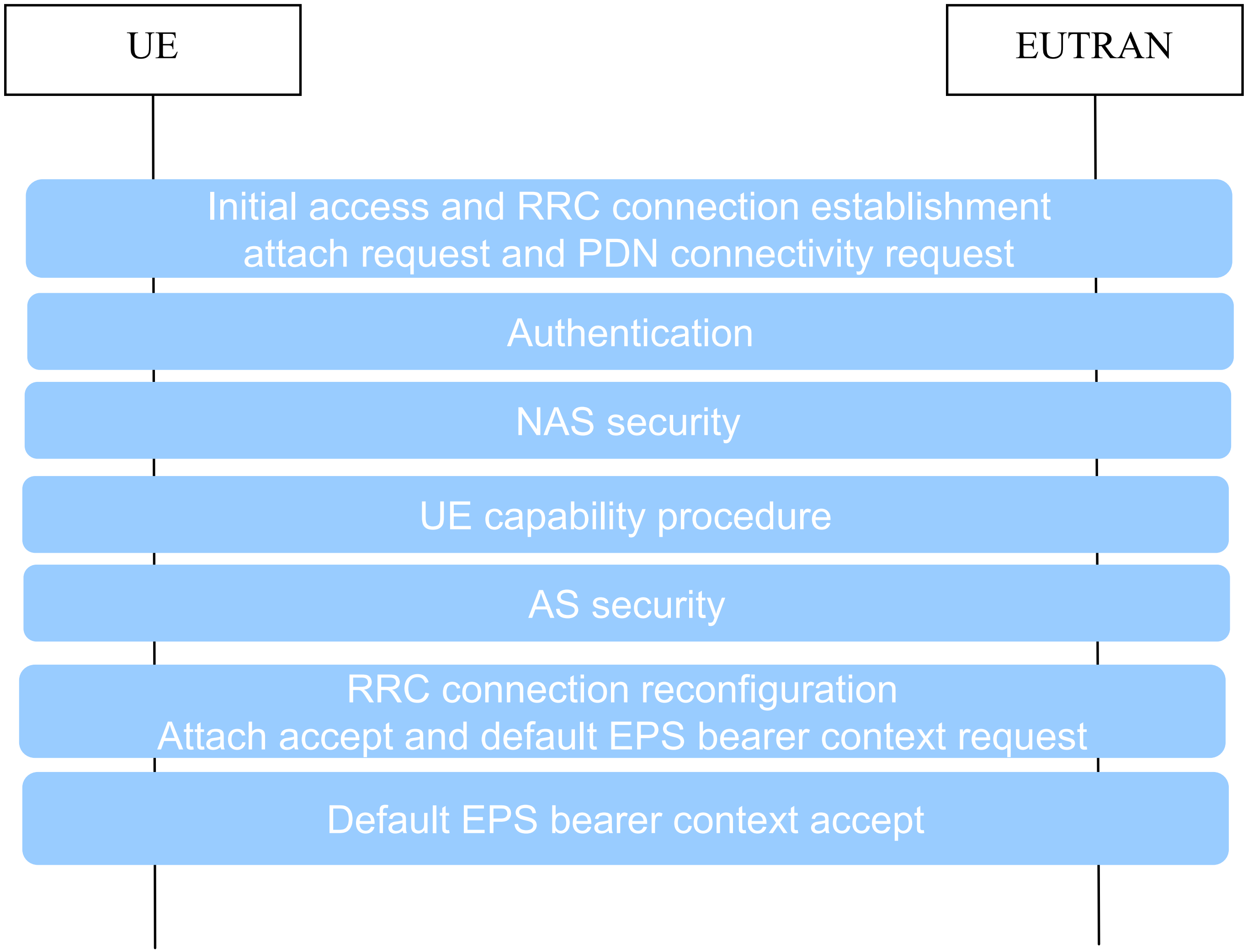




EPS Bearer Service Architecture

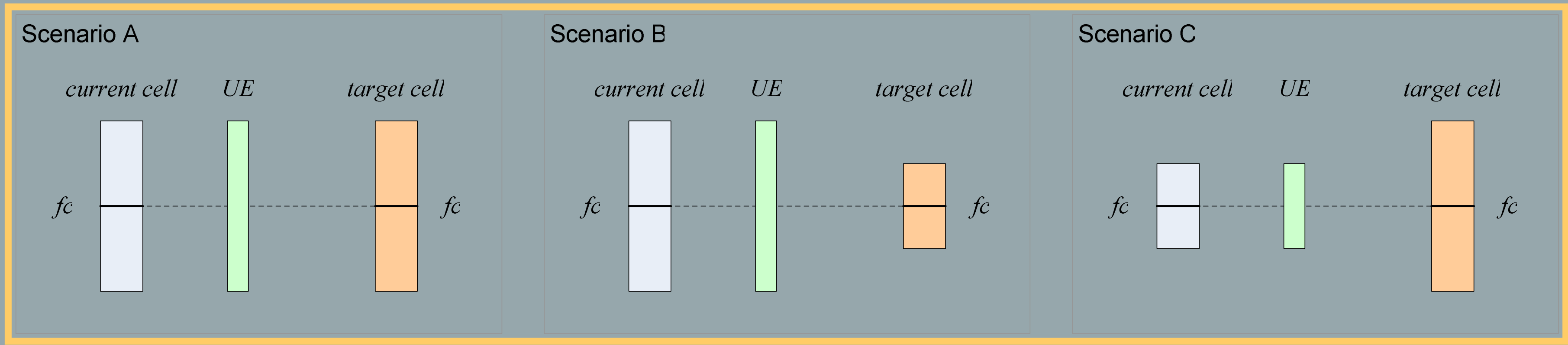


Default EPS bearer setup

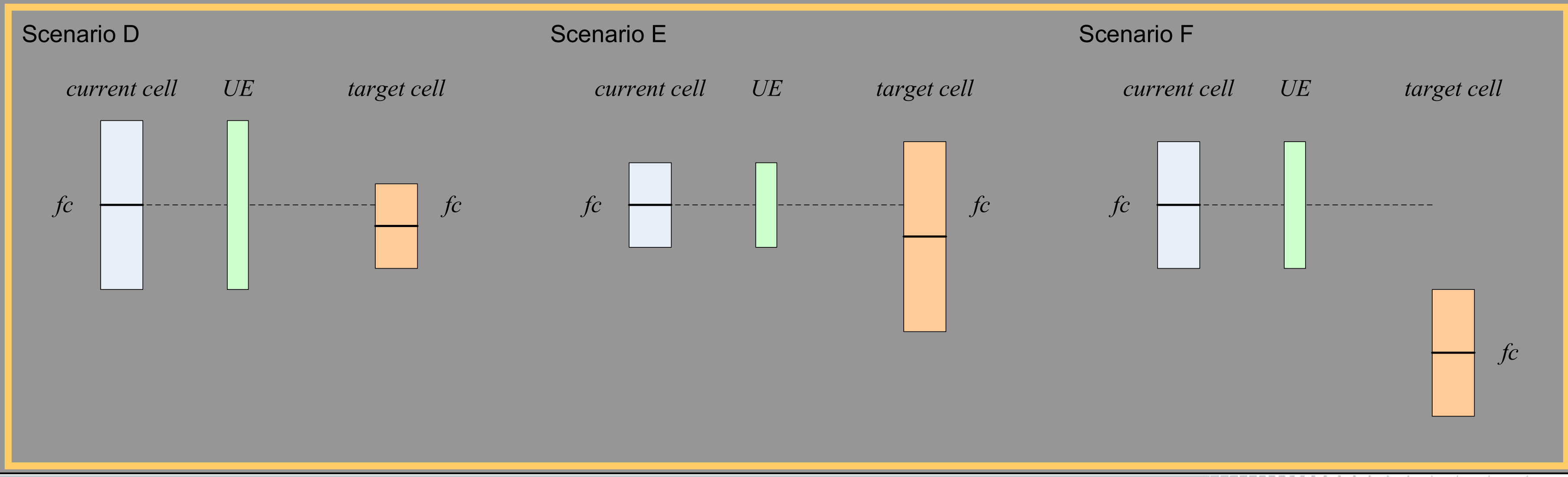


Intra and Inter-frequency measurements

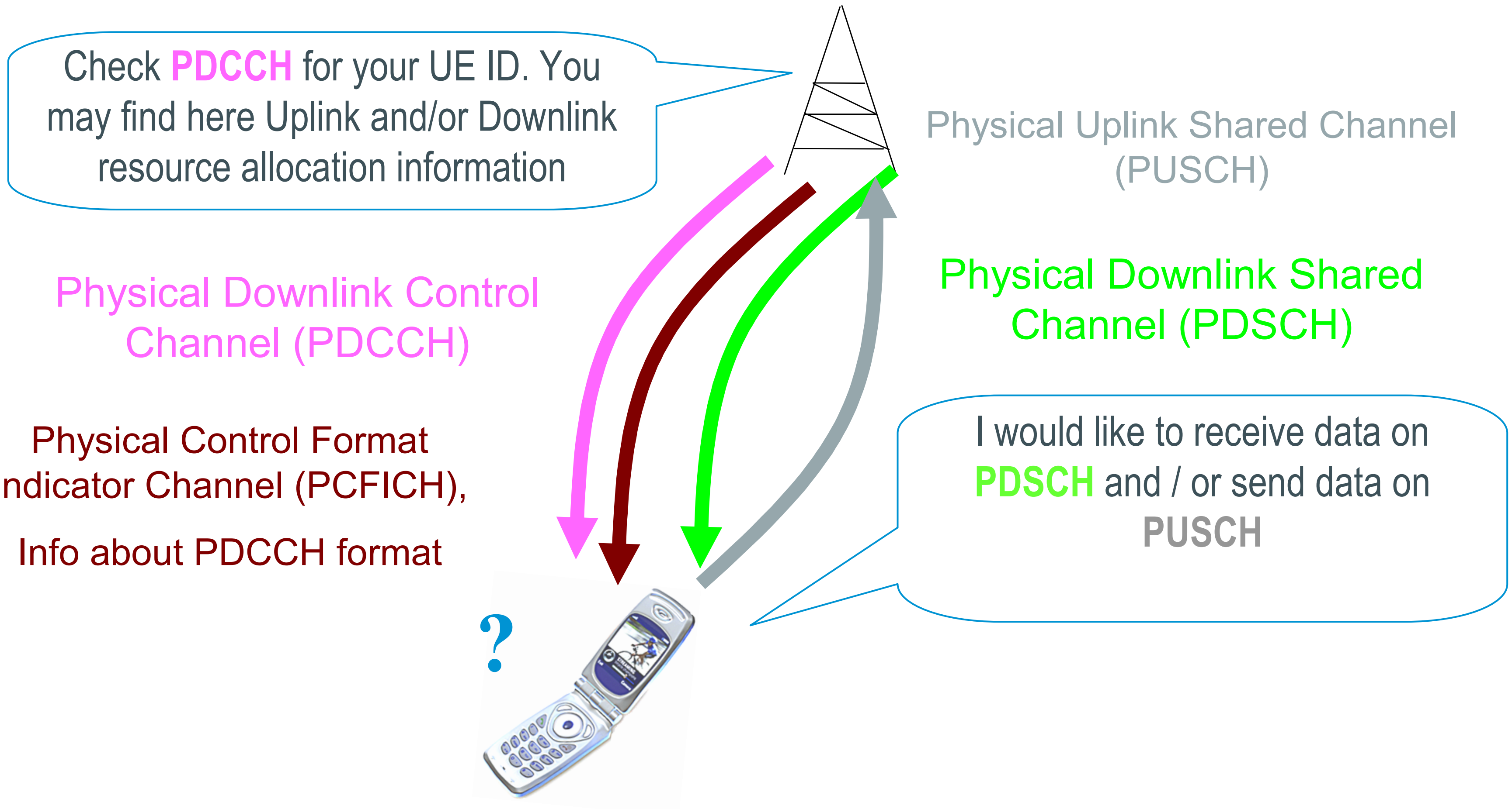
Not measurement gap assisted



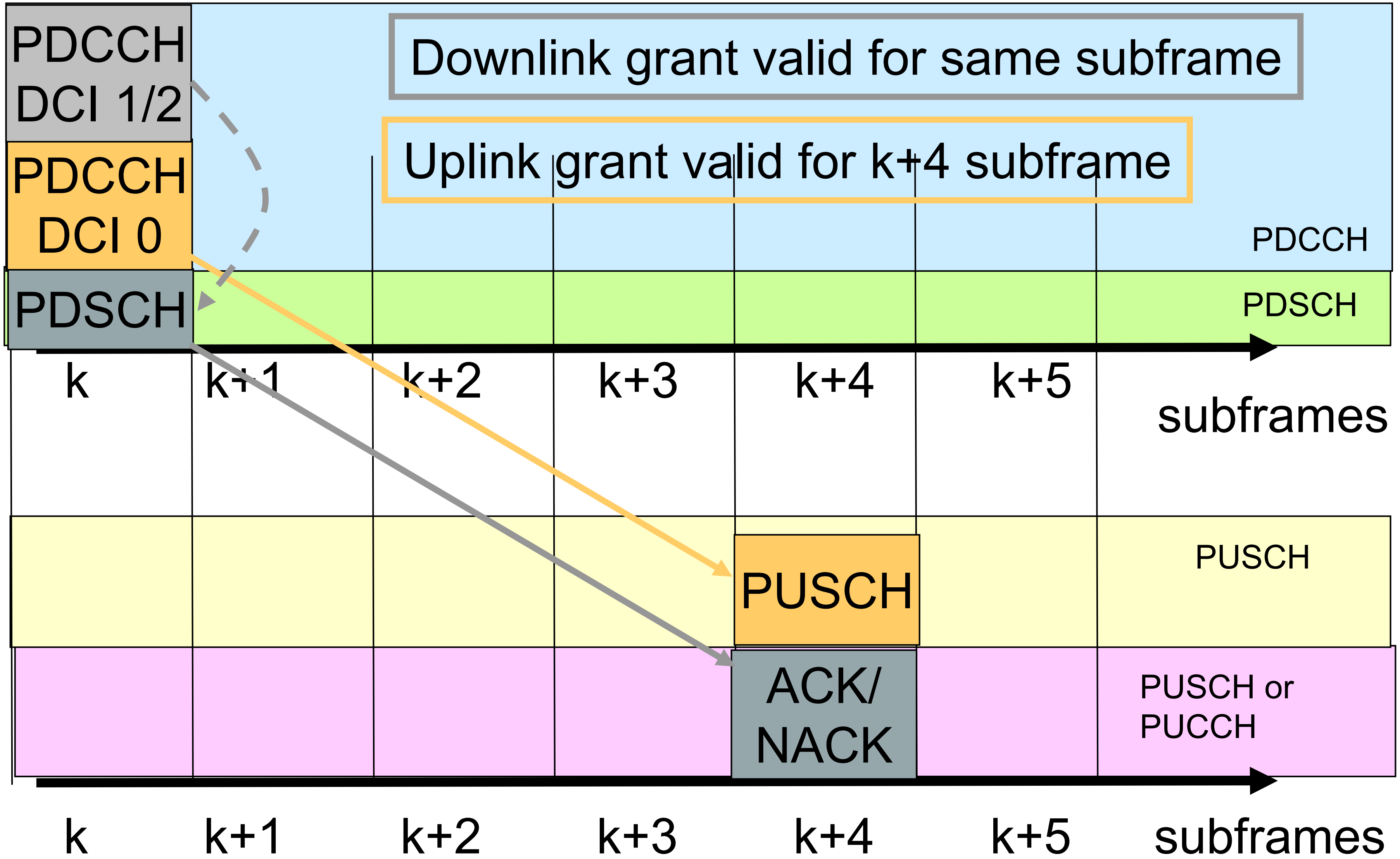
Measurement gap assisted



LTE resource allocation
Scheduling of downlink and uplink data



Resource allocation – timing aspects

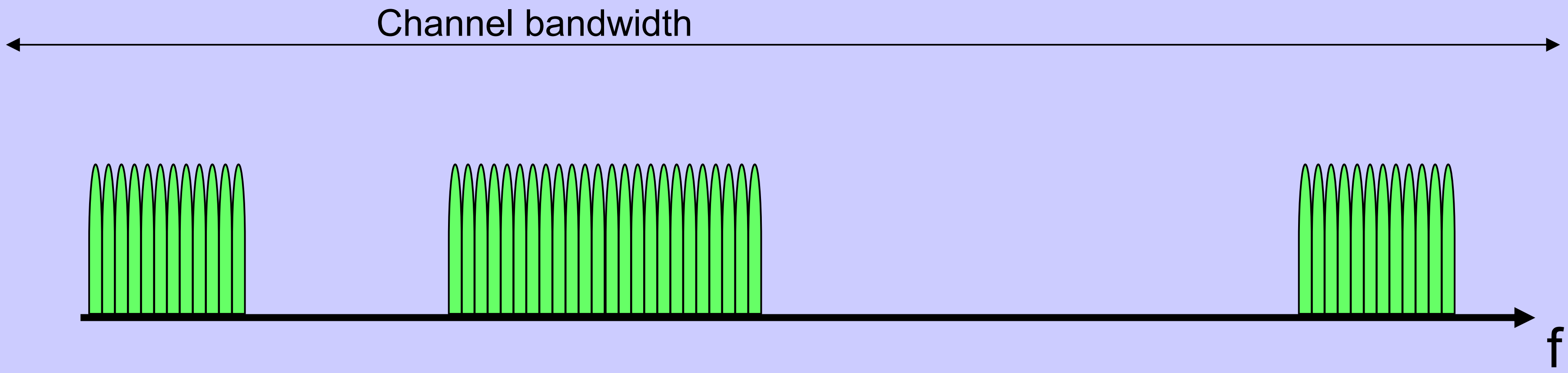


Resource allocation types in LTE

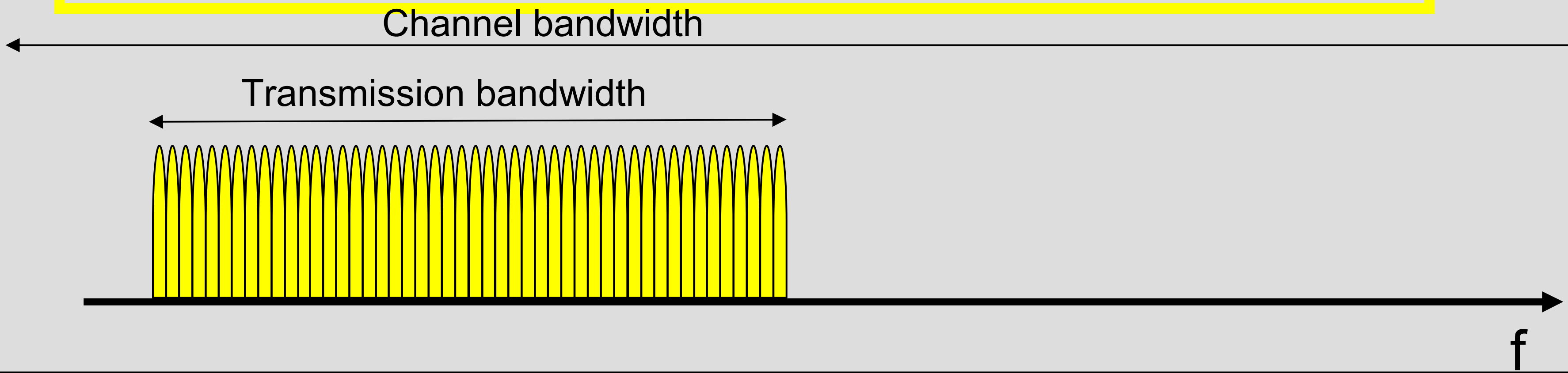
Allocation type	DCI Format	Scheduling Type	Antenna configuration
Type 0 / 1	DCI 1	PDSCH, one codeword	SISO, TxDiversity
	DCI 2A	PDSCH, two codewords	MIMO, open loop
	DCI 2	PDSCH, two codewords	MIMO, closed loop
Type 2	DCI 0	PUSCH	SISO
	DCI 1A	PDSCH, one codeword	SISO, TxDiversity
	DCI 1C	PDSCH, very compact codeword	SISO

Resource allocation types in LTE

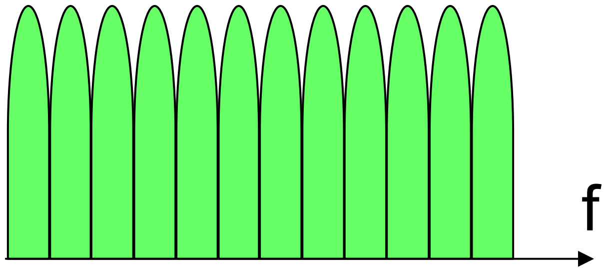
Type 0 and 1 for distributed allocation in frequency domain



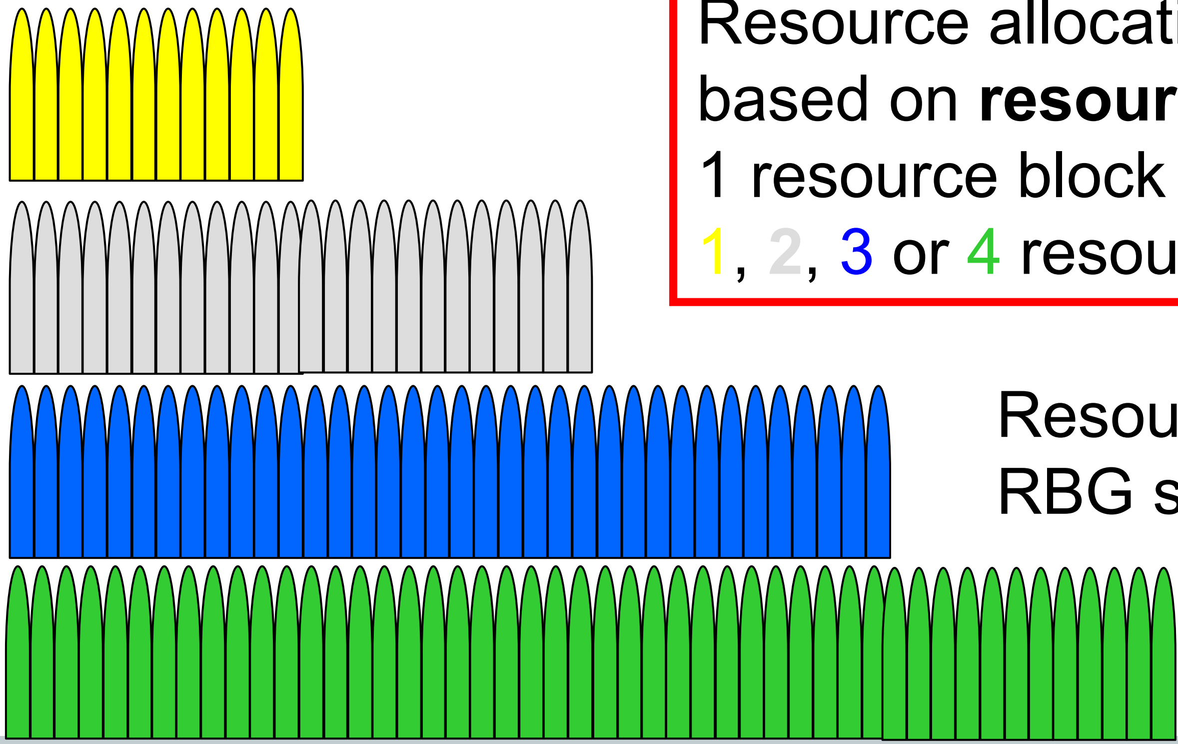
Type 2 for contiguous allocation in frequency domain



Resource Block Group



Reminder: 1 resource block =
12 subcarriers in frequency domain



Resource allocation is performed based on **resource block groups**.
1 resource block group may consist of 1, 2, 3 or 4 resource blocks

Resource block groups,
RBG sizes

Resource allocation type 0

Type 0 (for distributed frequency allocation of Downlink resource, SISO and MIMO possible)

- **Bitmap to indicate which resource block groups, RBG are allocated**
- **One RBG consists of 1-4 resource blocks:**

Channel bandwidth	RBG size P
≤10	1
11-26	2
27-63	3
64-110	4

- **Number of resource block groups N_{RBG} is given as:**

$$N_{RBG} = \left\lceil N_{\mathrm{RB}}^{\mathrm{DL}} / P \right\rceil$$

- **Allocation bitmap has same length than N_{RBG}**

Resource allocation type 0 example

Calculation example for type 0:

- **Channel bandwidth = 10MHz**
- **-> 50 resource blocks**
- **-> Resource block group RBG size = 3**
- **-> bitmap size = 17**

if $N_{\mathrm{RB}}^{\mathrm{DL}} \bmod P > 0$ then one of the RBGs is of size $N_{\mathrm{RB}}^{\mathrm{DL}} - P \cdot \left\lfloor N_{\mathrm{RB}}^{\mathrm{DL}} / P \right\rfloor$

i.e. here 50 mod 3 = 16, so the last resource block group has the size 2.

-> some allocations are not possible, e.g. here you can allocate 48 or 50 resource blocks, but not 49!

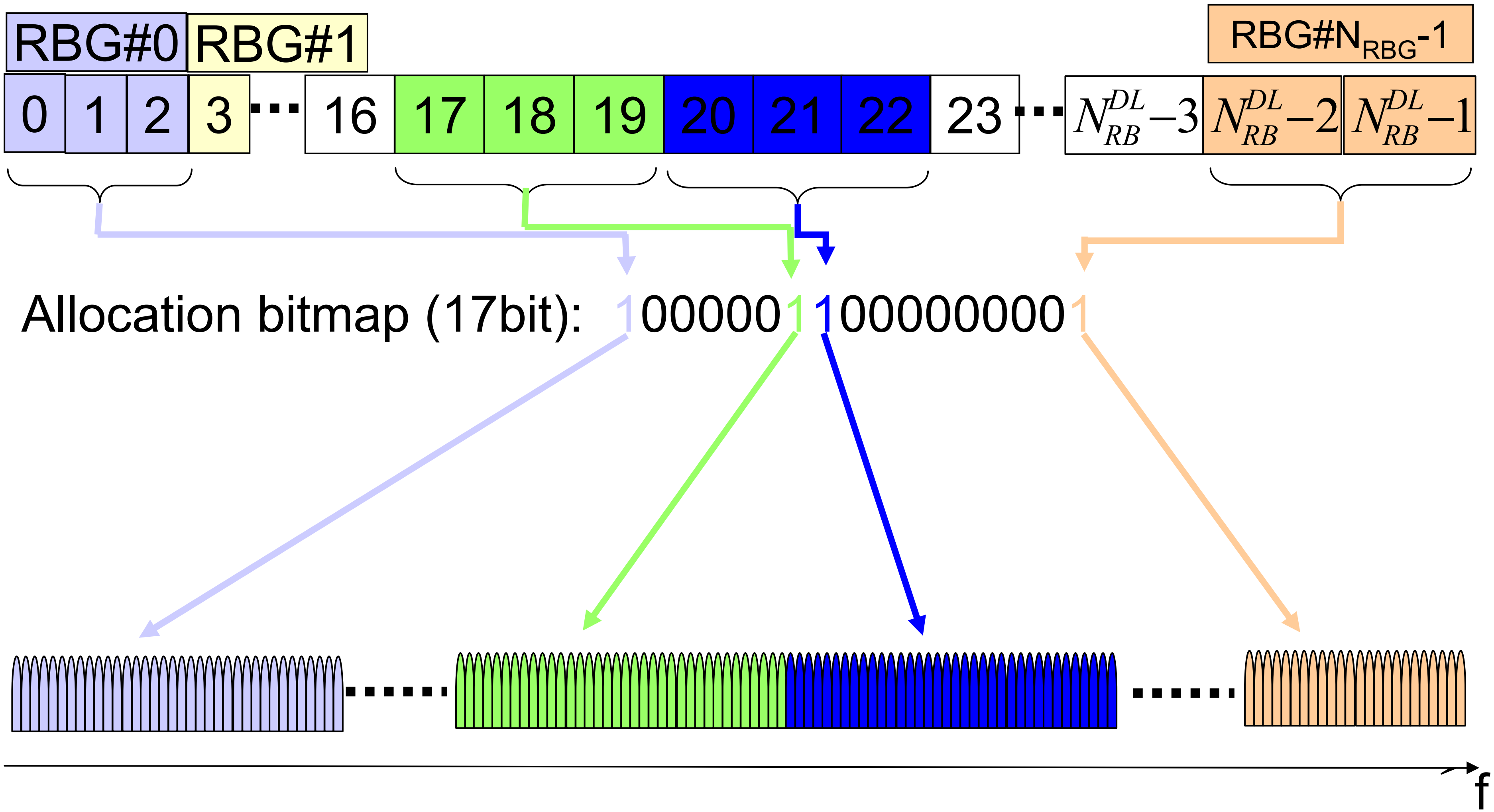
reminder

$N_{RBG} = \left\lceil N_{\mathrm{RB}}^{\mathrm{DL}} / P \right\rceil$ = round up, i.e. $\lceil 3.5 \rceil$ = 4

$\left\lfloor N_{\mathrm{RB}}^{\mathrm{DL}} / P \right\rfloor$ = round down, i.e. $\lfloor 3.49 \rfloor$ = 3

Resource allocation type 0

Channel bandwidth = 10MHz -> 50 RBs -> RBG size = 3 -> number of RBGs = 17



75 Years of Driving Innovation

Resource allocation type 1

Type 1 (for distributed frequency allocation of Downlink resource, SISO and MIMO possible)

- **RBs are divided into $\lceil \log_2(P) \rceil$ RBG subsets**

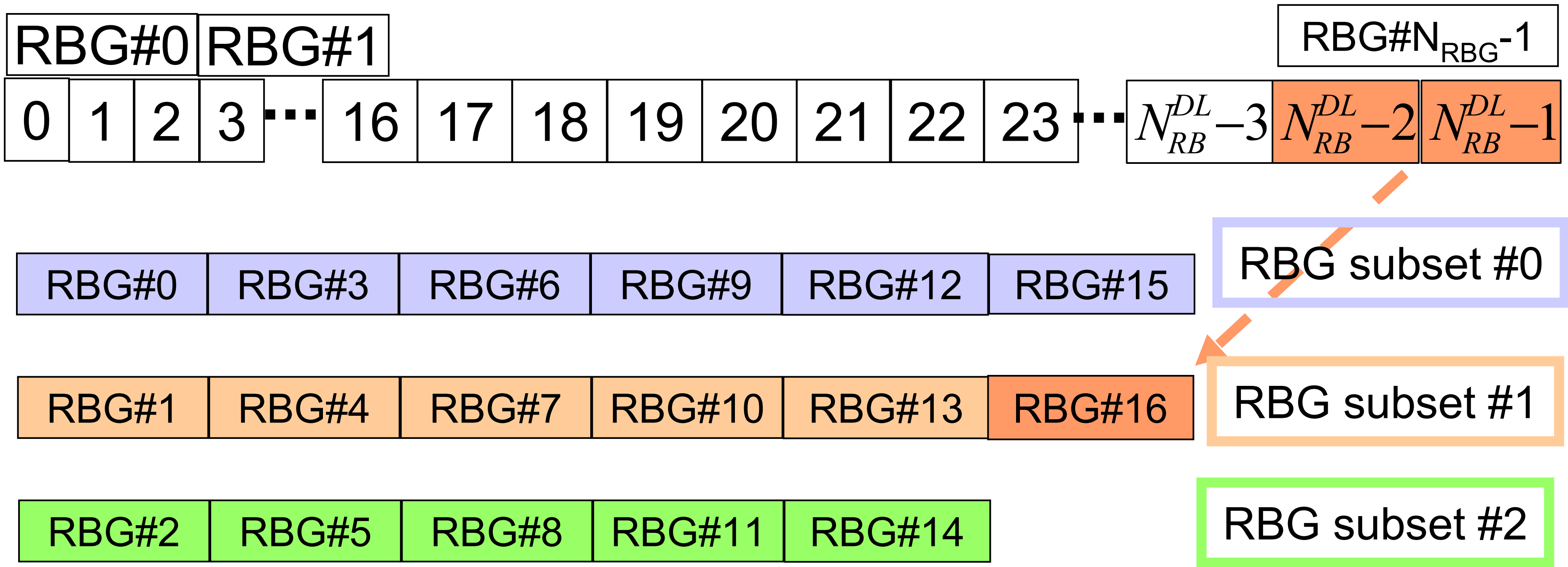
Channel bandwidth	RBG size P
≤10	1
11-26	2
27-63	3
64-110	4

- **Bitmap indicates RBs inside a RBG subset allocated to the UE**

- **Resource block assignment consists of 3 fields:**
  - Field to indicate the selected RBG
  - Field to indicate a shift of the resource allocation
  - Field to indicate the specific RB within a RBG subset

Resource allocation type 1

Channel bandwidth = 10MHz -> 50 RBs -> RBG size = 3 -> number of RBGs = 17



P= Number of RBG subsets with length:

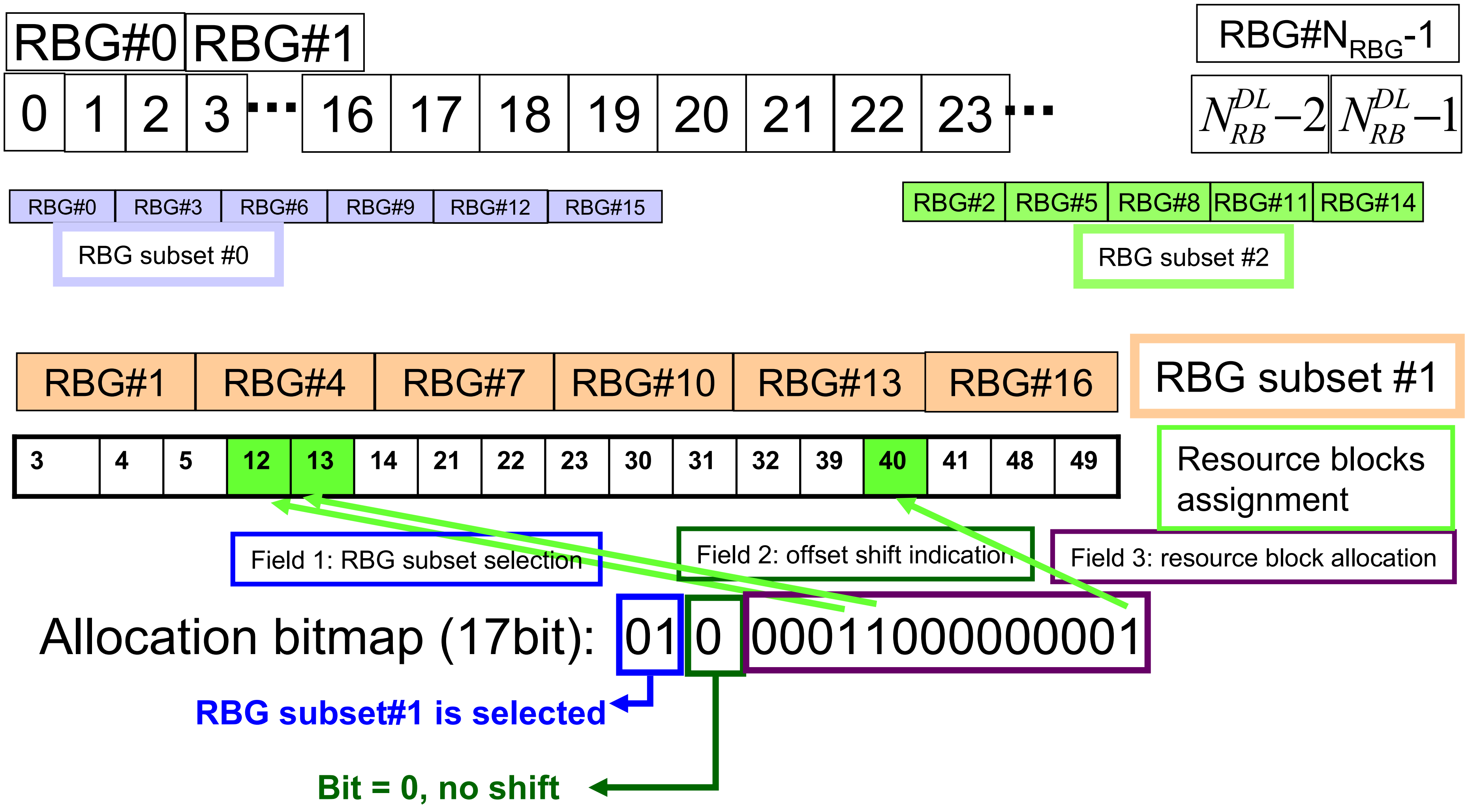
$$\lceil \log_2(P) \rceil$$

Number of bits to indicate subset

$$N_{\mathrm{RB}}^{\mathrm{RBG\ subset}}(p) = \begin{cases} \left\lfloor \frac{N_{\mathrm{RB}}^{\mathrm{DL}}-1}{P^2} \right\rfloor \cdot P + P & , p < \left\lfloor \frac{N_{\mathrm{RB}}^{\mathrm{DL}}-1}{P} \right\rfloor \bmod P \\ \left\lfloor \frac{N_{\mathrm{RB}}^{\mathrm{DL}}-1}{P^2} \right\rfloor \cdot P + (N_{\mathrm{RB}}^{\mathrm{DL}}-1) \bmod P + 1 & , p = \left\lfloor \frac{N_{\mathrm{RB}}^{\mathrm{DL}}-1}{P} \right\rfloor \bmod P \\ \left\lfloor \frac{N_{\mathrm{RB}}^{\mathrm{DL}}-1}{P^2} \right\rfloor \cdot P & , p > \left\lfloor \frac{N_{\mathrm{RB}}^{\mathrm{DL}}-1}{P} \right\rfloor \bmod P \end{cases}$$

Resource allocation type 1

Channel bandwidth = 10MHz -> 50 RBs -> RBG size = 3 -> number of RBGs = 17

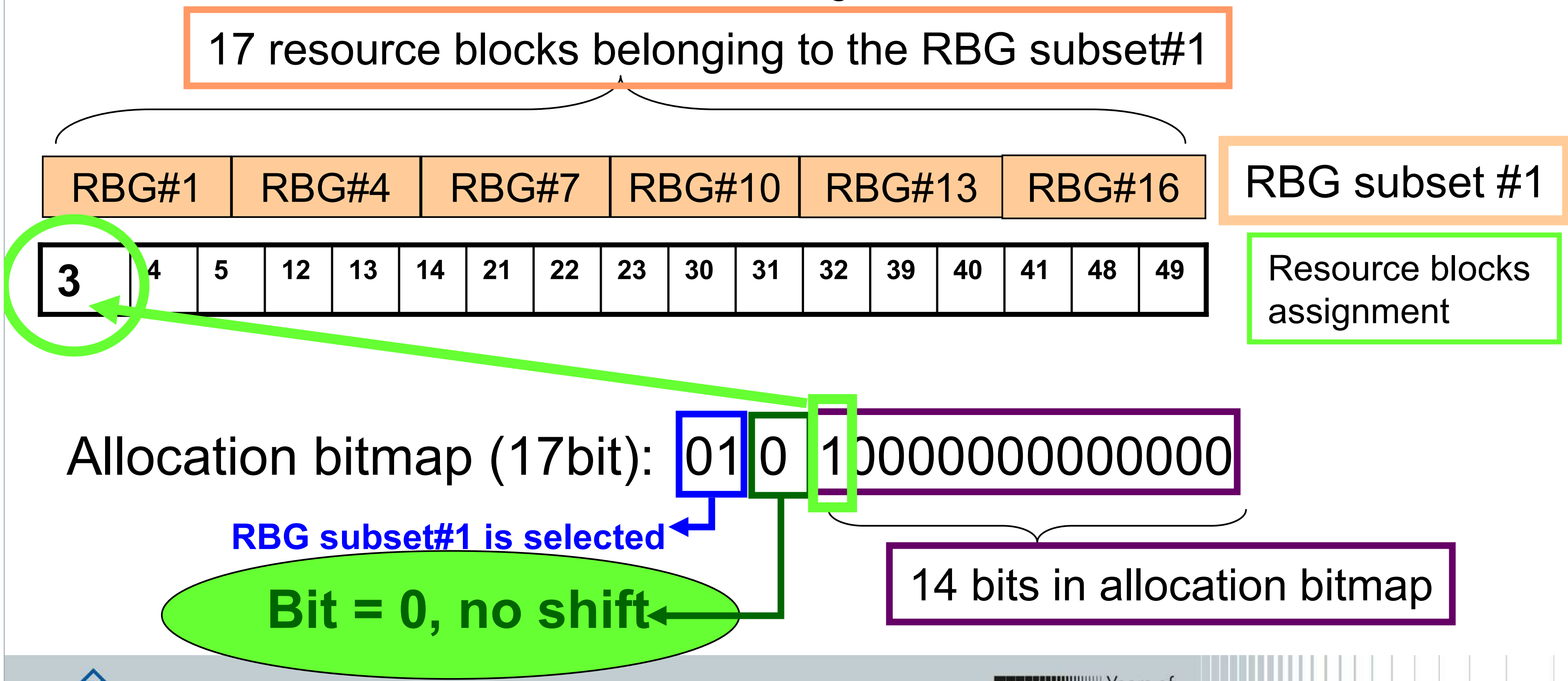


Resource allocation type 1

Channel bandwidth = 10MHz -> 50 RBs -> RBG size = 3 -> number of RBGs = 17

The meaning of the shift offset bit:

Number of resource blocks in one RBG subset is bigger than the allocation bitmap
-> you can not allocate all the available resource blocks
-> offset shift to indicate which RBs are assigned



Resource allocation type 1

Channel bandwidth = 10MHz -> 50 RBs -> RBG size = 3 -> number of RBGs = 17

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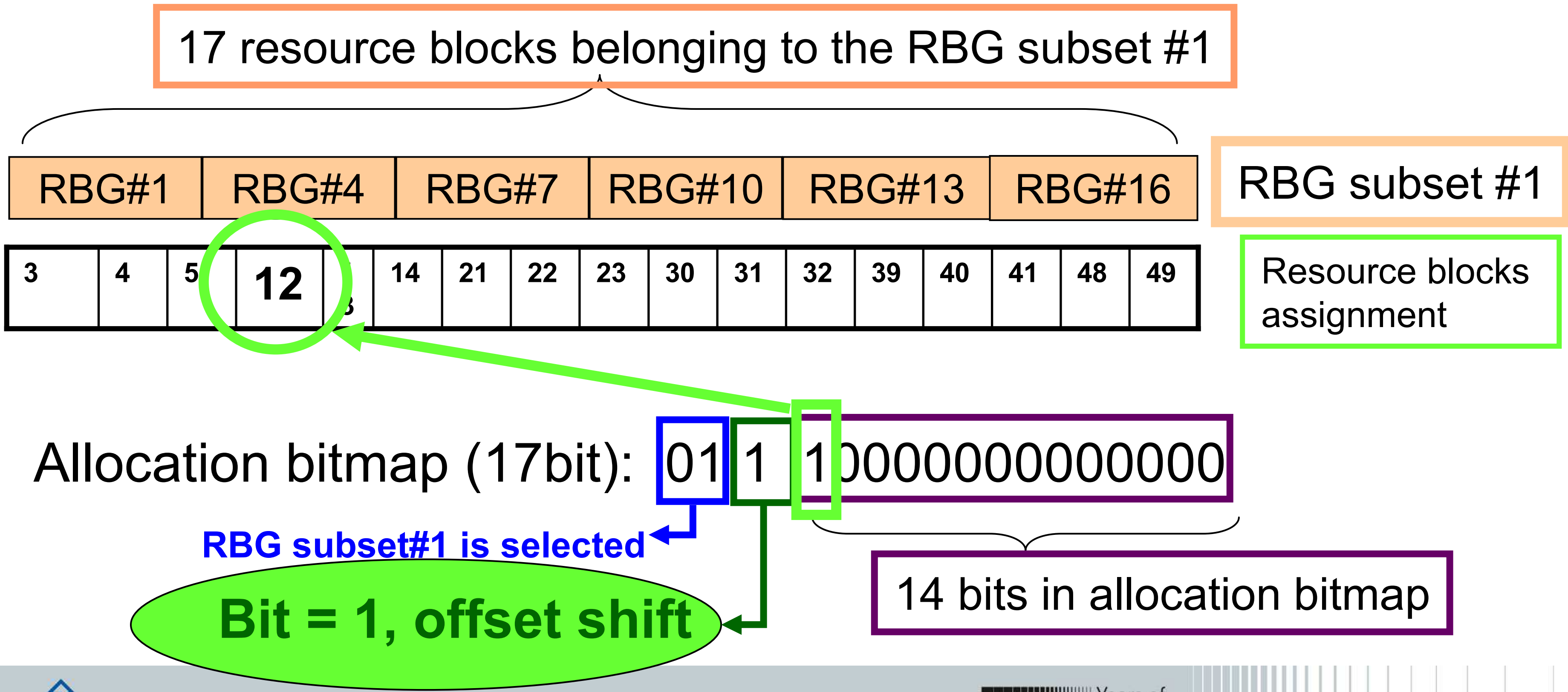
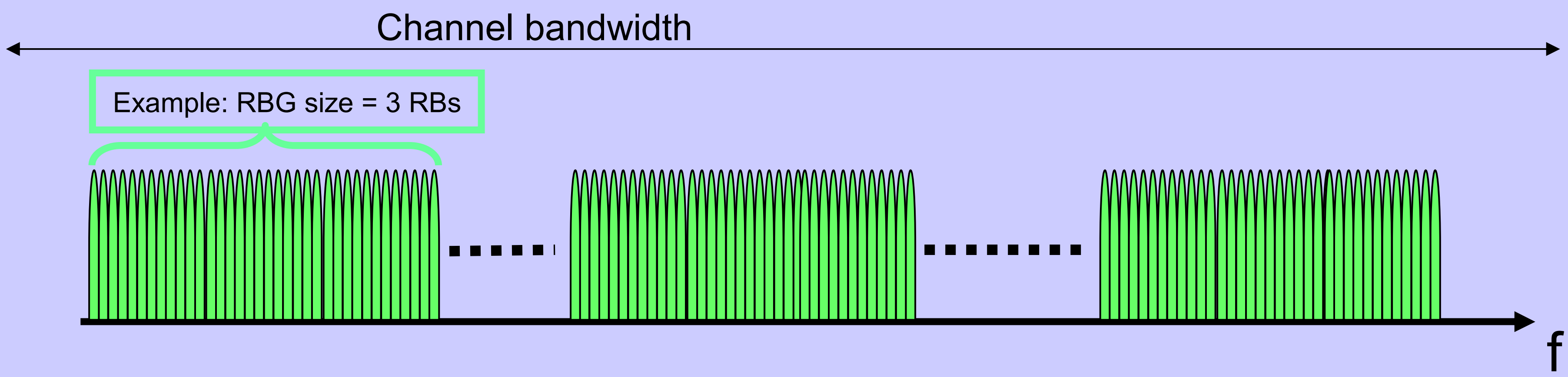
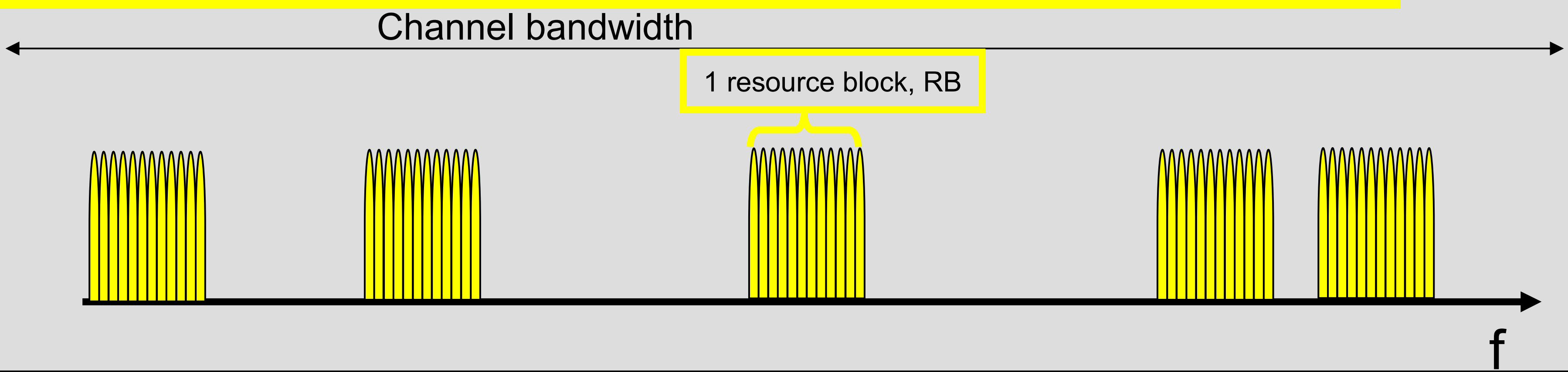


Resource allocation types in LTE

Type 0 allows the allocation based on **resource block groups** granularity



Type 1 allows the allocation based on **resource block** granularity



Resource allocation type 2

Type 2 (for contiguously allocated localized or distributed virtual frequency allocation of Uplink and Downlink resource, SISO only)

- **Virtual Resource blocks are mapped onto Physical resource blocks**
- **2 possible modes:**

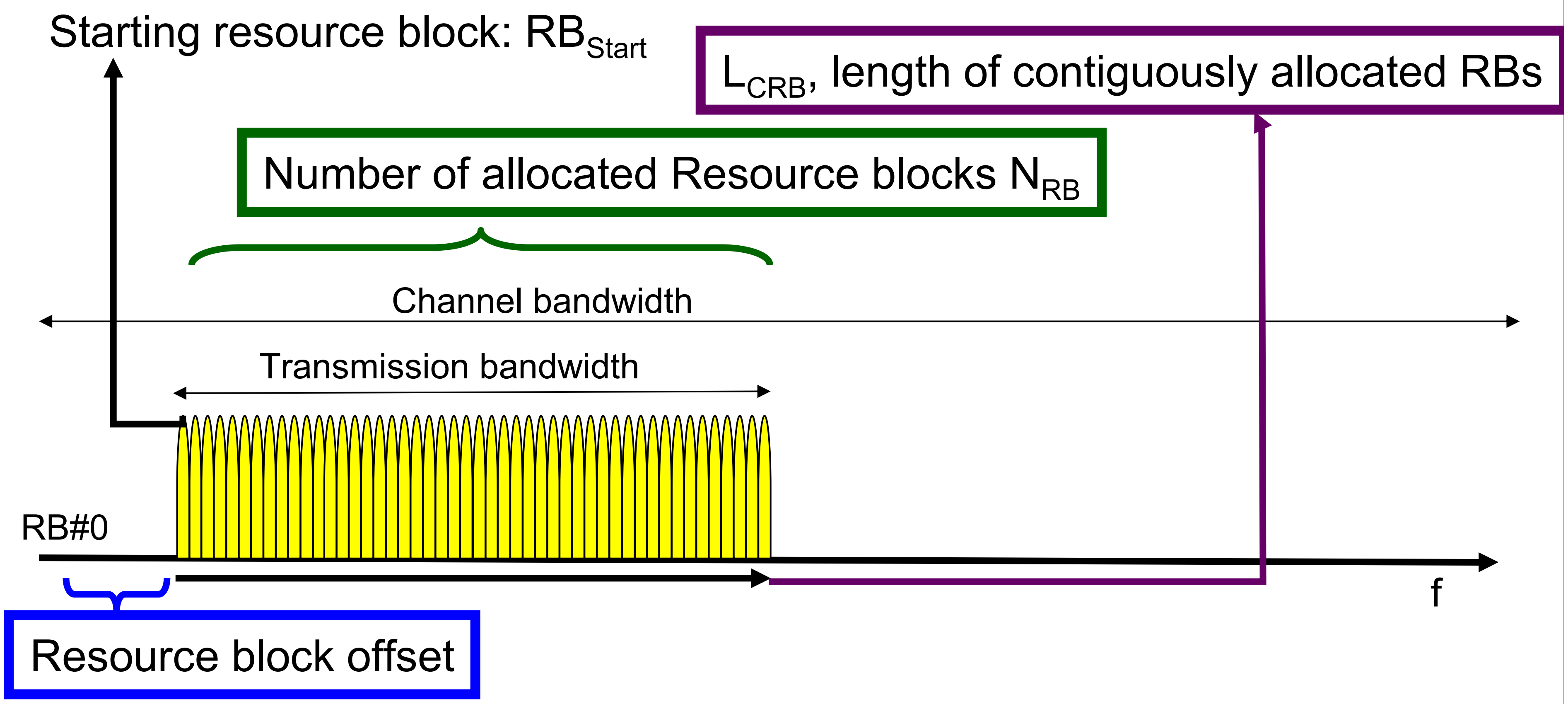
Localized mode

Distributed mode

- **Resource indication value, RIV on PDCCH indicates the number of allocated RBs**
- **Distributed allocation depending on assigned RNTI**

Resource allocation type 2

Localized mode



Resource indication value, RIV

Type 0: bitmap used to indicate the resource allocation:

$\lceil N_{\mathrm{RB}}^{\mathrm{DL}} / P \rceil$ = Length of allocation bitmap (17bit): 10000011000000001

RIV = bin to dec conversion

Type 1: bitmap used to indicate the resource allocation, with 3 fields: Resource block group subset, shift indictor + resource allocation

Allocation bitmap (17bit): 01 1 10000000000000

Type 2: TS 36.213 section 7.1.6.3. gives formula to calculate RIV:

if $(L_{CRBs} - 1) \leq \lfloor N_{RB}^{DL} / 2 \rfloor$

then

$$\boxed{RIV = N_{RB}^{DL}(L_{CRBs} - 1) + RB_{start}}$$

else

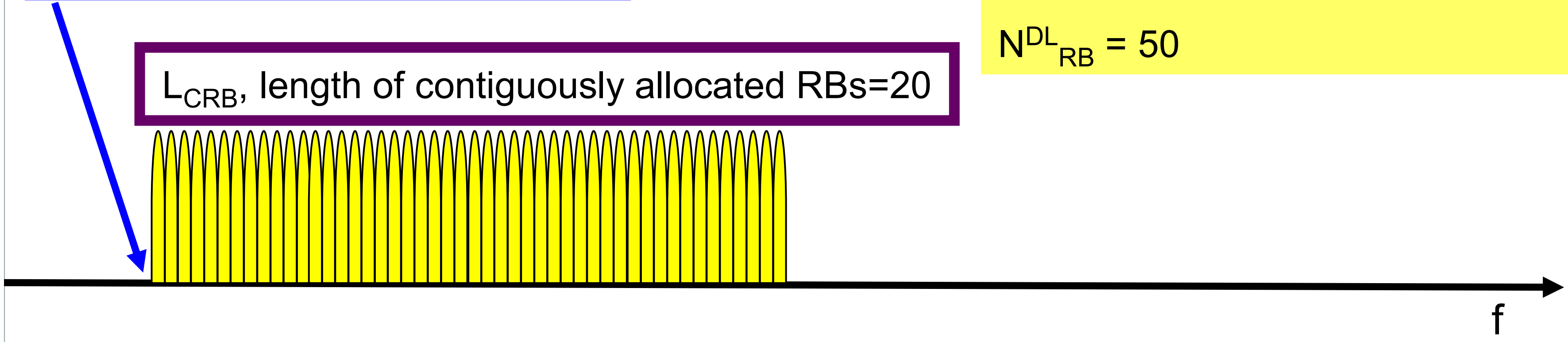
$$\boxed{RIV = N_{RB}^{DL}(N_{RB}^{DL} - L_{CRBs} + 1) + (N_{RB}^{DL} - 1 - RB_{start})}$$

Resource indication value, RIV in type 2 allocation

How to calculate the RIV value in allocation type 2, according to TS 36.213

Starting resource block: RB_{Start}=5

L_{CRB}, length of contiguously allocated RBs=20



Assumptions and given:

Localized mode, RB_{Start} = 5, L_{CRB} = 20

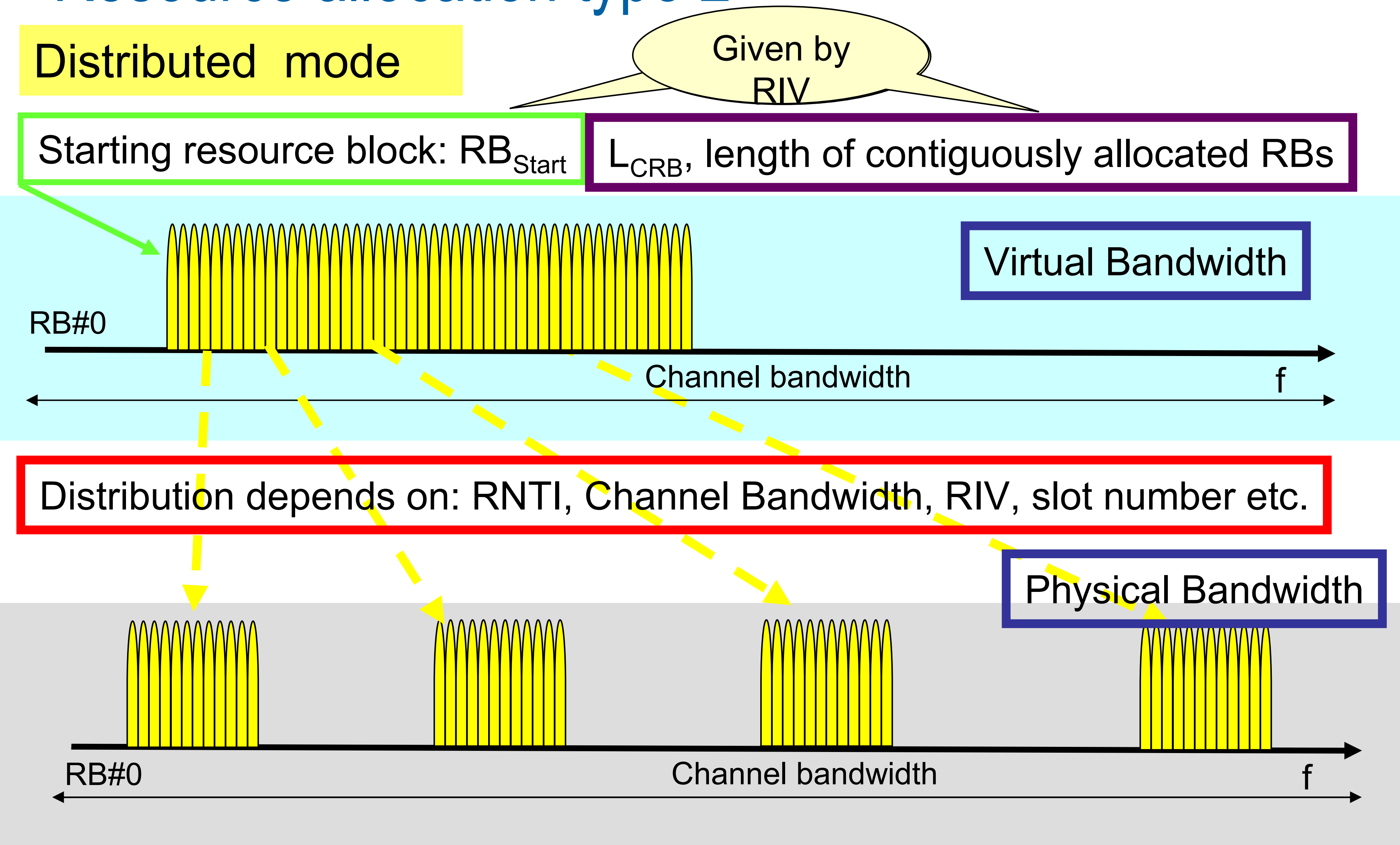
N^{DL}_{RB} = 50

$$RIV = N_{RB}^{DL}(L_{CRBs} - 1) + RB_{start}$$

Formula from TS 36.213

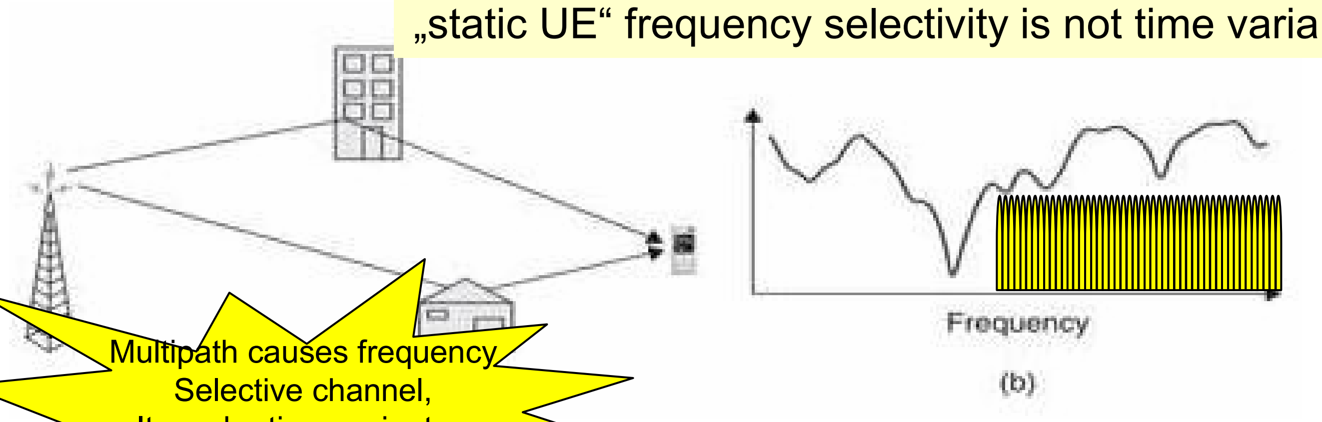
Here:
RIV = 50 * (20-1) + 5
RIV = 955

Resource allocation type 2



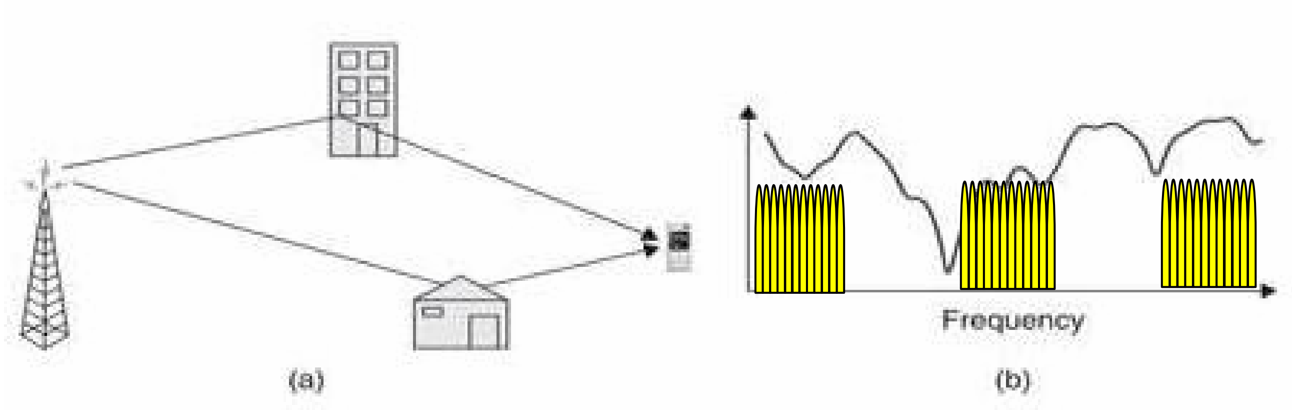
Benefit of localized or distributed mode

„static UE“ frequency selectivity is not time variant -> localized allocation



Multipath causes frequency
Selective channel,
It can be time variant or
Non-time variant

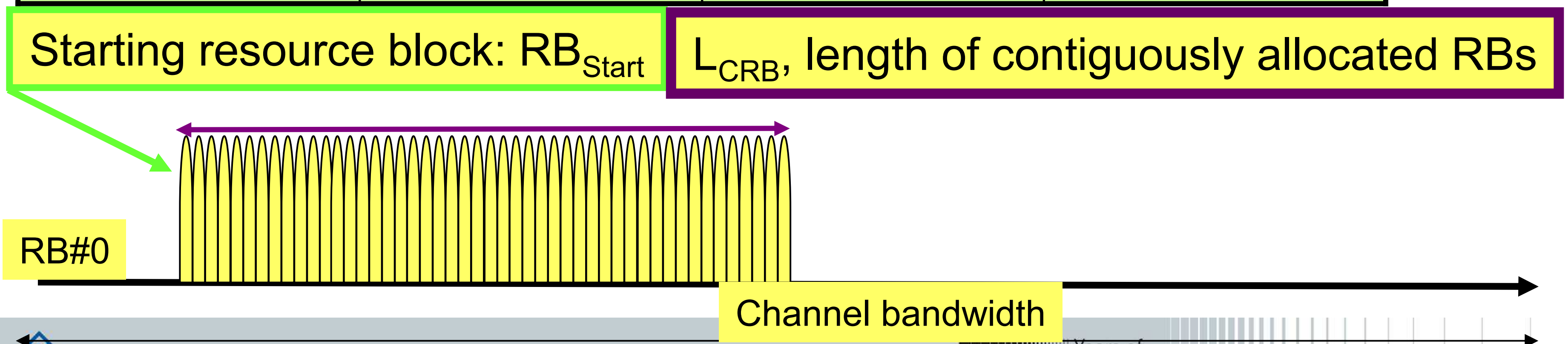
„high velocity UE“ frequency selectivity is time variant -> distributed allocation



Resource allocation Uplink

LTE Uplink uses Type 2 allocation

Allocation type	DCI Format	Scheduling Type	Antenna configuration
Type 0 / 1	DCI 1	PDSCH, one codeword	SISO, TxDiversity
	DCI 2A	PDSCH, two codewords	MIMO, open loop
	DCI 2	PDSCH, two codewords	MIMO, closed loop
Type 2	**DCI 0**	**PUSCH**	**SISO**
	DCI 1A	PDSCH, one codeword	SISO, TxDiversity
	DCI 1C	PDSCH, very compact codeword	SISO



LTE Uplink: allocation of UL ressource

Scheduled UL bandwidth

UL bandwidth configuration

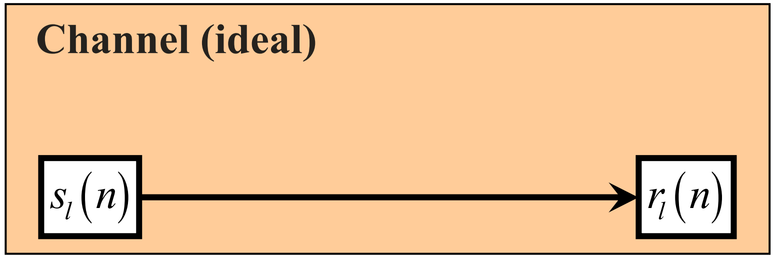
$$M_{\mathrm{RB}}^{\mathrm{PUSCH}} = 2^{\alpha_2} \cdot 3^{\alpha_3} \cdot 5^{\alpha_5} \leq N_{\mathrm{RB}}^{\mathrm{UL}}$$

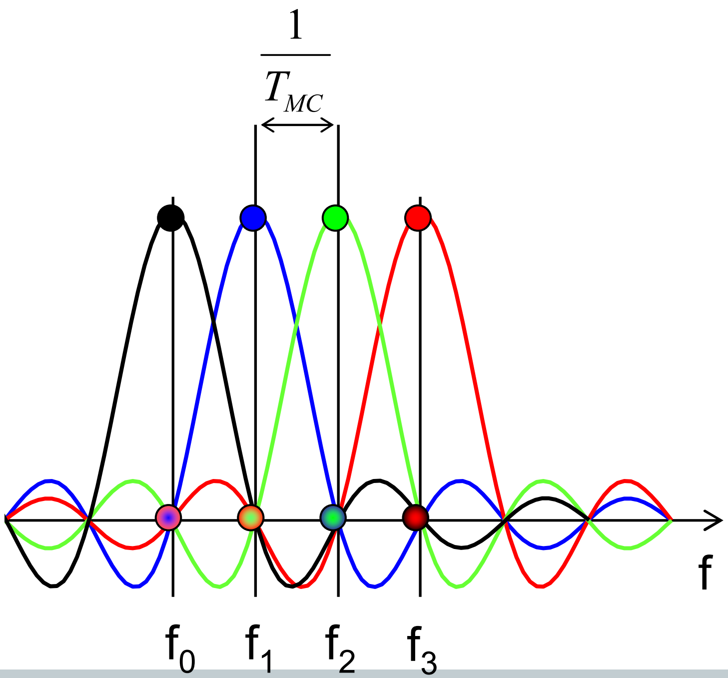
Scheduled number of ressource blocks in UL must fullfill formula above(α_x are integer). Possible values are:

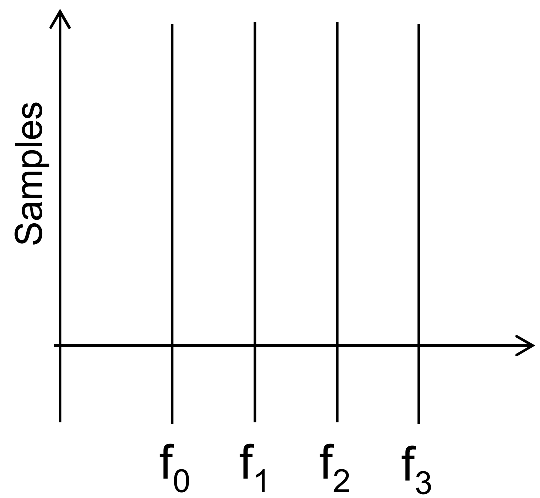
1	**2**	**3**	**4**	**5**	**6**	**8**	**9**	**10**	**12**
15	**16**	**18**	**20**	**24**	**25**	**27**	**30**	**32**	**36**
40	**45**	**48**	**50**	**54**	**60**	**64**	**72**	**75**	**80**
81	**90**	**96**	**100**						

LTE measurements

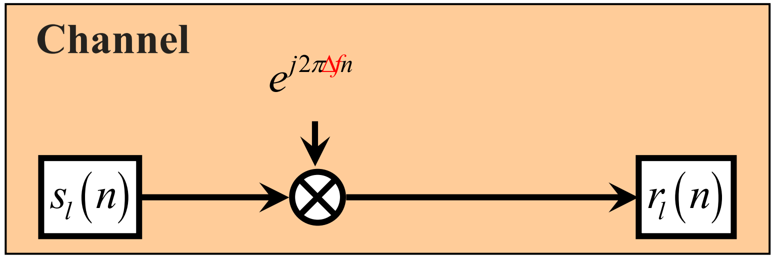
OFDM risk: Degradation

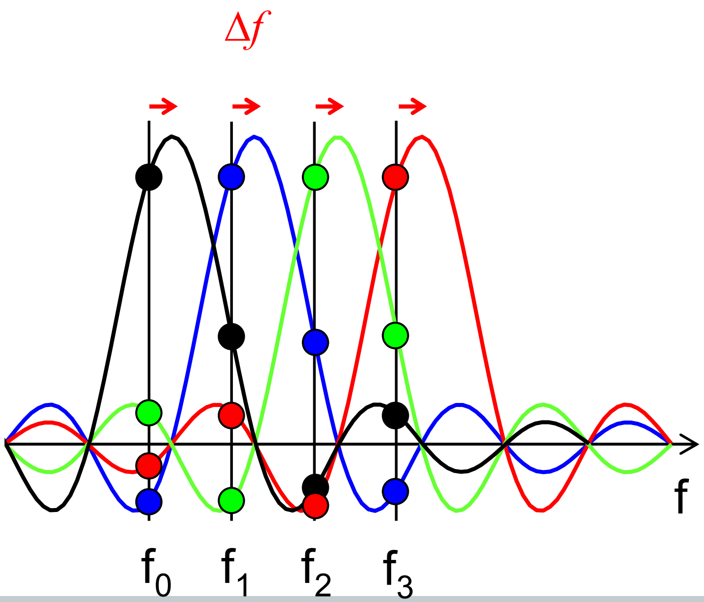


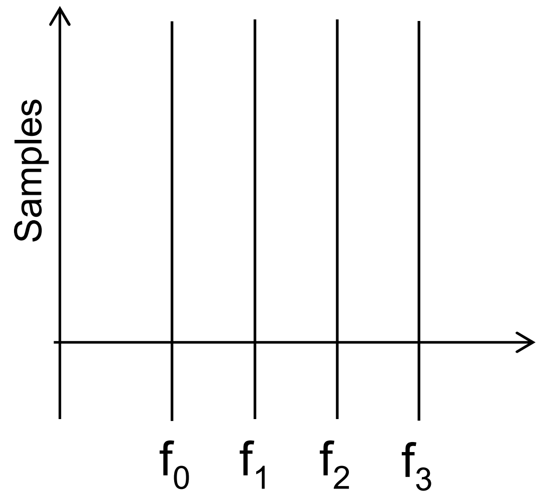




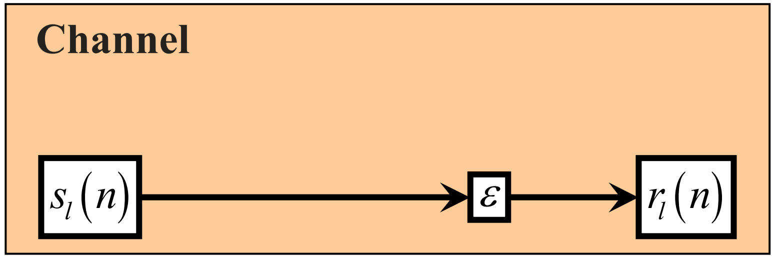
OFDM risk: Degradation due to Frequency Offset

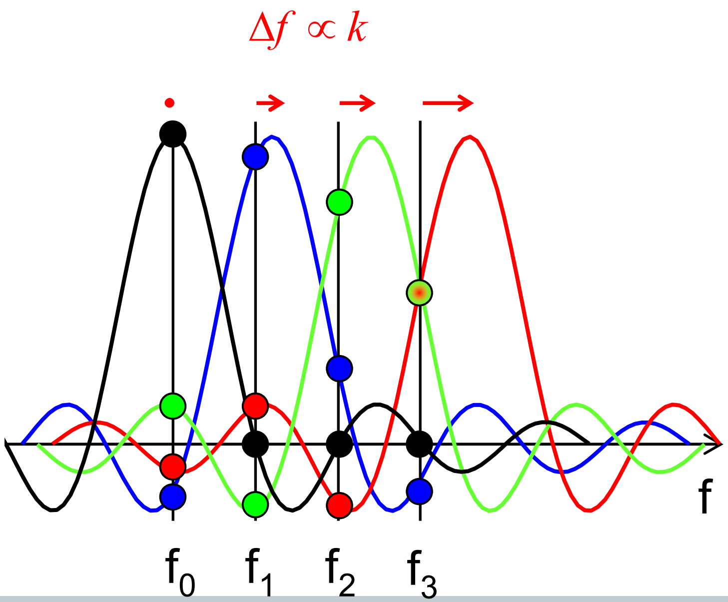


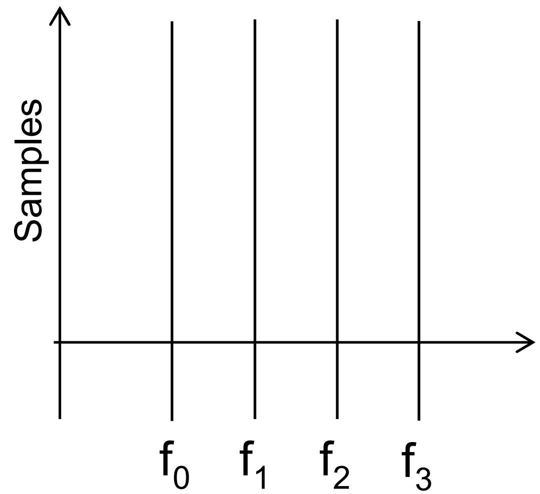




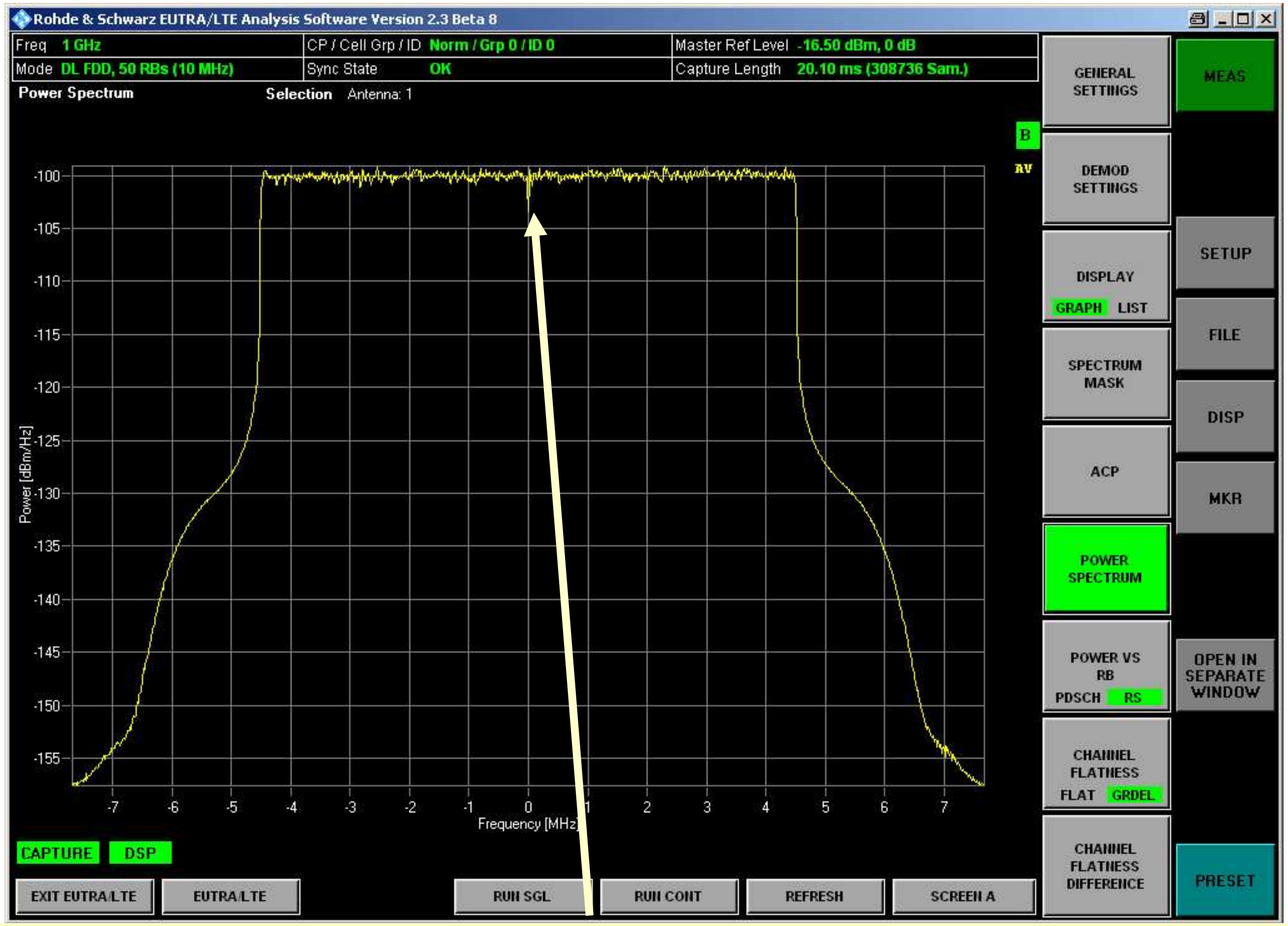
OFDM risk: Degradation due to Clock Offset





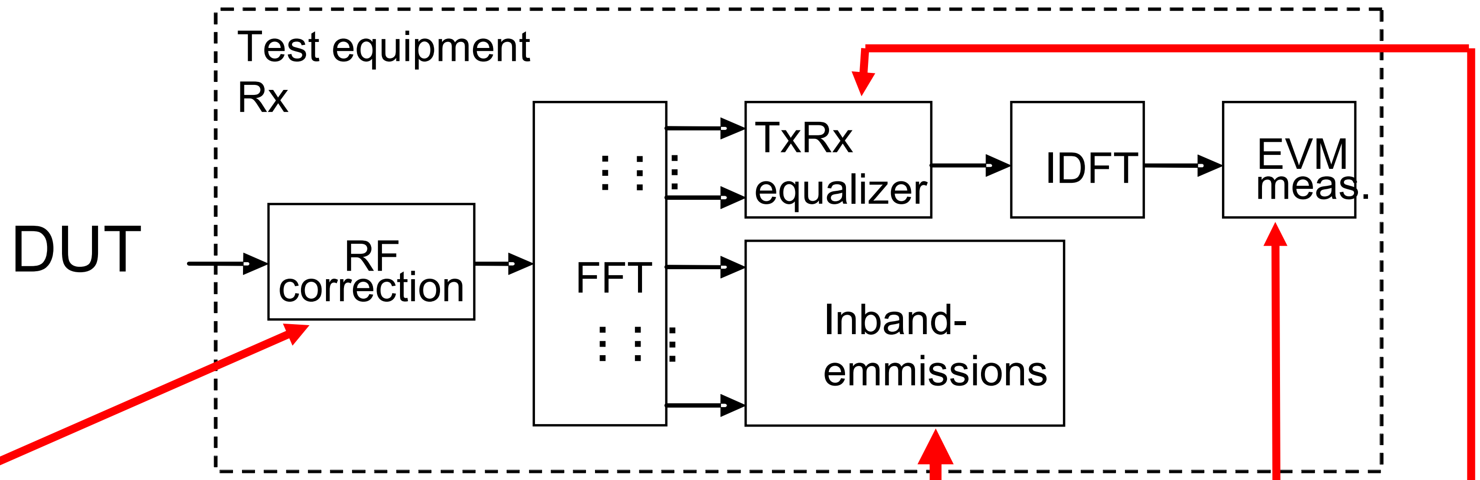


LTE: DC subcarrier usage



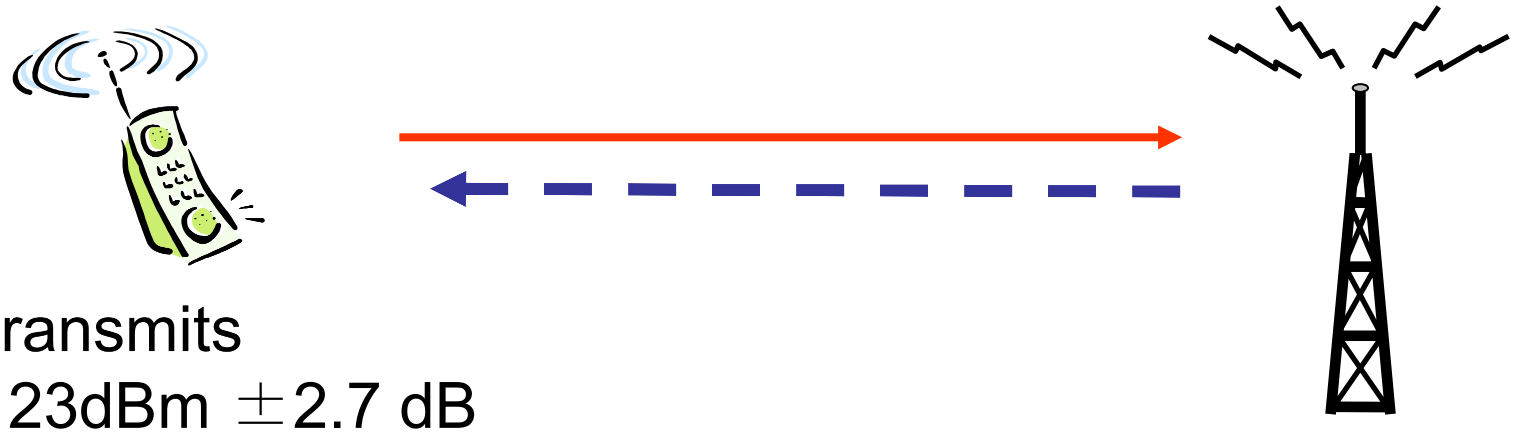
DC subcarrier or subcarrier 0 is not used in downlink!

UE Signal quality



- Carrier Frequency error
- EVM (Error Vector Magnitude)
- Origin offset + IQ offset
- Unwanted emissions, falling into non allocated resource blocks.
- Spectrum flatness

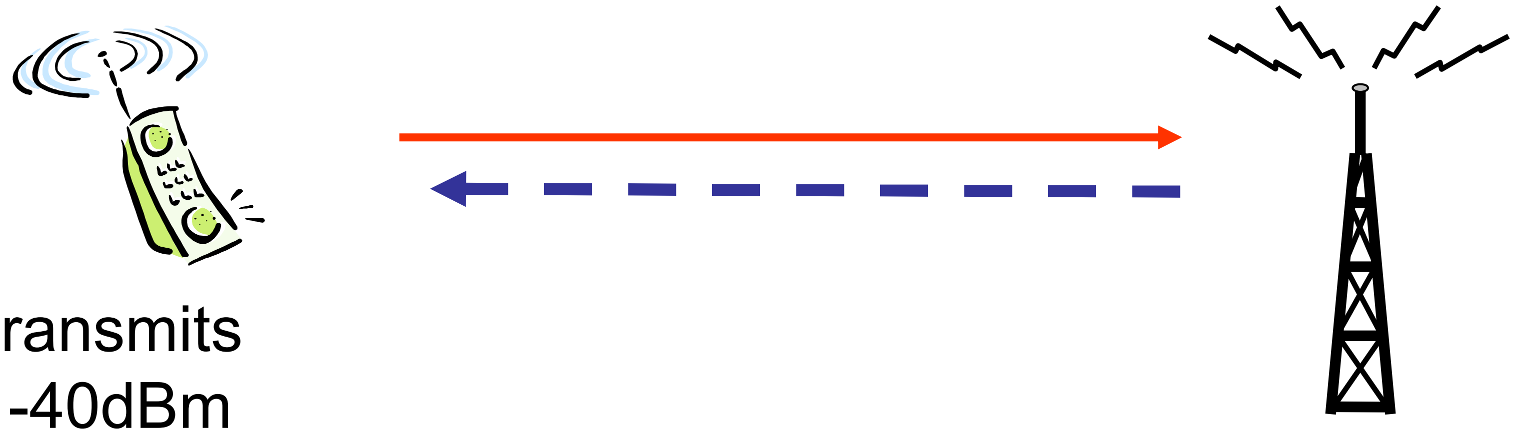
LTE RF Testing: UE Maximum Power



UE transmits
with 23dBm ±2.7 dB

QPSK modulation is used. All channel bandwidths are tested separately. Max power is for all band classes

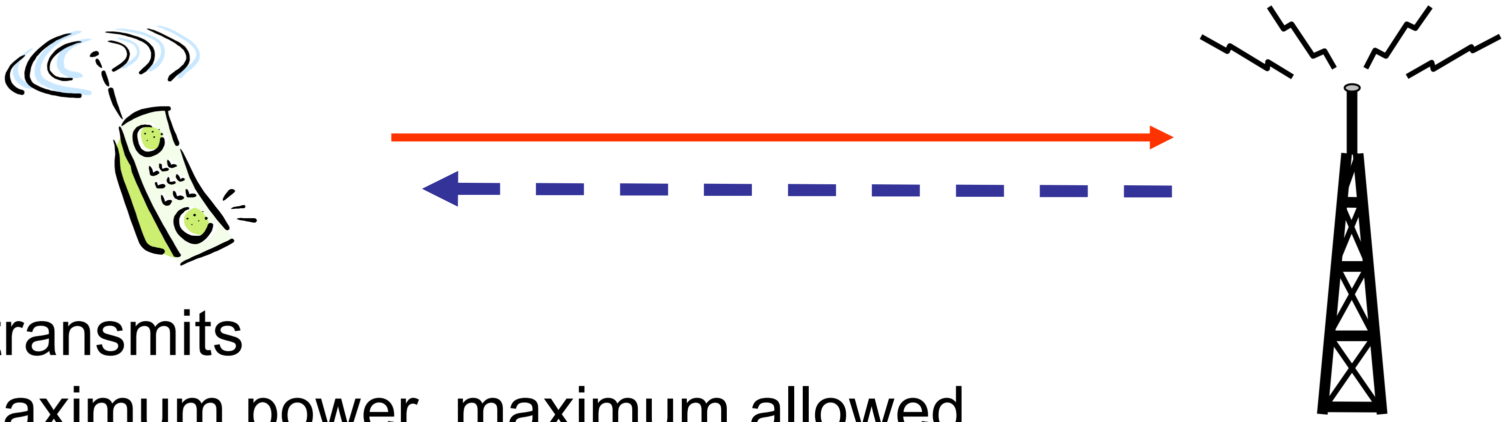
LTE RF Testing: UE Minimum Power



UE transmits
with -40dBm

All channel bandwidths are tested separately.
Minimum power is for all band classes < -39 dBm

UE Maximum Power Reduction



UE transmits
at maximum power, maximum allowed
TX power reduction is given as

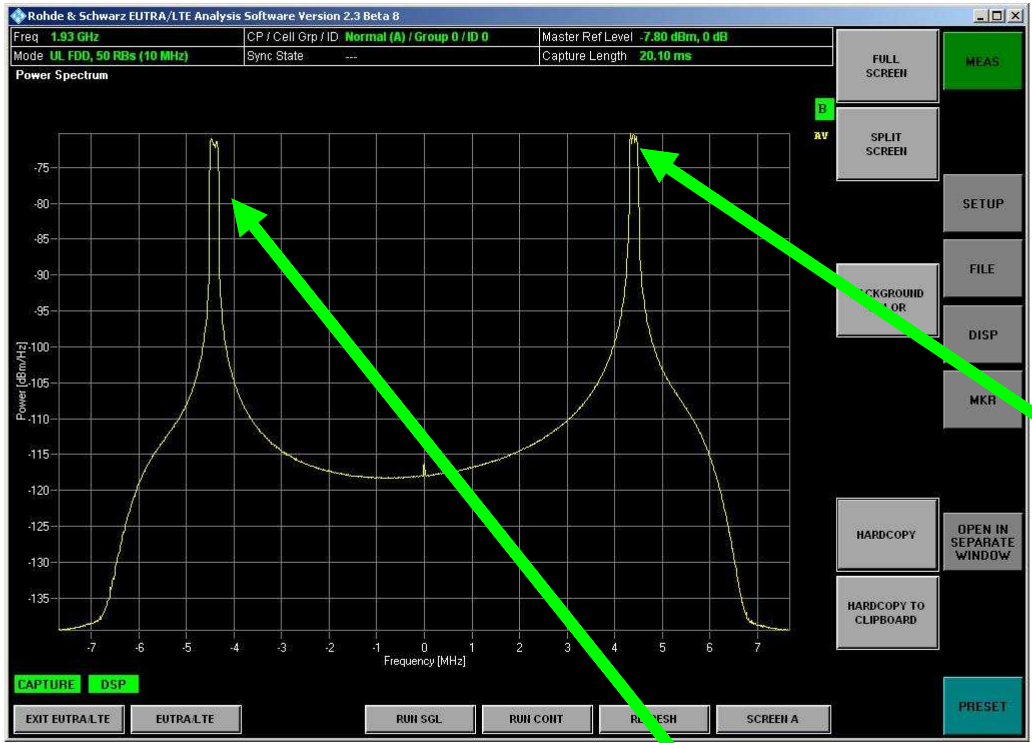
Modulation	Channel bandwidth / Transmission bandwidth configuration [RB]						MPR (dB)
	1.4 MHz	3.0 MHz	5 MHz	10 MHz	15 MHz	20 MHz	
QPSK	> 5	> 4	> 8	> 12	> 16	> 18	≤ 1
16 QAM	≤ 5	≤ 4	≤ 8	≤ 12	≤ 16	≤ 18	≤ 1
16 QAM Full	> 5	> 4	> 8	> 12	> 16	> 18	≤ 2

Tx power aspects

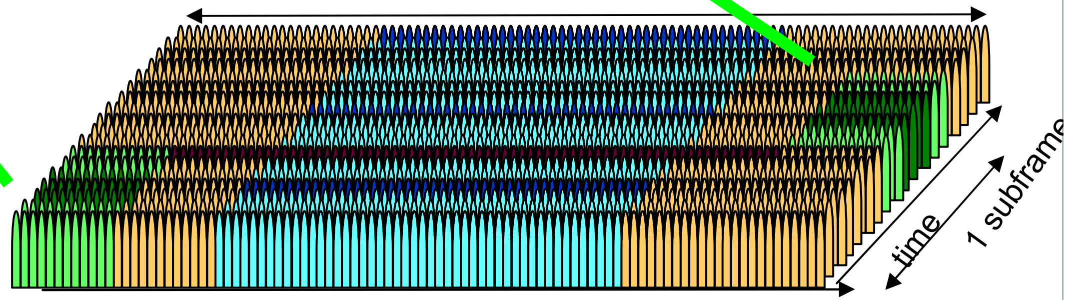
RB power = Ressource Block Power, power of 1 RB

TX power = integrated power of all assigned RBs

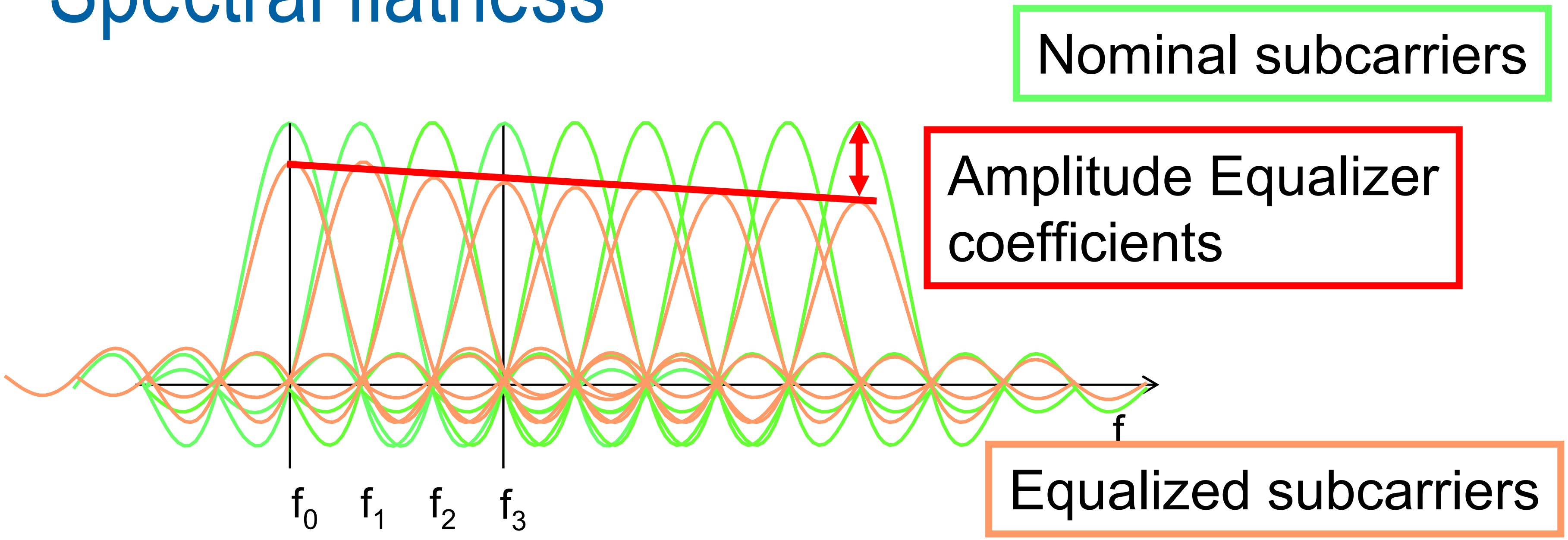
LTE Uplink: PUCCH



Allocation of PUCCH only.



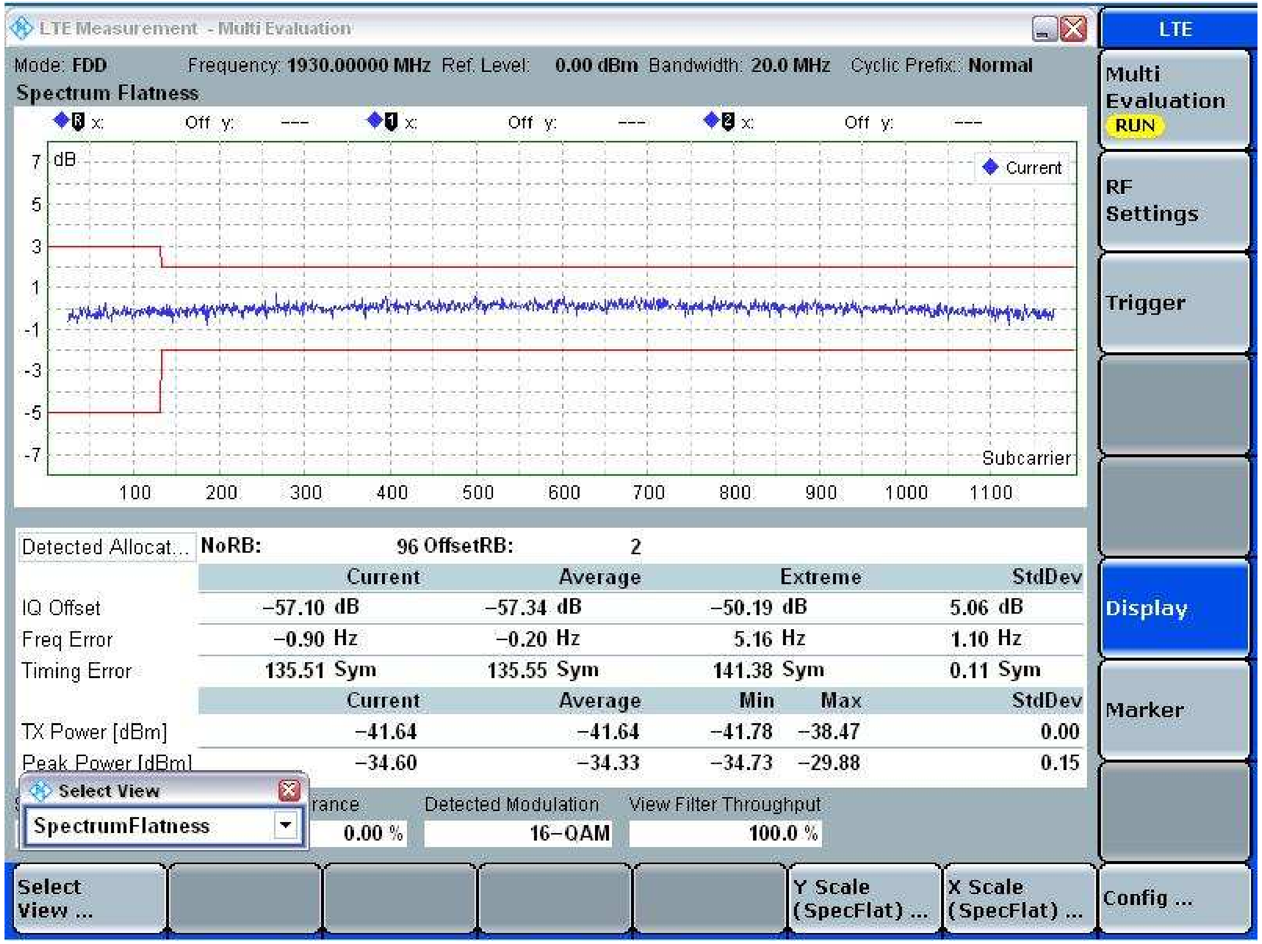
Spectral flatness



$$\Delta P(f) = 10 * \log \frac{\frac{1}{12 * N_{RB}} \sum_{12 * N_{RB}} |A(EC(f))|^2}{|A(EC(f)|^2}$$

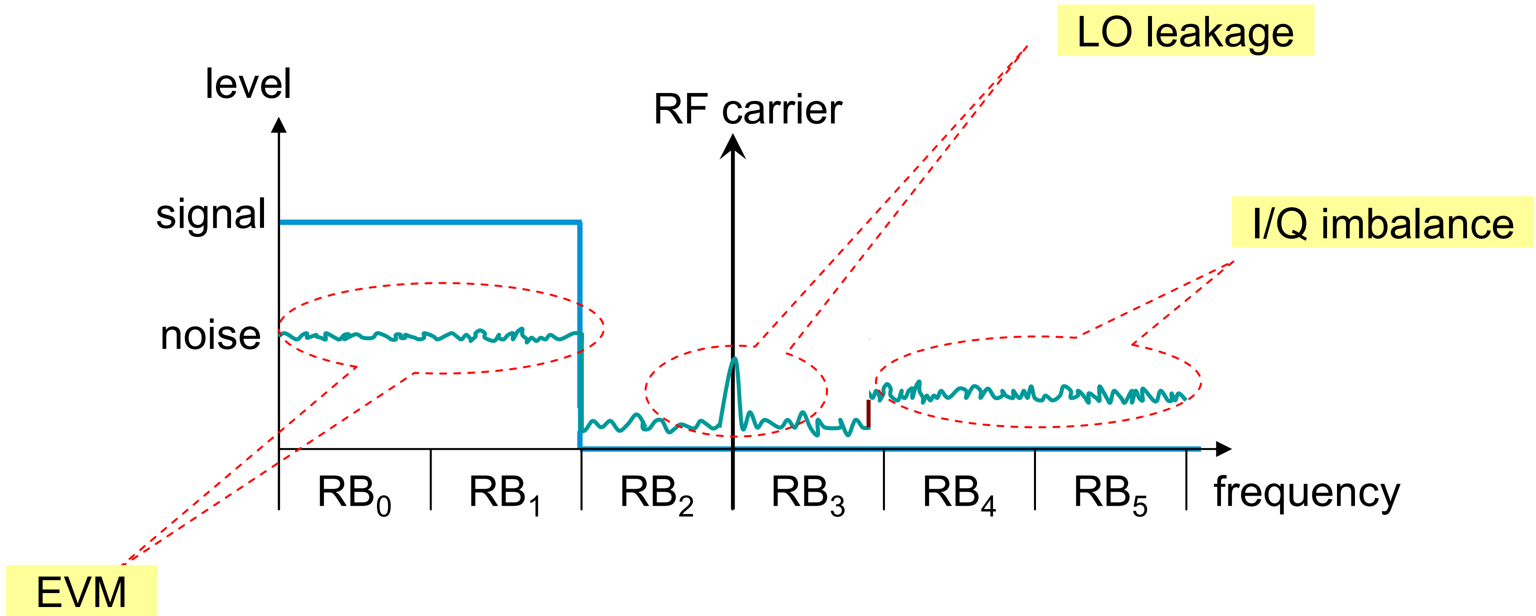
Integration of all Amplitude Equalizer Coefficients to display spectral flatness curve

Spectral flatness



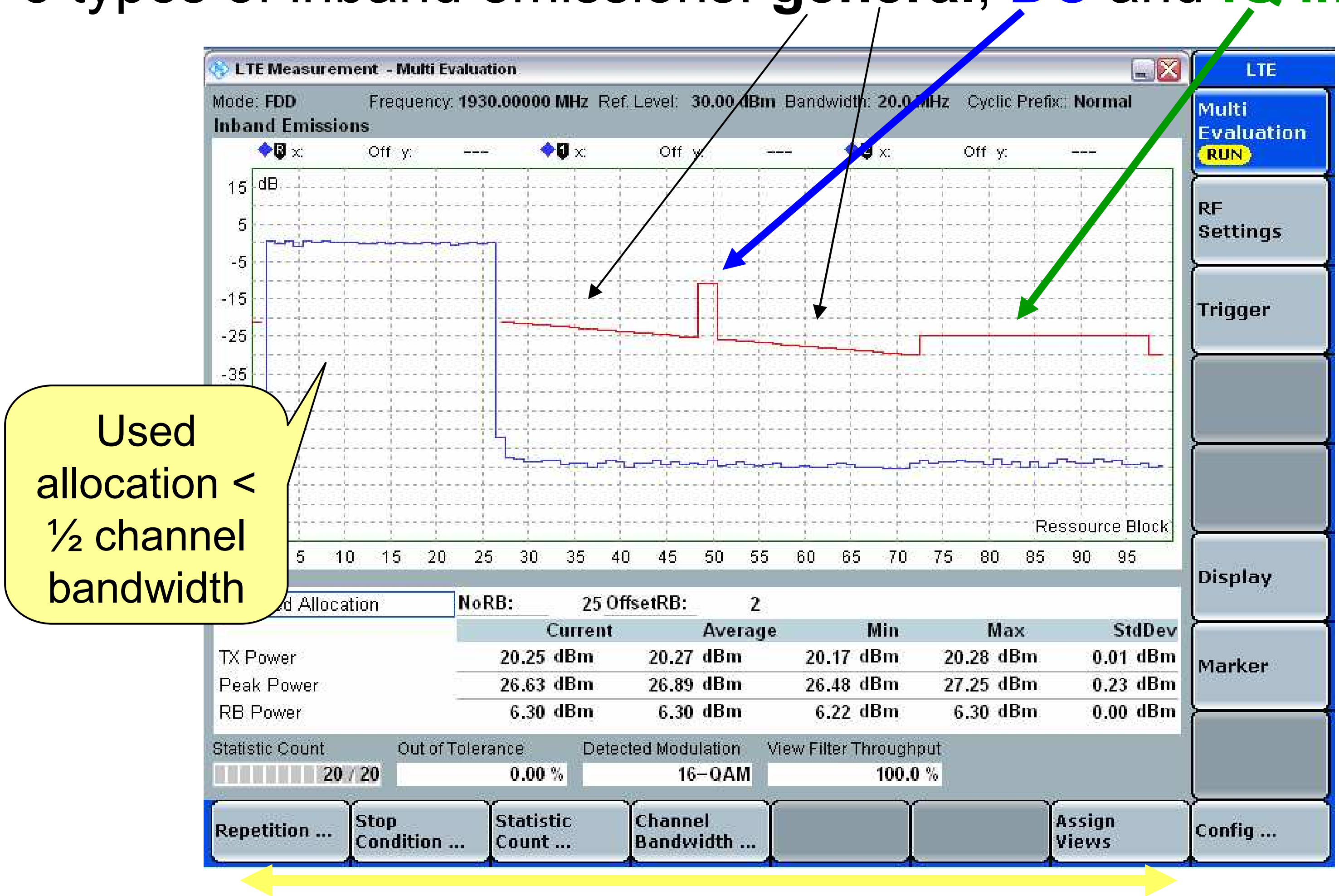
Impact on Tx modulation accuracy evaluation

- **3 modulation accuracy requirements**
  - EVM for the allocated RBs
  - LO leakage for the centred RBs ! LO spread on all RBs
  - I/Q imbalance in the image RBs



Inband emissions

3 types of inband emissions: **general**, **DC** and **IQ image**



channel bandwidth

Inband emmission – error cases

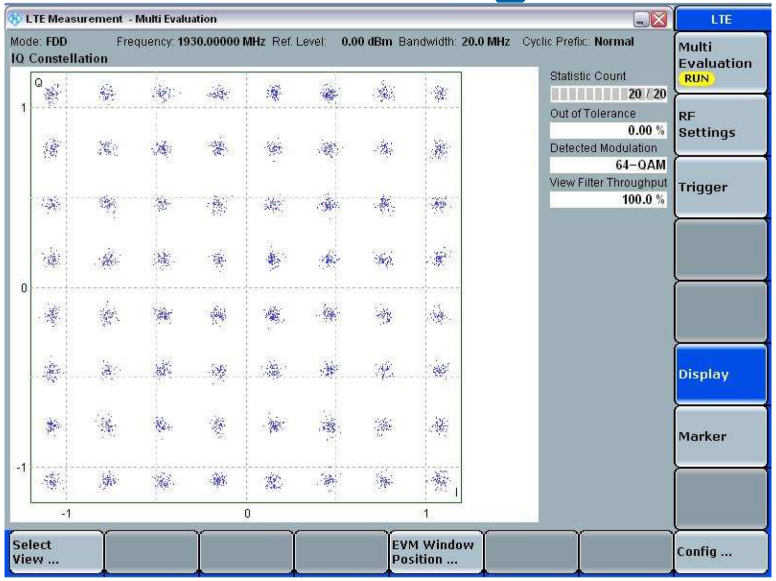
DC carrier leakage due to IQ offset

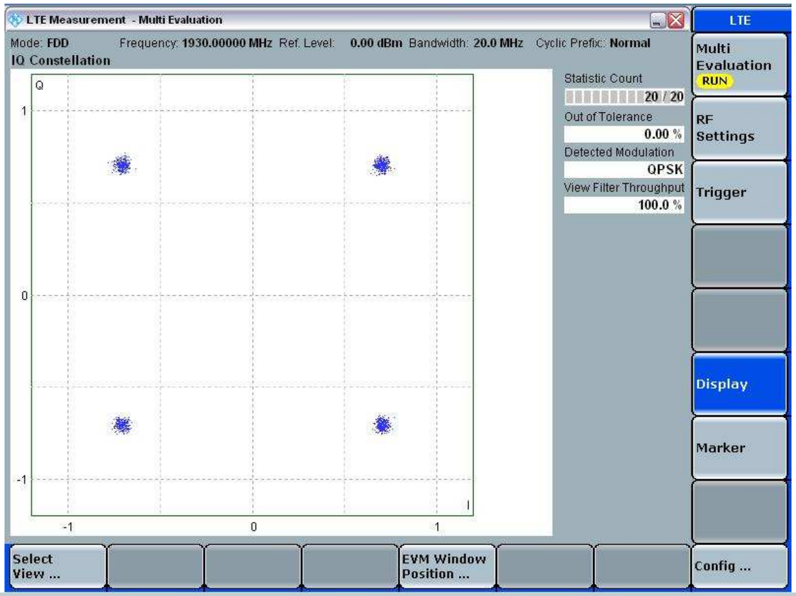
Inband emmission – error cases

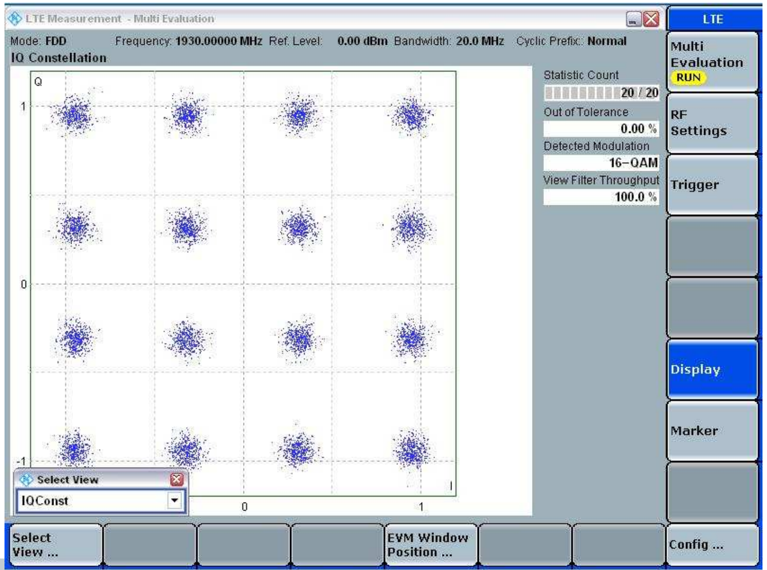
Inband image
due to IQ inbalance

Modulation quality: Constellation diagram

LTE PUSCH uses
QPSK, 16QAM
and 64 QAM modulation
schemes.
In UL there is only 1 scheme
allowed per subframe







Modulation quality: Constellation diagram

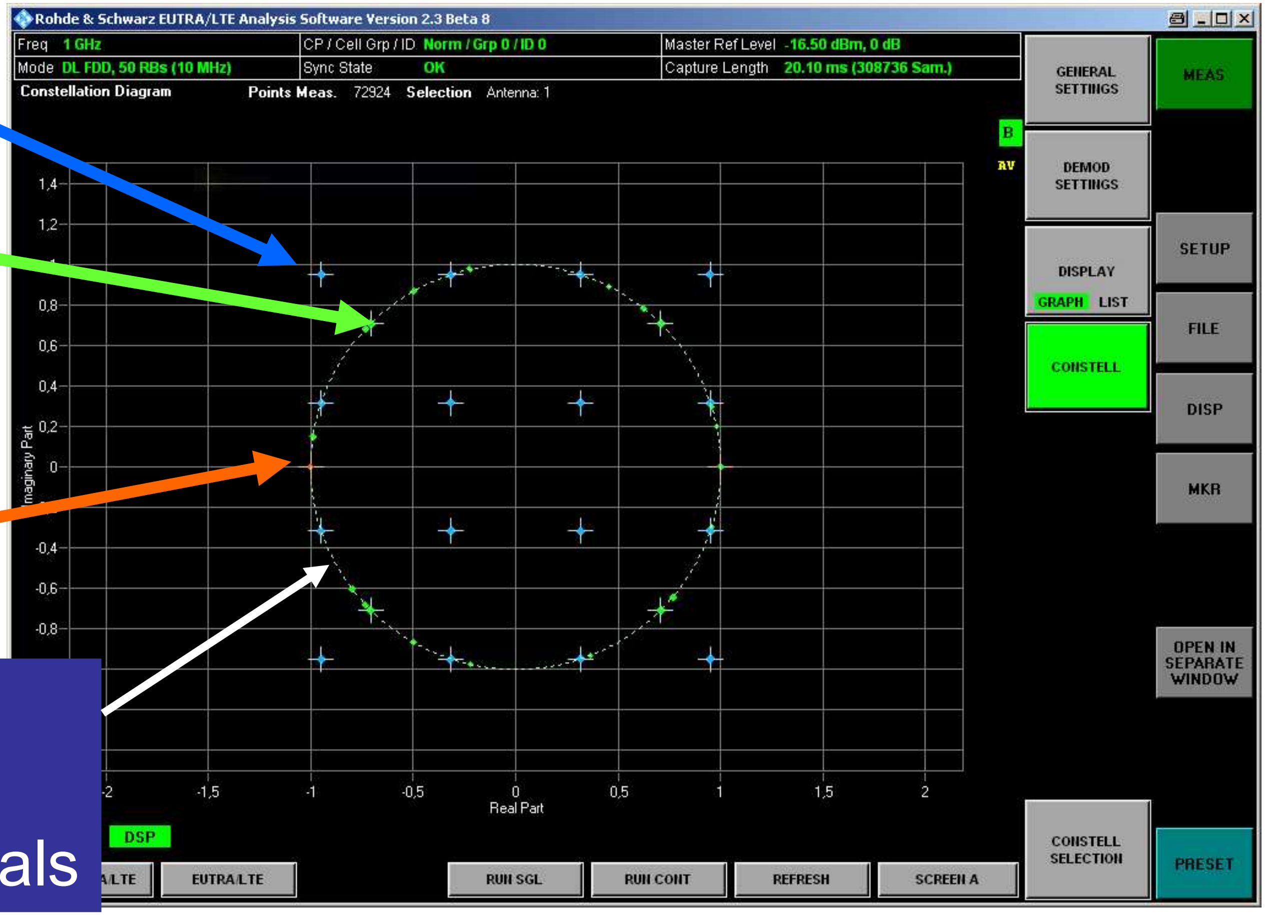
LTE downlink: several channels can be seen (example):

PDSCH with 16 QAM

PDCCH + PBCH with QPSK

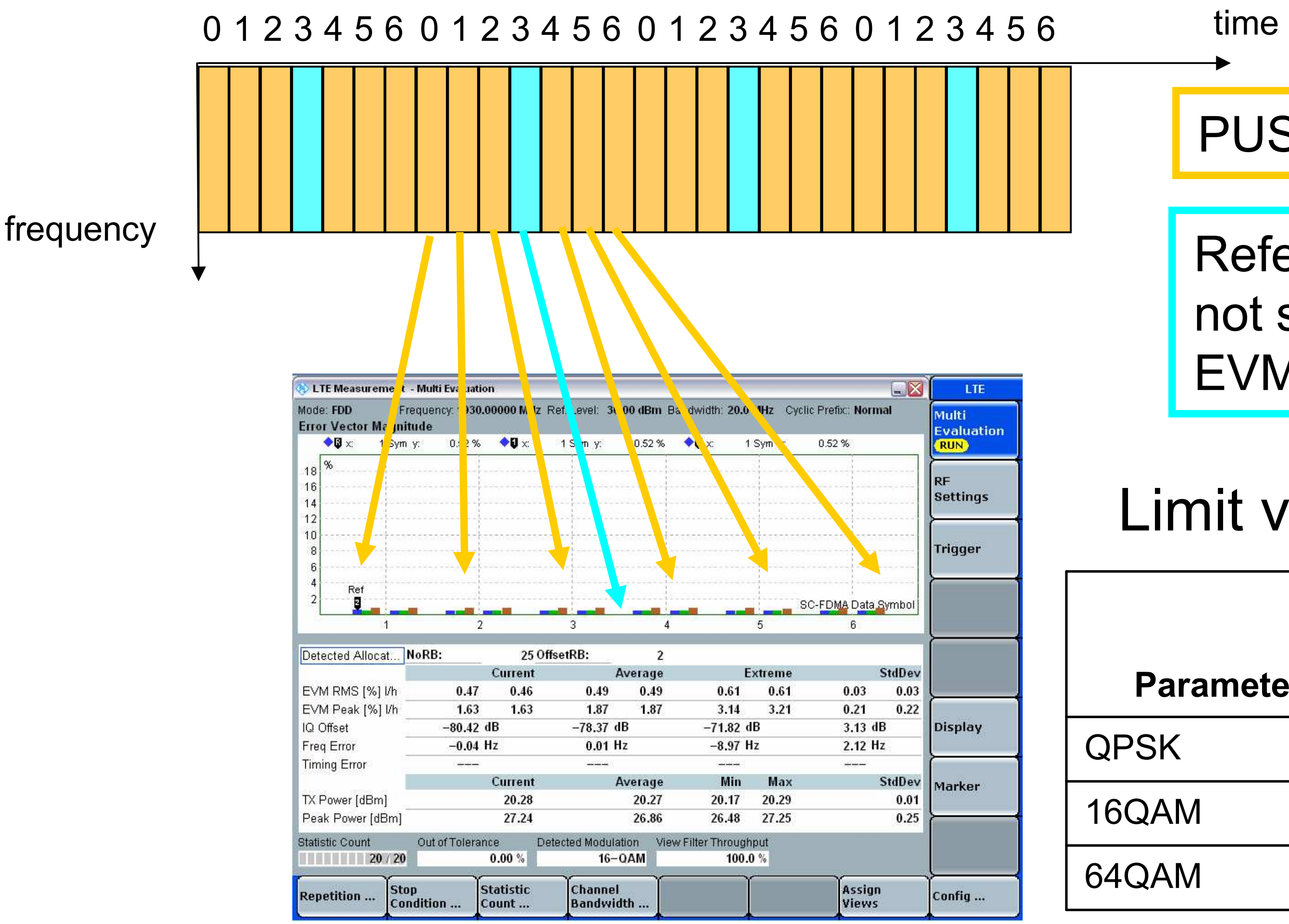
S-SCH with BPSK

CAZAC Sequences, Reference signals



Error Vector Magnitude, EVM

7 symbols / slot



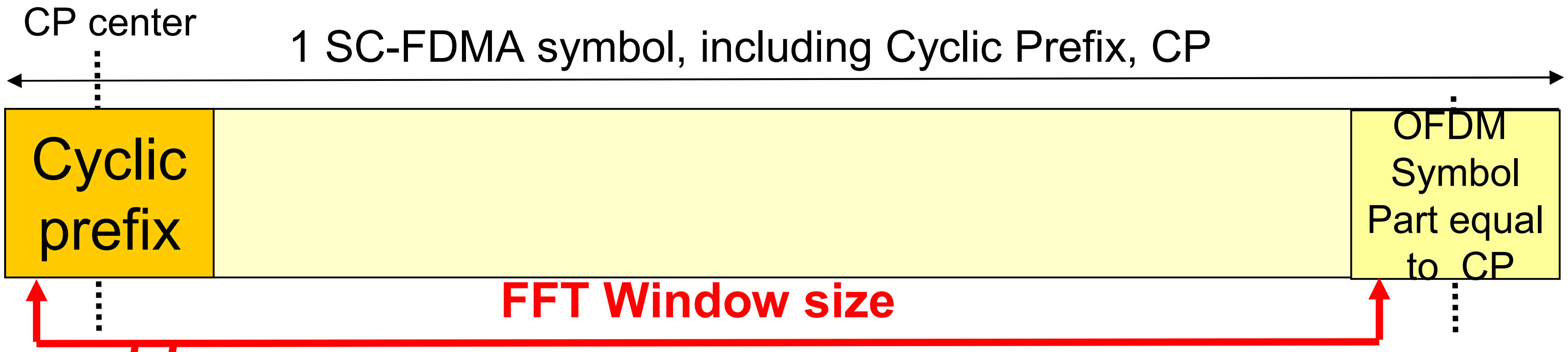
PUSCH symbol

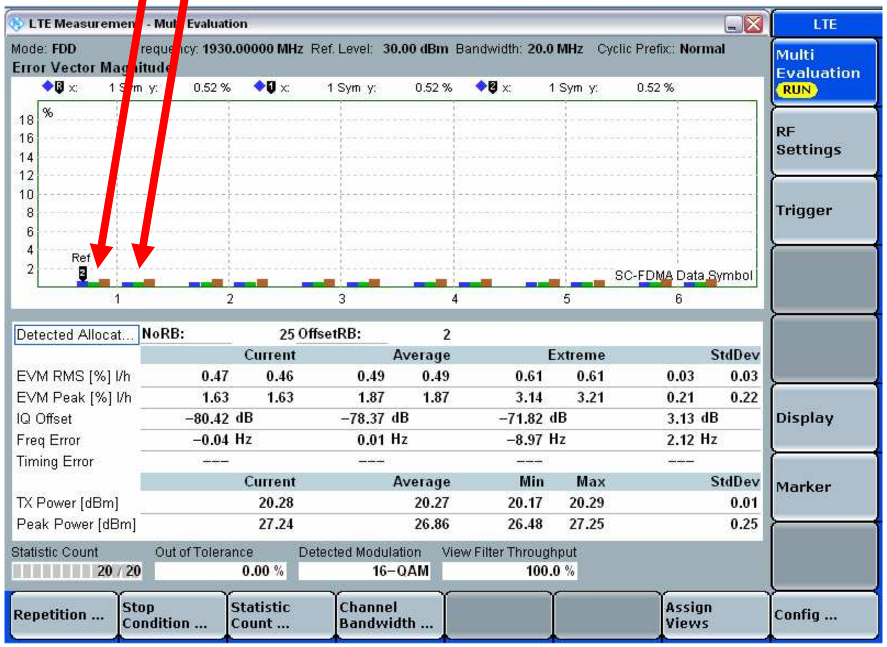
Reference symbol, not shown in EVM measurement

Limit values

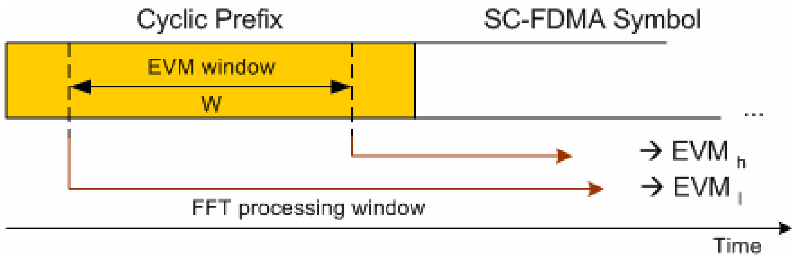
Parameter	Unit	Level
QPSK	%	17.5
16QAM	%	12.5
64QAM	%	[tbd]

Error Vector Magnitude, EVM

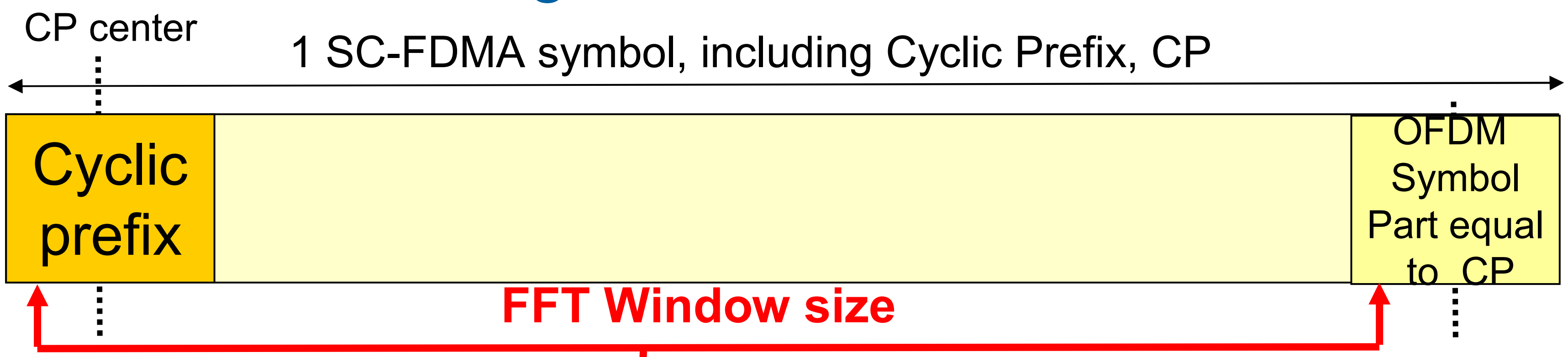




FFT window size depends on channel bandwidth and extended/normal CP length



Error Vector Magnitude, EVM



FFT window size depends on channel bandwidth and extended/normal CP length

Channel Bandwidth MHz	Cyclic prefix length: N_{cp} for symbol 0	Cyclic prefix length: N_{cp} for symbols 1 to 6	Nominal FFT size	Cyclic prefix for symbols 1 to 6 in FFT samples	EVM window length *W*	Ratio of *W* to CP for symbols 1 to 6*
1.4	160	144	128	9	[5]	[55.6]
3			256	18	[12]	[66.7]
5			512	36	[32]	[88.9]
10			1024	72	[66]	[91.7]
15			1536	108	[102]	[94.4]
20			2048	144	[136]	[94.4]

* Note: These percentages are informative and apply to symbols 1 through 6. Symbol 0 has a longer CP and therefore a lower percentage.

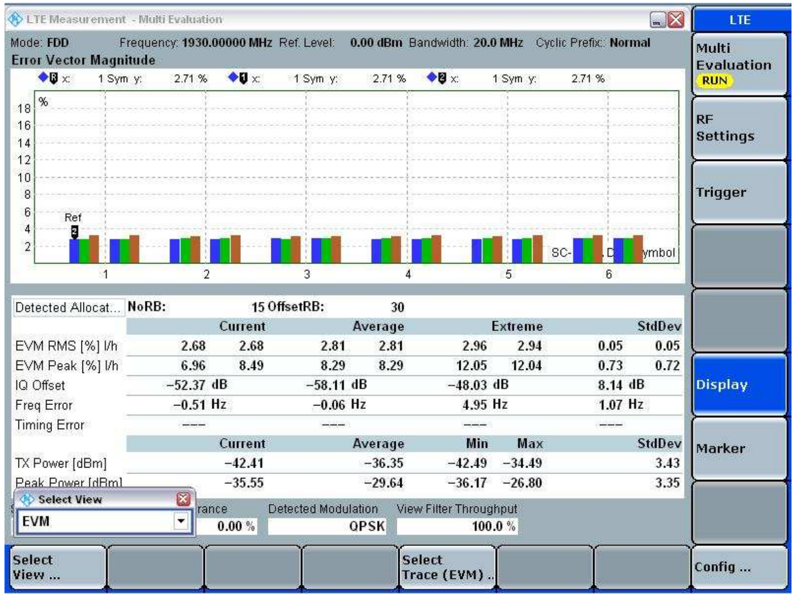
Table from TS 36.101 for normal CP

FFT window does not capture the full length: OFDM Symbol + CP

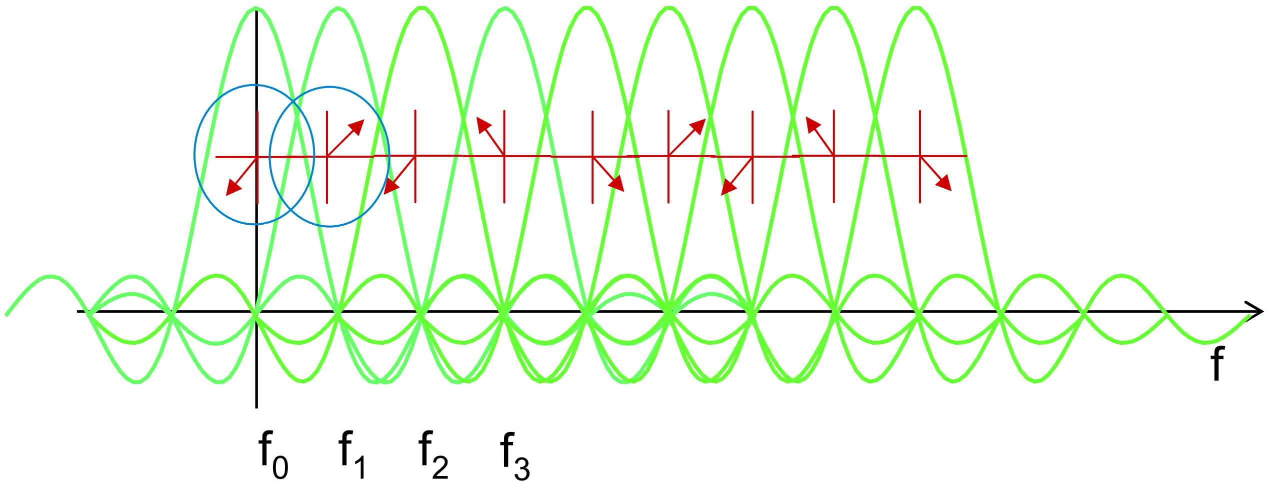
EVM, Phase error and Magnitude error

Phase error of UL signal
with extended cyclic prefix
-> 5 SC-FDMA symbols/slot

EVM of UL signal
with normal cyclic prefix
-> 6 SC-FDMA symbols/slot



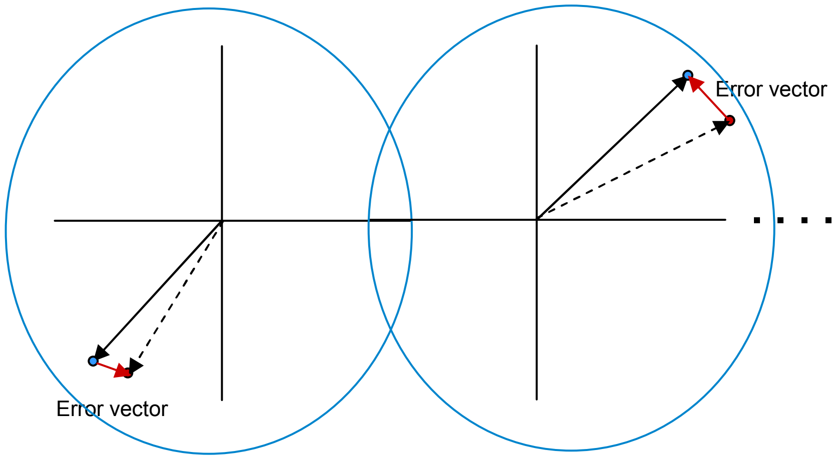
EVM vs. subcarrier

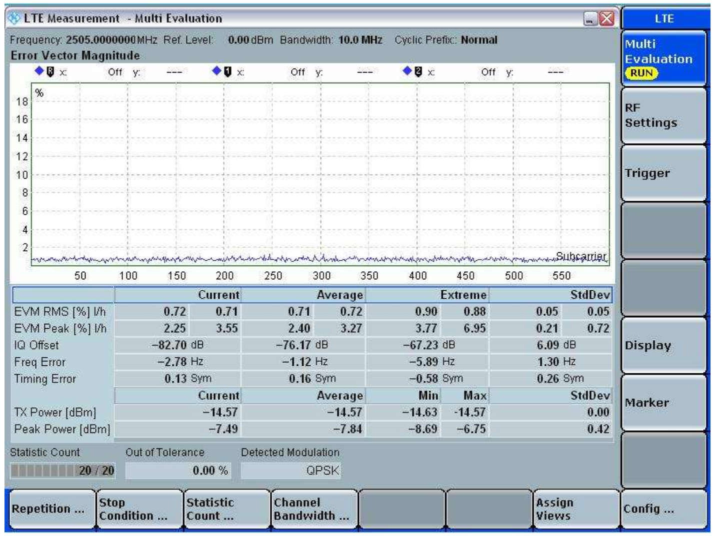


Nominal subcarriers

Each subcarrier Modulated with e.g. QPSK

Integration of all Error Vectors to Display EVM curve

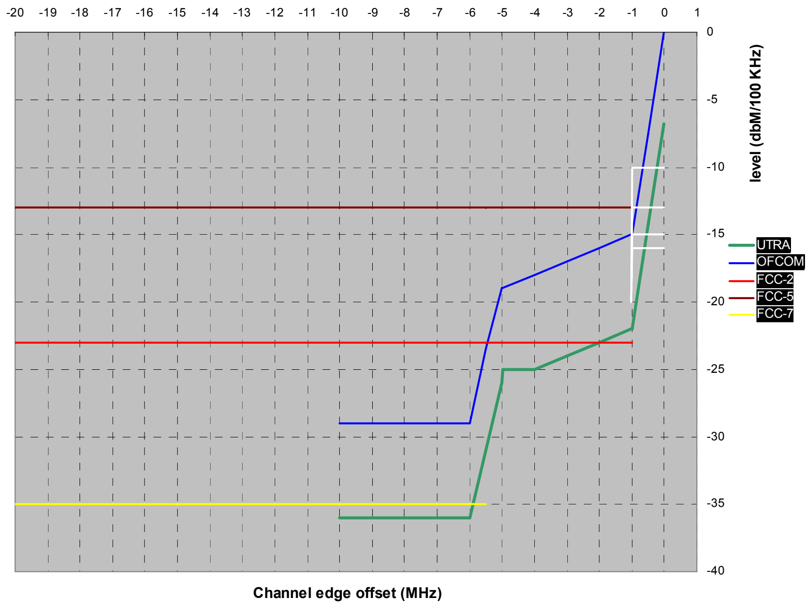




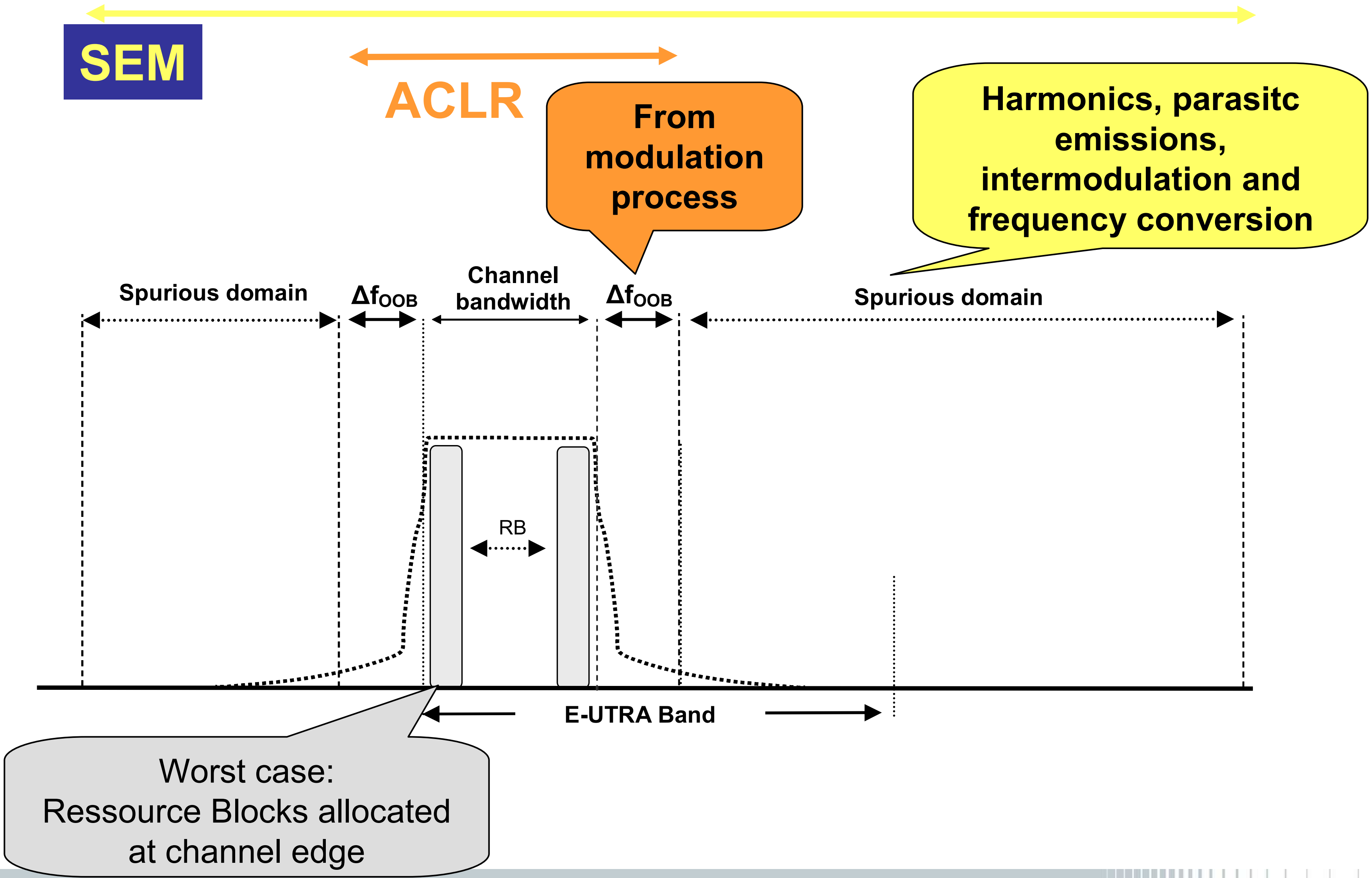
EVM vs. subcarrier

Why constraining Out of Band emissions?

- **spectrum sharing regulatory requirements in some countries >> SEM**
  - PHS protection limits for Japan
  - FCC for US deployment in certains frequency bands
- **operating near GSM and WCDMA systems >> ACLR**

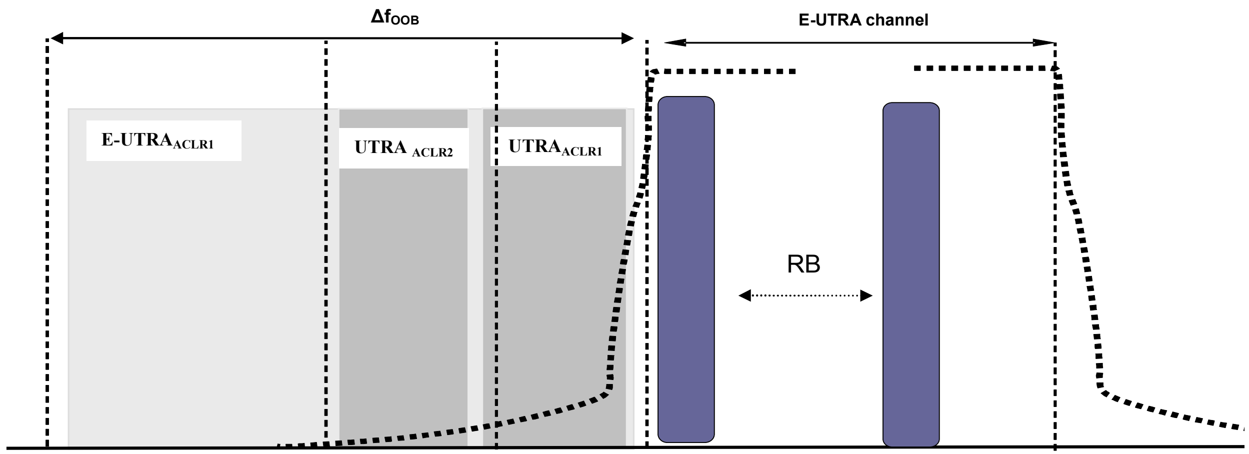


Output RF spectrum emissions

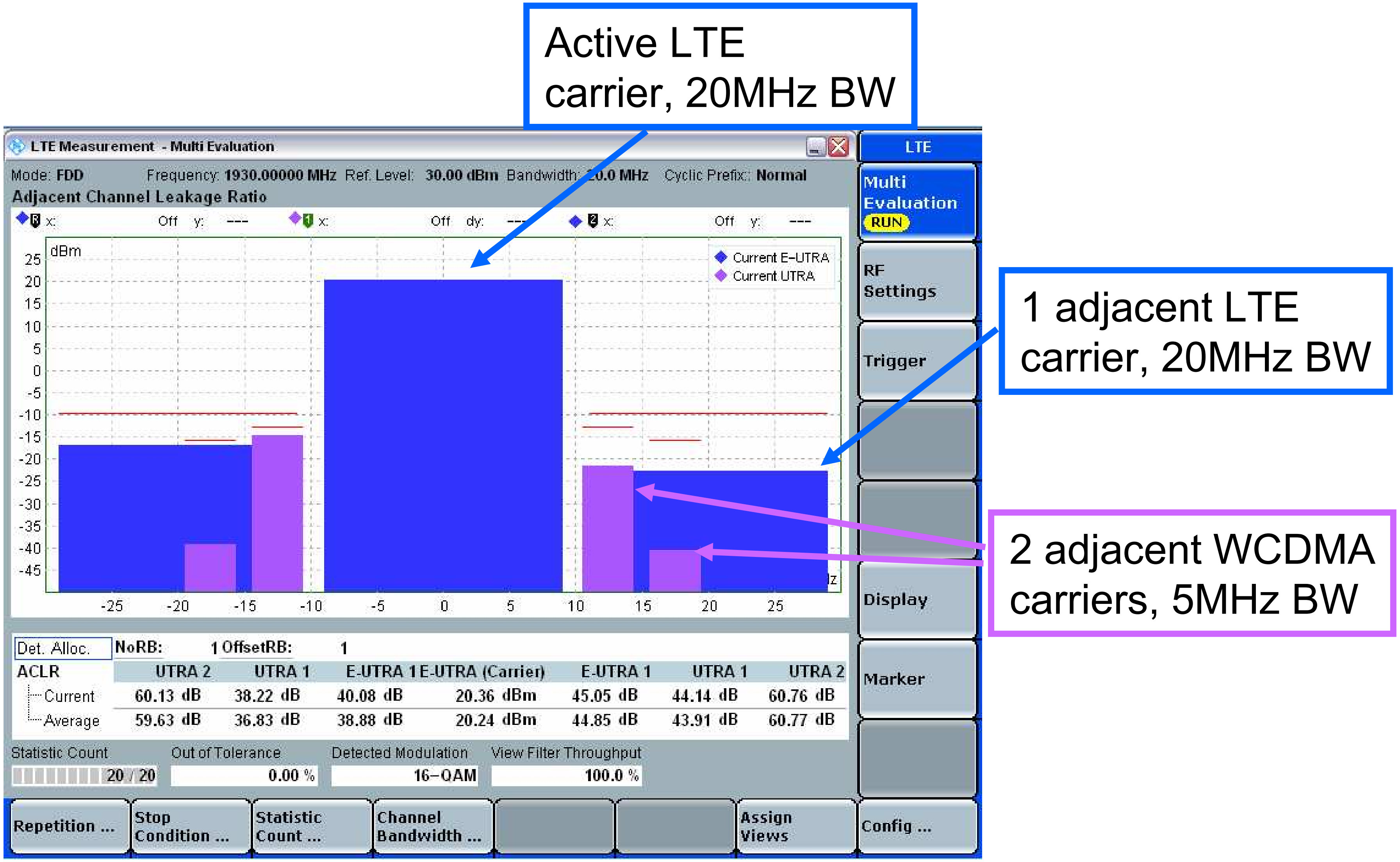


LTE ACLR requirements

- UTRA ACLR 1+2
- EUTRA ACLR
- EUTRA measured with rectangular filter, WCDMA measured with RRC filter
- additional requirements for relaxation



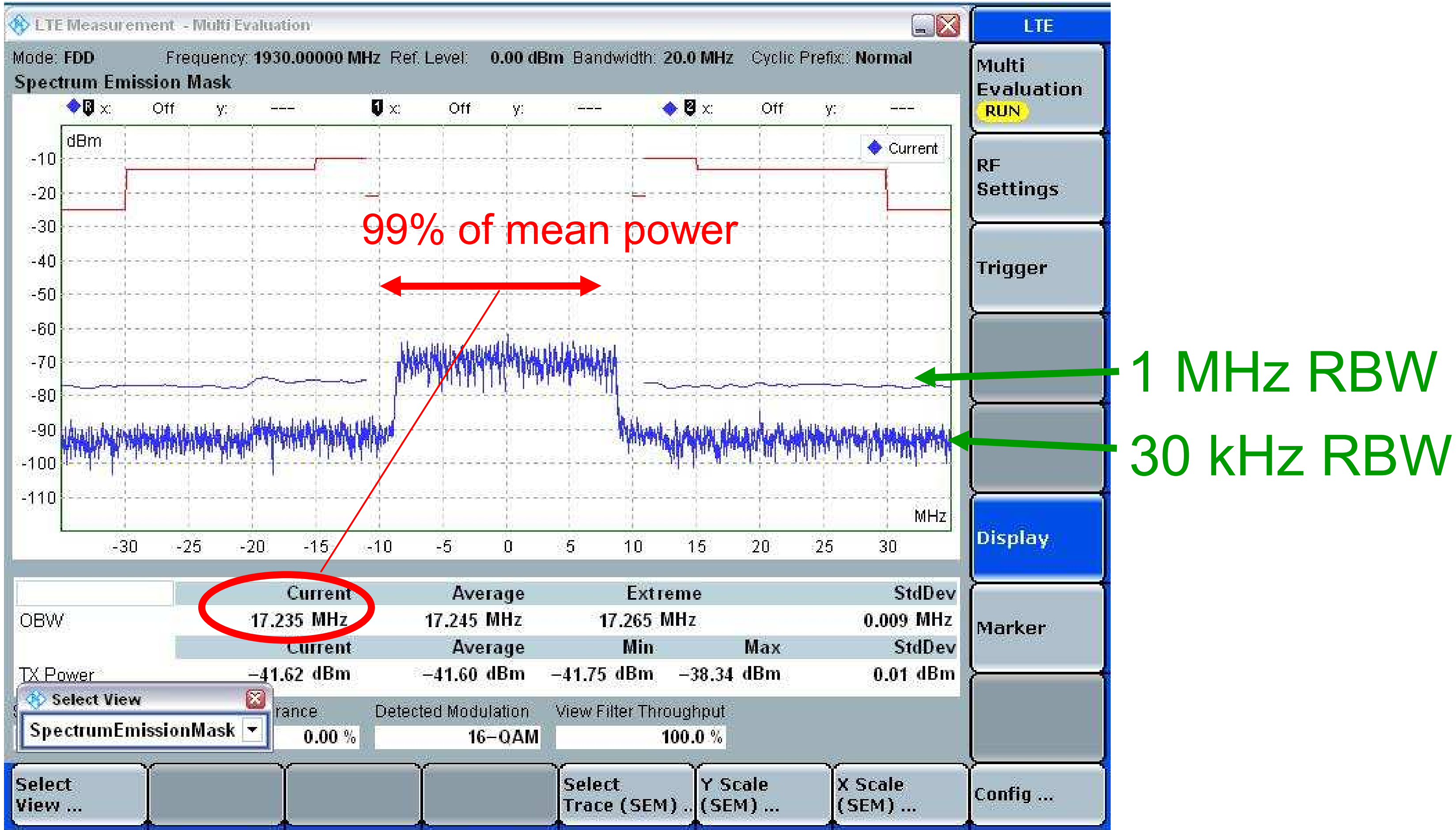
Adjacent Channel Leakage Ratio, ACLR



Spectrum Emission Mask, SEM

OBW: Occupied bandwidth, defined as 99% of mean power

SEM: Spectrum ,Emission Mask, measured with different resolution bandwidth, 1 MHz or 30 kHz RBW

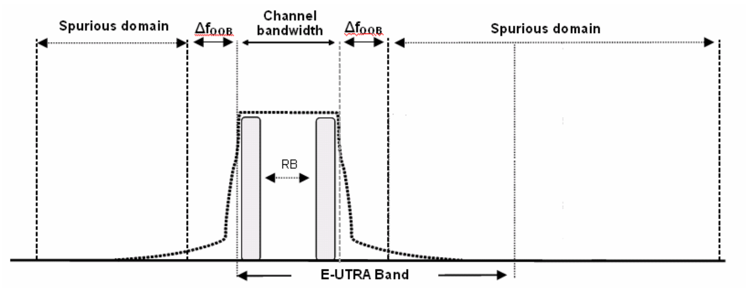


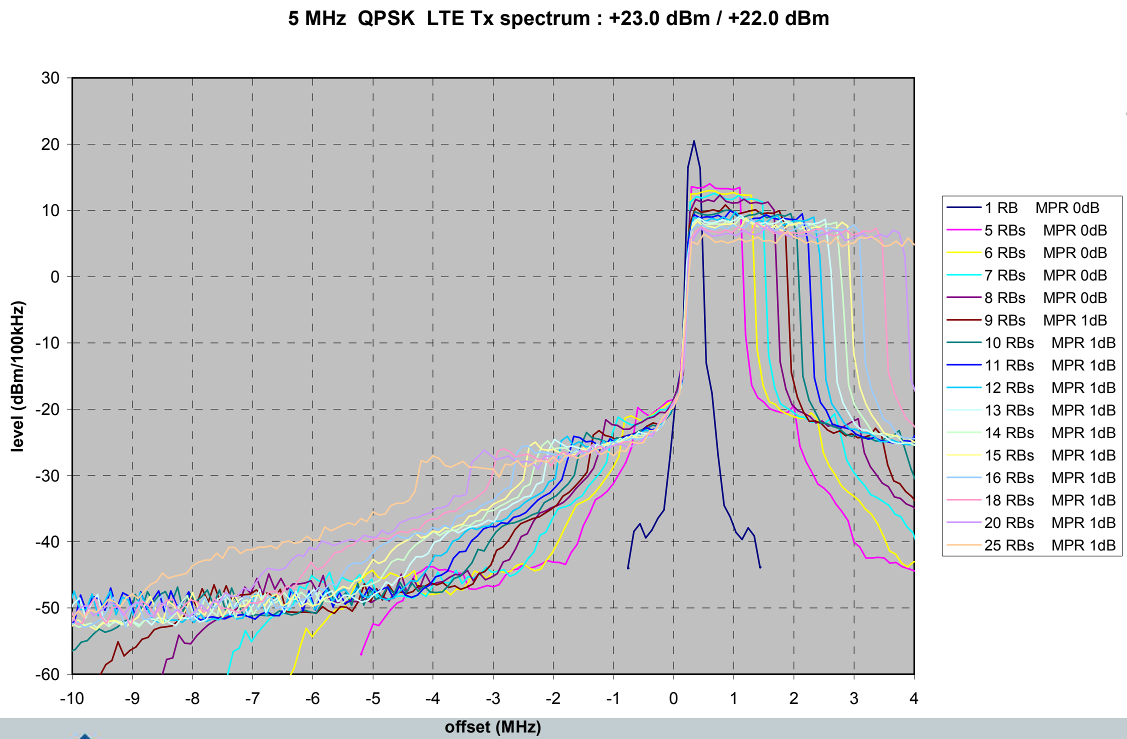
75 Years of Driving Innovation

Impact on SEM definition

- **SEM defined for worst case scenario: RBs allocated at channel edge**
- **OOB emission scales with channel BW configuration**

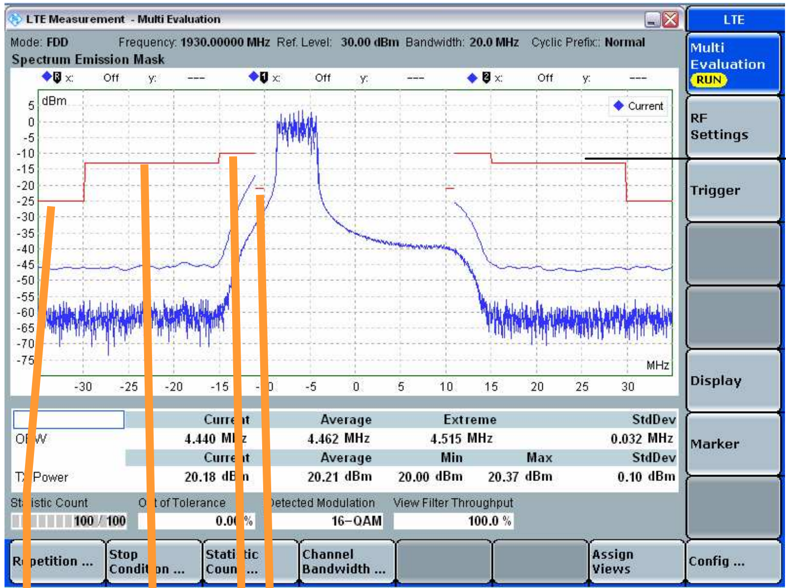
>> a SEM per channel BW





Channel bandwidth $BW_{Channel}$ [MHz]	1.4	3	5	10	15	20
Length of OOB domain on one side [MHz]	5	6	10	15	20	25

Impact on SEM limit definition



Limits depend on channel bandwidth

Limits vary dependent on offset from assigned BW

Spectrum emission limit (dBm)/ Channel bandwidth							
Δf_{OOB} (MHz)	1.4 MHz	3.0 MHz	5 MHz	10 MHz	15 MHz	20 MHz	Measurement bandwidth
± 0-1	-10	-13	-15	-18	-20	-21	30 kHz
± 1-2.5	-10	-10	-10	-10	-10	-10	1 MHz
± 2.5-5	-25	-10	-10	-10	-10	-10	1 MHz
± 5-6		-25	-13	-13	-13	-13	1 MHz
± 6-10			-25	-13	-13	-13	1 MHz
± 10-15				-25	-13	-13	1 MHz
± 15-20					-25	-13	1 MHz
± 20-25						-25	1 MHz

LTE measurements

RSRP = Reference Signal Received Power

Definition	Reference signal received power, the mean measured power of the reference symbols during the measurement period.
Applicable for	TBD

E-UTRA Carrier RSSI

Definition	E-UTRA Carrier Received Signal Strength Indicator, comprises the total received wideband power observed by the UE from all sources, including co-channel serving and non-serving cells, adjacent channel interference, thermal noise etc.
Applicable for	TBD

general info on RX measurements

- **very few progress**
- **baseline receiver: 2 Rx antennas**
- **same measurements as in WCDMA**
  - Rx sensitivity level
  - max input level
  - adjacent channel selectivity (ACS)
  - blocking
  - spurious emissions
  - intermodulation
- **1 requirement pro BW**
- **requirements in terms of throughput instead of BER**
  - RMC not defined yet, maybe QPSK R=1/3 and 64QAM R=3/4

RX sensitivity level

Criterion: throughput shall be > 95% of possible maximum (depend on RMC)

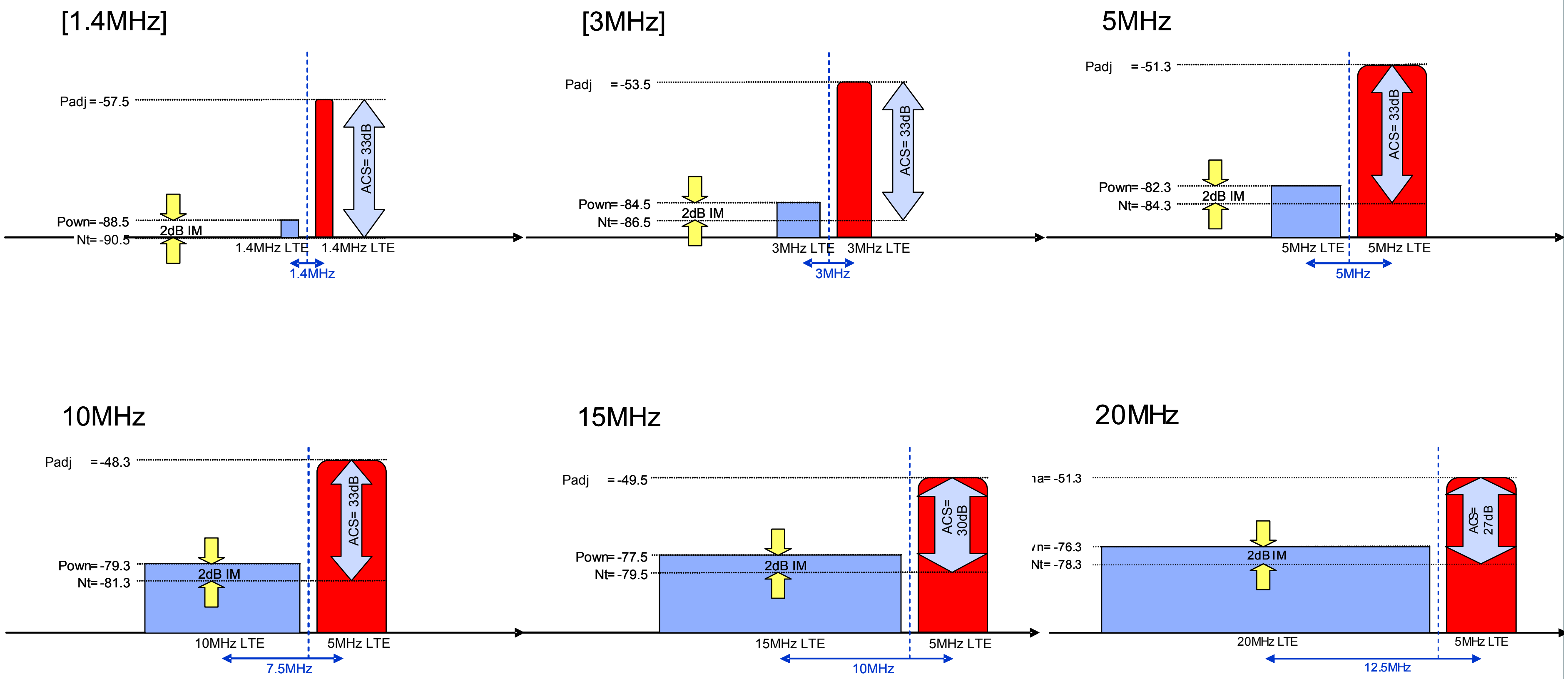
Channel bandwidth							
E-UTRA Band	**1.4 MHz (dBm)**	**3 MHz (dBm)**	**5 MHz (dBm)**	**10 MHz (dBm)**	**15 MHz (dBm)**	**20 MHz (dBm)**	**Duplex Mode**
1	-	-	-100	-97	-95.2	-94	FDD
2	-104.2	-100.2	-98	-95	-93.2	-92	FDD
3	-103.2	-99.2	-97	-94	-92.2	-91	FDD
4	-106.2	-102.2	-100	-97	-95.2	-94	FDD
5	-104.2	-100.2	-98	-95			FDD
6	-	-	-100	-97			FDD

Extract from TS 36.521

Sensitivity depends on band, channel bandwidth and RMC under test

Adjacent Channel Selectivity (ACS)

- 1 req pro BW, LTE interferer



There will be enough topics

for future trainings ☺

Thank you for your attention!

Comments and questions welcome!