UMTS Long Term Evolution (LTE)

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75 Years of Driving Innovation

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Overview 3GPP UMTS Evolution
Driven by Data Rate and Latency Requirements

WCDMA	HSDPA/HSUPA	HSPA+	LTE
384 kbps downlink 128 kbps uplink	14 Mbps peak downlink 5.7 Mbps peak uplink	28 Mbps peak downlink 11 Mbps peak uplink	100 Mbps peak downlink 50 Mbps peak uplink
RoundTripTime~150ms	RoundTripTime<100ms	RoundTripTime <50 ms	RoundTripTime~10 ms
3GPP Release 99/4	3GPP Release 5/6	3GPP Release 7	3GPP Release 8
2003/4	2005/6 (HSDPA) 2007/8 (HSUPA)	2008/9	2009/10

Approx. year of network roll-out

Overview 3GPP UMTS evolution

	WCDM	HSDPA HSUP	HSPA	LTE an HSPA	LTE advance
3GP releas	3GPP Release 99/4	3GPP Release 5/	3GPP Release 7	3GPP Release 8	3GPP Study Item initiate
App. year of network rollou	2003/4	2005/6 (HSDPA) 2007/8 (HSUPA)	2008/2009	2010	
Downlink data rat	384 kbps (typ	14 Mbps (peak	28 Mbps (peak	LTE: 150 Mbps* (peak) HSPA+: 42 Mbps (peal	100 Mbps high mobility 1 Gbps low mobility
Uplink data rat	128 kbps (typ	5.7 Mbps (peal	11 Mbps (peak)	LTE: 75 Mbps (peak) HSPA+: 11 Mbps (peal	
Round Trip Time	150 m	< 100 ms	< 50 ms	LTE: ~10 m	

*based on 2x2 MIMO and 20 MHz operatio

Overview TD-SCDMA evolution towards LTE TDD

	TD-SCDMA	HSDPA	HSUPA	TD-LTE HSPA+
3GPP release	3GPP Release 4	3GPP Release 5	3GPP Release 7	3GPP Release 8
Downlink data rate	384/128 kbps (typ.)	2.8 Mbps (peak)	2.8 Mbps (peak)*	LTE:100 Mbps(req.)
Uplink data rate	128 kbps (typ.)	128 kbps (typ.)	2.2 Mbs (peak)*	LTE: 50 Mbps (req.)

* Higher data rate with the use of multi carrier possible

What LTE could mean also …

- Live Telecommunication Ecosystem
- Long Term Employment
- LTE Telephones Everywhere
- Love The Enemy
- Life Time Eternal
- Let's Take it Easy
- Live communication To Everyone
- Loads of Traffic for Everyone
- Little Televisions Everywhere
- Look, Talk, and Enjoy
- Late Troublesome Expensive
- Laugh Track Escapade
- Luscious Telephony Experience
- Linking The Earth
- Let‘s Transmit Everything
- …

Why LTE?
Ensuring Long Term Competitiveness of UMTS

- **LTE is the next UMTS evolution step after HSPA and HSPA+.**
- **LTE is also referred to as**
  EUTRA(N) = Evolved UMTS Terrestrial Radio Access (Network).
- **Main targets of LTE:**
  - Peak data rates of 100 Mbps (downlink) and 50 Mbps (uplink)
  - Scaleable bandwidths up to 20 MHz
  - Reduced latency
  - Cost efficiency
  - Operation in paired (FDD) and unpaired (TDD) spectrum

Major technical challenges in LTE

New radio transmission schemes (OFDMA / SC-FDMA)	FDD and TDD mode
MIMO multiple antenna schemes	Throughput / data rate requirements
Timing requirements (1 ms transm.time interval)	Multi-RAT requirements (GSM/EDGE, UMTS, CDMA)
Scheduling (shared channels, HARQ, adaptive modulation)	System Architecture Evolution (SAE)

Introduction to UMTS LTE: Key parameters

Frequency Range	**UMTS FDD bands and UMTS TDD bands**					
Channel bandwidth, 1 Resource Block=180 kHz	**1.4 MHz**	**3 MHz**	**5 MHz**	**10 MHz**	**15 MHz**	**20 MHz**
	6 Resource Blocks	15 Resource Blocks	25 Resource Blocks	50 Resource Blocks	75 Resource Blocks	100 Resource Blocks
Modulation Schemes	**Downlink:** QPSK, 16QAM, 64QAM **Uplink:** QPSK, 16QAM, 64QAM (optional for handset)					
Multiple Access	**Downlink:** OFDMA (Orthogonal Frequency Division Multiple Access) **Uplink:** SC-FDMA (Single Carrier Frequency Division Multiple Access)					
MIMO technology	**Downlink:** Wide choice of MIMO configuration options for transmit diversity, spatial multiplexing, and cyclic delay diversity (max. 4 antennas at base station and handset) **Uplink:** Multi user collaborative MIMO					
Peak Data Rate	**Downlink:** 150 Mbps (UE category 4, 2x2 MIMO, 20 MHz) 300 Mbps (UE category 5, 4x4 MIMO, 20 MHz) **Uplink:** 75 Mbps (20 MHz)					

LTE/LTE-A Frequency Bands (FDD)

E-UTRA Operating Band	Uplink (UL) operating band BS receive UE transmit F_{UL_low} – F_{UL_high}			Downlink (DL) operating band 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
18	815 MHz	–	830 MHz	860 MHz	–	875 MHz	FDD
19	830 MHz	–	845 MHz	875 MHz	–	890 MHz	FDD
20	832 MHz	-	862 MHz	791 MHz	-	821 MHz	FDD
21	1447.9 MHz	-	1462.9 MHz	1495.9 MHz	-	1510.9 MHz	FDD
22	3410 MHz	-	3500 MHz	3510 MHz	-	3600 MHz	FDD

LTE/LTE-A Frequency Bands (TDD)

E-UTRA Operating Band	Uplink (UL) operating band BS receive UE transmit			Downlink (DL) operating band BS transmit UE receive			Duplex Mode
	F_{UL_low}	–	F_{UL_high}	F_{DL_low}	–	F_{DL_high}	
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
41	3400 MHz – 3600MHz			3400 MHz – 3600MHz			TDD

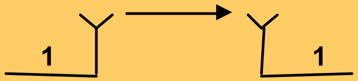
MIMO =

Multiple Input Multiple Output Antennas

MIMO is defined by the number of Rx / Tx Antennas

and not by the Mode which is supported

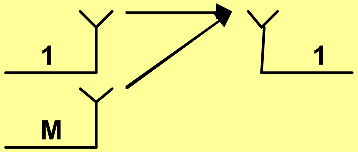
Mode



SISO

Single Input Single Output

Typical todays wireless Communication System

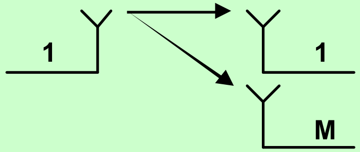


MISO

Multiple Input Single Output

Transmit Diversity

- Maximum Ratio Combining (MRC)
- Matrix A also known as STC
- Space Time / Frequency Coding (STC / SFC)

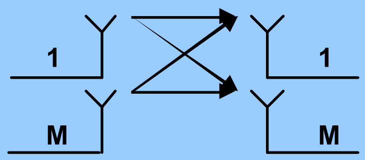


SIMO

Single Input Multiple Output

Receive Diversity

- Maximum Ratio Combining (MRC)



MIMO

Multiple Input Multiple Output

Definition is seen from Channel
Multiple In = Multiple Transmit Antennas

Receive / Transmit Diversity

Spatial Multiplexing (SM) also known as:

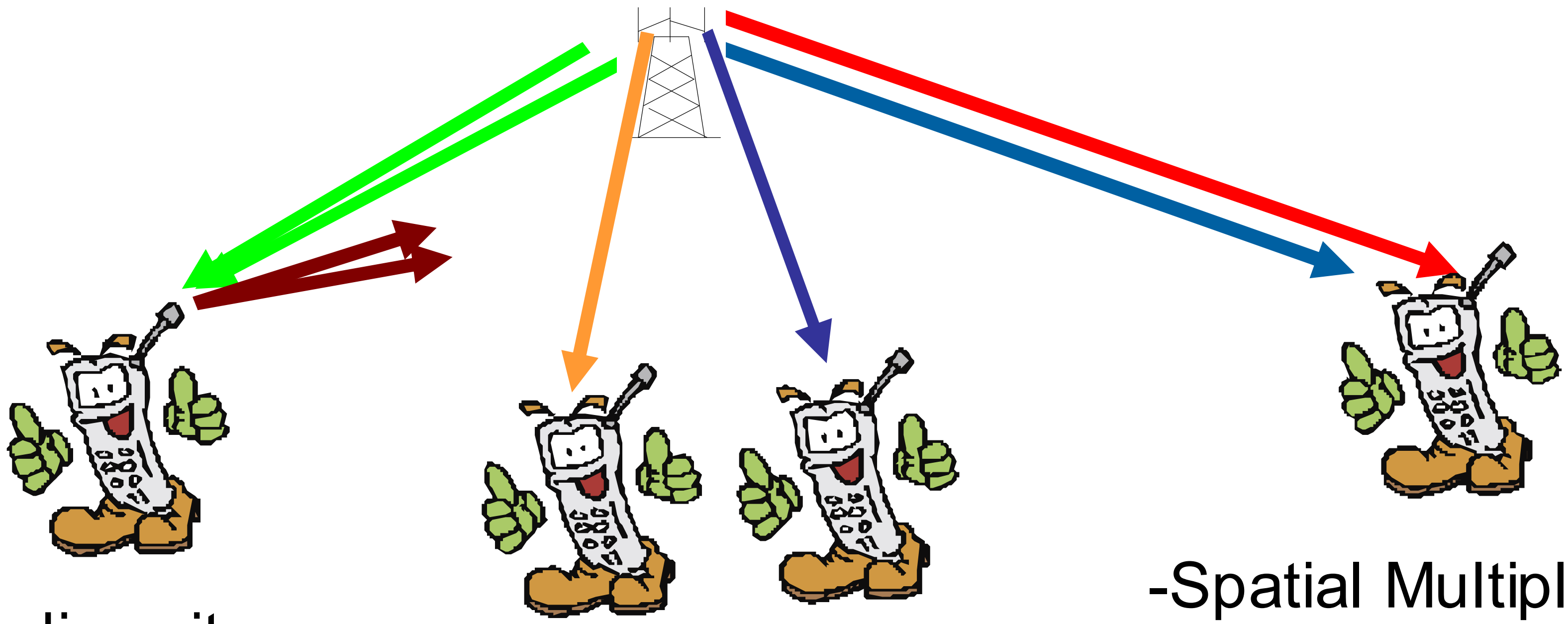
- Space Division Multiplex (SDM)
- True MIMO
- Single User MIMO (SU-MIMO)
- Matrix B

Space Division Multiple Access (SDMA) also known as:

- Multi User MIMO (MU MIMO)
- Virtual MIMO
- Collaborative MIMO

Beamforming

MIMO modes in LTE



-Tx diversity
-Beamforming
-Rx diversity

Better S/N

-Multi-User MIMO

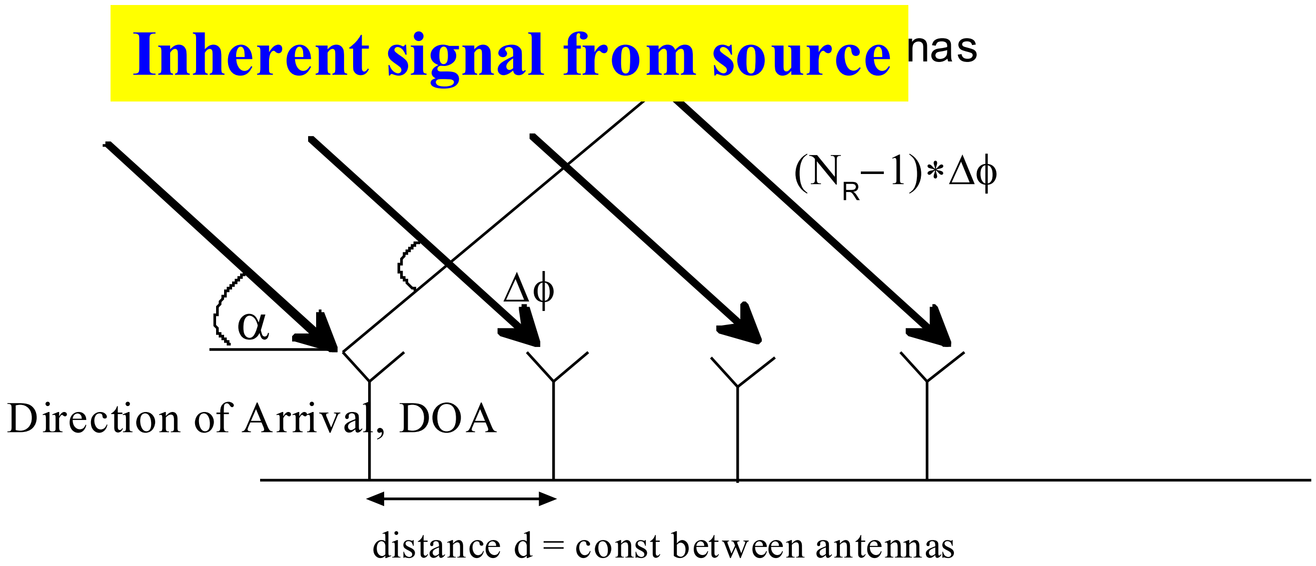
Increased Throughput at Node B

-Spatial Multiplexing

Increased Throughput per UE

Intelligent antennas

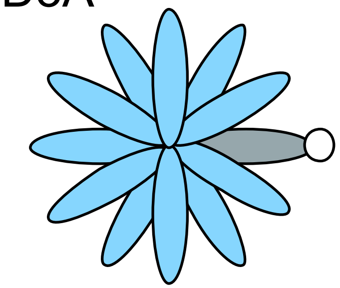
Principle of beamforming



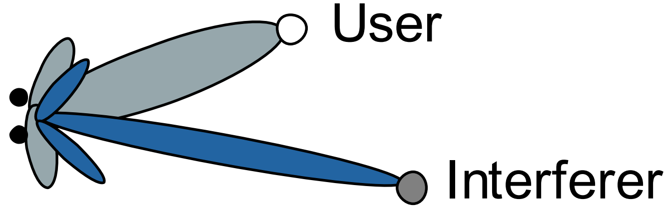
Beamforming due to phase shift of source signal at each receive antenna -> multiplication of Rx signal with steering vector to obtain directional beam

Different Beamforming Implementations

- **Switched Beamforming**
  - electrical calculation of DoA
  - switch one beam on



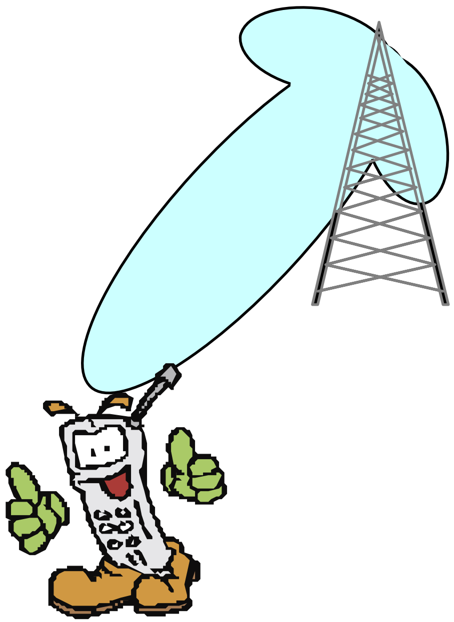
- **Adaptive Beamforming**
  - electrical calculation of DoA
  - steer a user specific beam



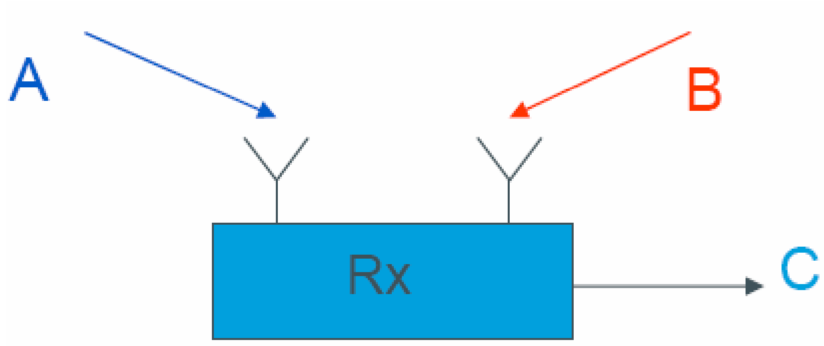
Beamforming increases S/N Ratio

- **Adaptive Beamforming**
  - Follows the User / User Group dynamically
  - Increases S/N Ratio
  - The Focus of the Beam is stronger with increasing number of antennas

But, beamforming in OFDM systems, has to be done on each subcarrier separately!

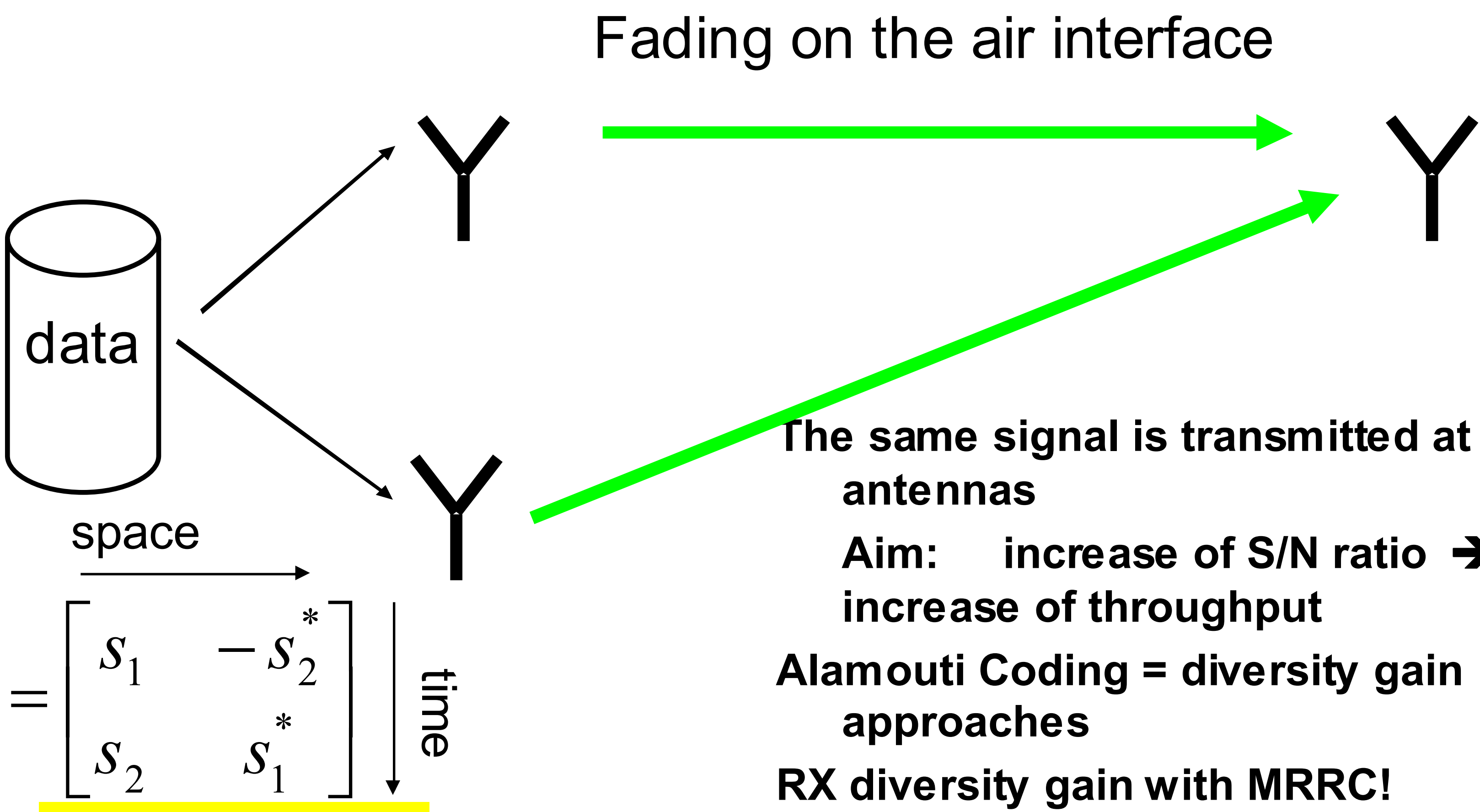


RX Diversity



Maximum Ratio Combining depends on different fading of the two received signals. In other words decorrelated fading channels

TX Diversity: Space Time Coding



$$S_2 = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix}$$

Alamouti Coding

The same signal is transmitted at differnet antennas

Aim: increase of S/N ratio ➔ increase of throughput

Alamouti Coding = diversity gain approaches

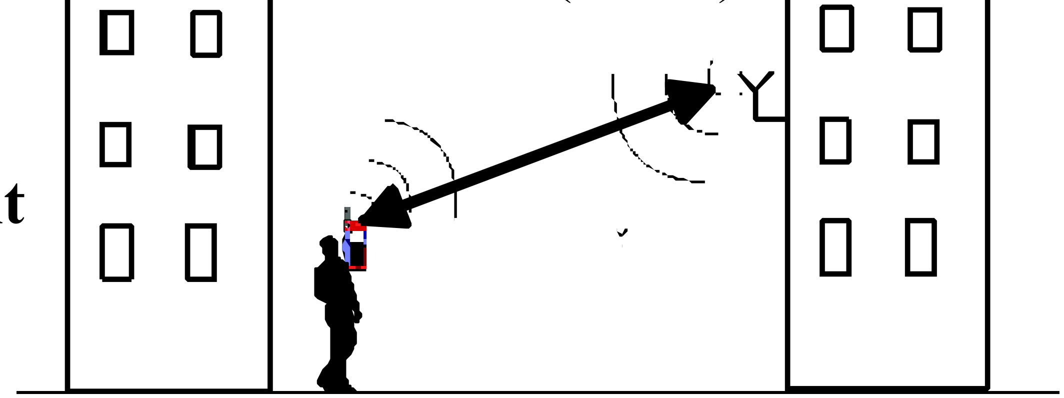
RX diversity gain with MRRC!

-> benefit for mobile communications

MIMO Spatial Multiplexing

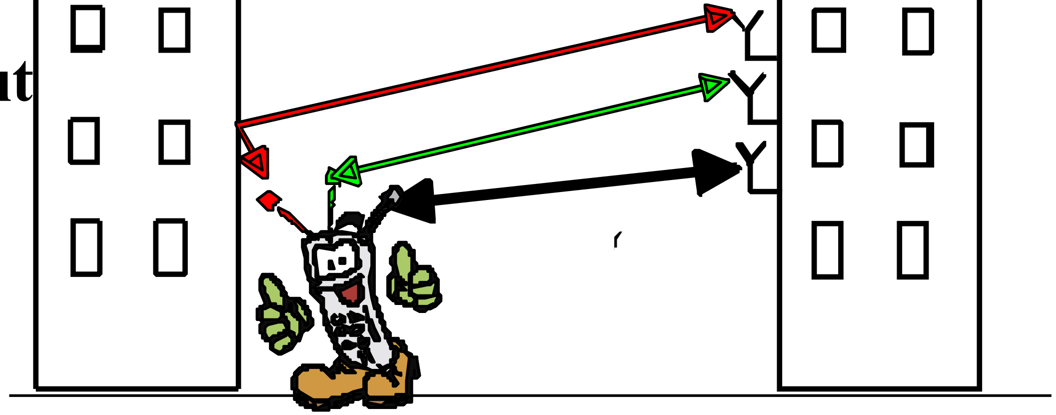
SISO:
Single Input
Single Output

$$C=B*T*ld(1+S/N)$$



MIMO:
Multiple Input
Multiple Output

$$C=\sum_{i=1}^{\min(N_T,N_R)} T \bullet B_i \bullet ld\,(1+\frac{S_i}{N_i})\ ?$$



Increasing capacity per cell

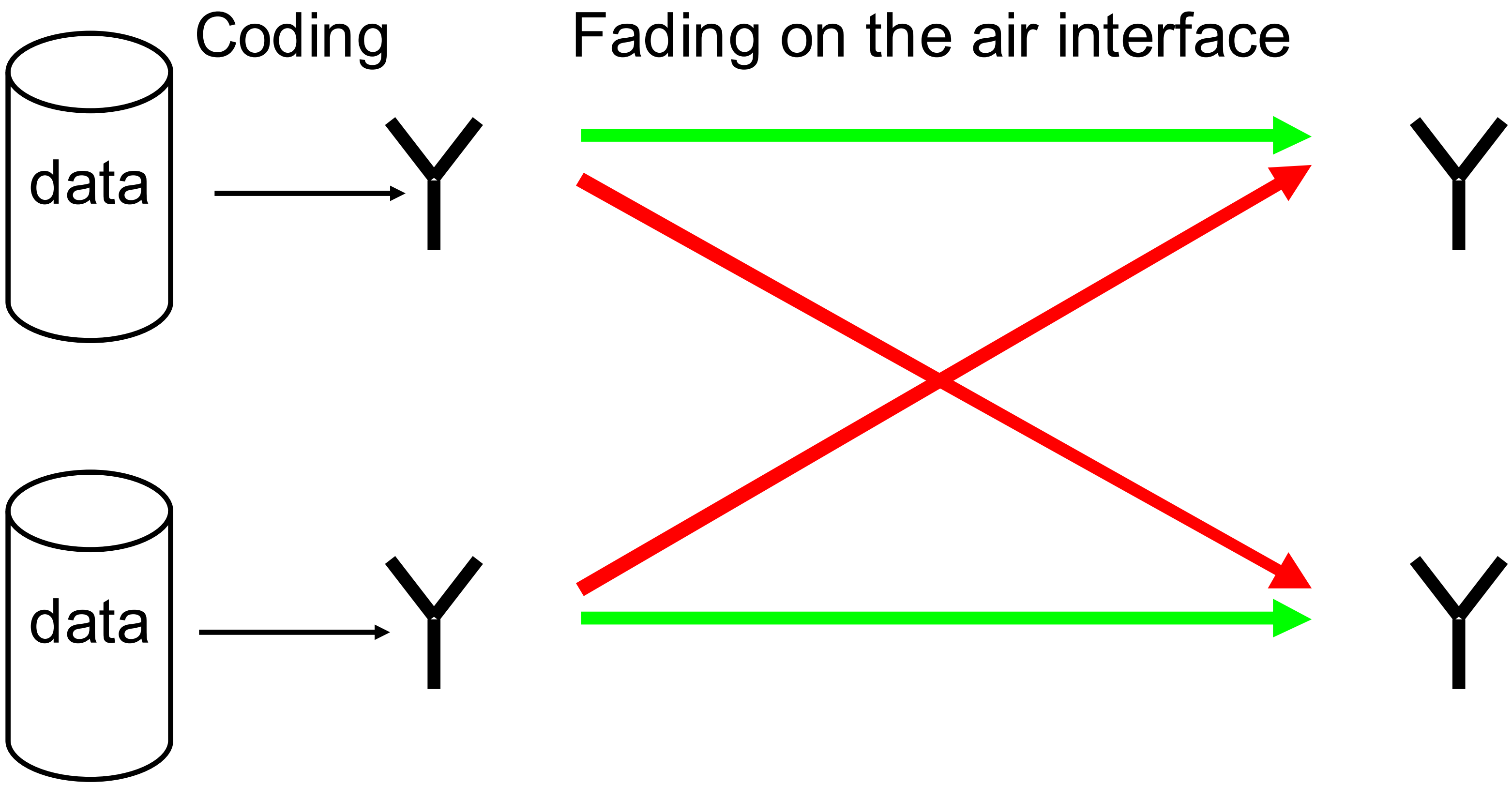
The MIMO promise

- **Channel capacity grows linearly with antennas ☺**

$$\text{Max Capacity} \sim \min(N_{TX}, N_{RX})$$

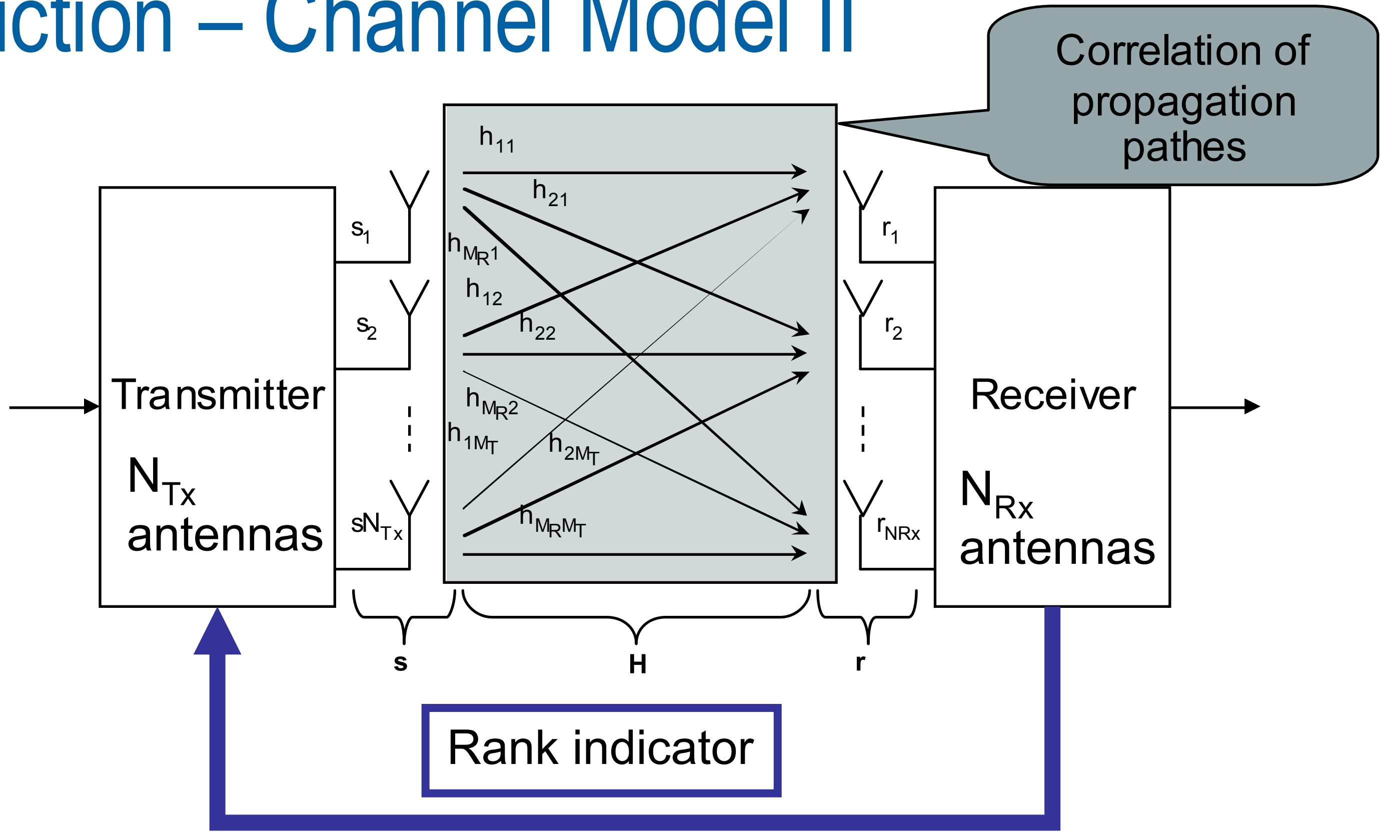
- **Assumptions ☹**
  - Perfect channel knowledge
  - Spatially uncorrelated fading
- **Reality 😐**
  - Imperfect channel knowledge
  - Correlation $\neq 0$ and rather unknown

Multiplexing



Throughput: **<200%**

Introduction – Channel Model II



Capacity ~ min(N_{TX}, N_{RX}) → max. possible rank!

But effective rank depends on channel, i.e. the correlation situation of H

MIMO: channel interference + precoding

MIMO channel models: different ways to combat against channel impact:

I.: Receiver cancels impact of channel

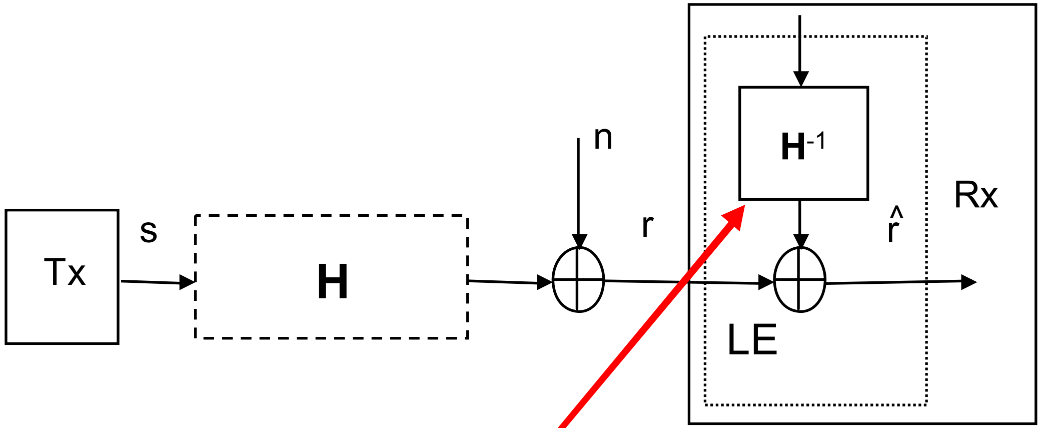
II.: Precoding by using codebook. Transmitter assists receiver in cancellation of channel impact

III.: Precoding at transmitter side to cancel channel impact

MIMO: Principle of linear equalizing

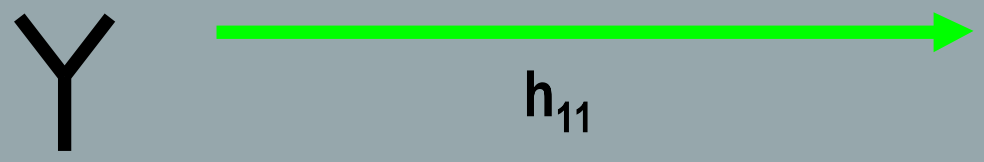
$$\boxed{R = S*H + n}$$

Transmitter will send reference signals or pilot sequence to enable receiver to estimate H.



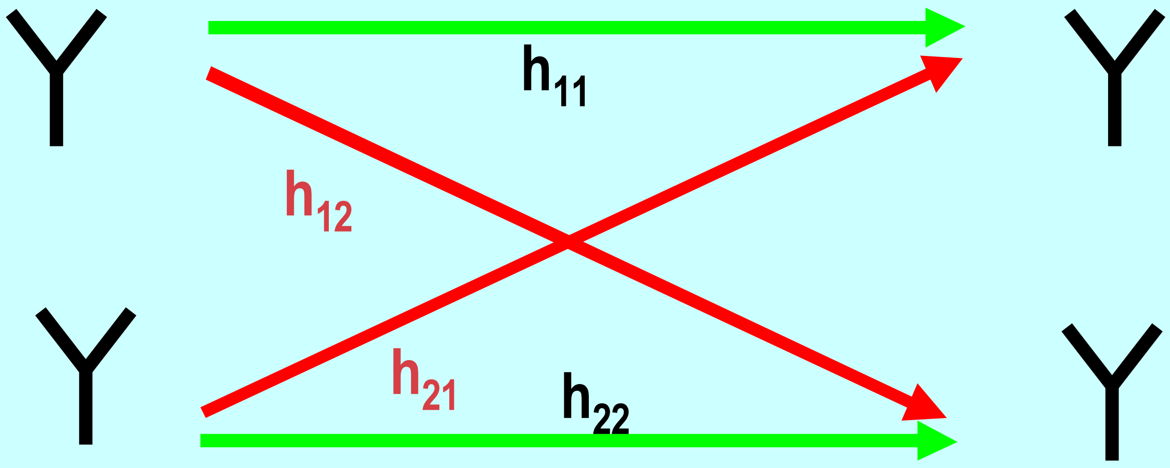
The receiver multiplies the signal r with the Hermetian conjugate complex of the transmitting function to eliminate the channel influence.

Linear equalization – compute power increase



$$H = h_{11}$$

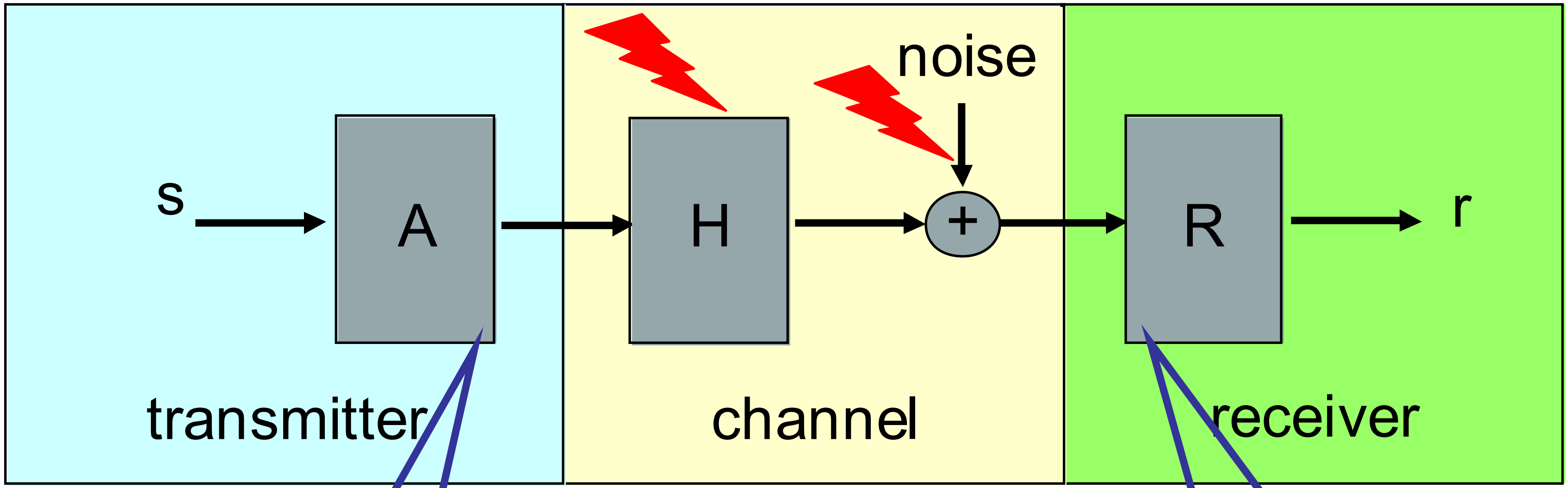
SISO: Equalizer has to estimate 1 channel



$$H = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix}$$

2x2 MIMO: Equalizer has to estimate 4 channels

transmission – reception model

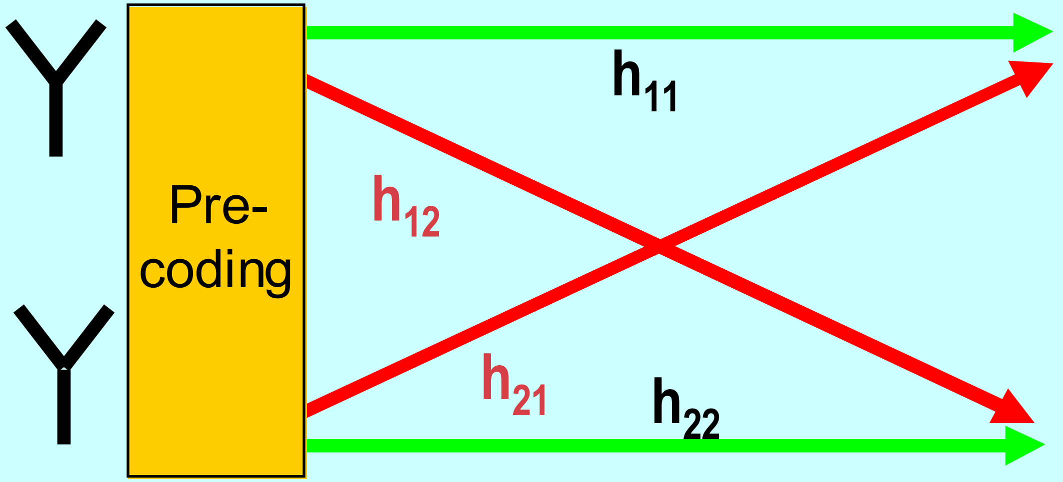


- Modulation,
- Power
- „precoding“,
- etc.

Linear equalization
at receiver is not
very efficient, i.e.
noise can not be cancelled

- detection,
- estimation
- Eliminating channel impact
- etc.

MIMO precoding introduction



$$r_1 = h_{11} \cdot s_1 + h_{21} \cdot s_2$$

$$r_2 = h_{12} \cdot s_1 + h_{22} \cdot s_2$$

Precoding = Transmitter changes the way how to transmit the signal to assist the receiver!

Current situation does not permit the proper receiption of both antennas!

Can be estimated due to reference signals

MIMO Precoding in LTE (DL)

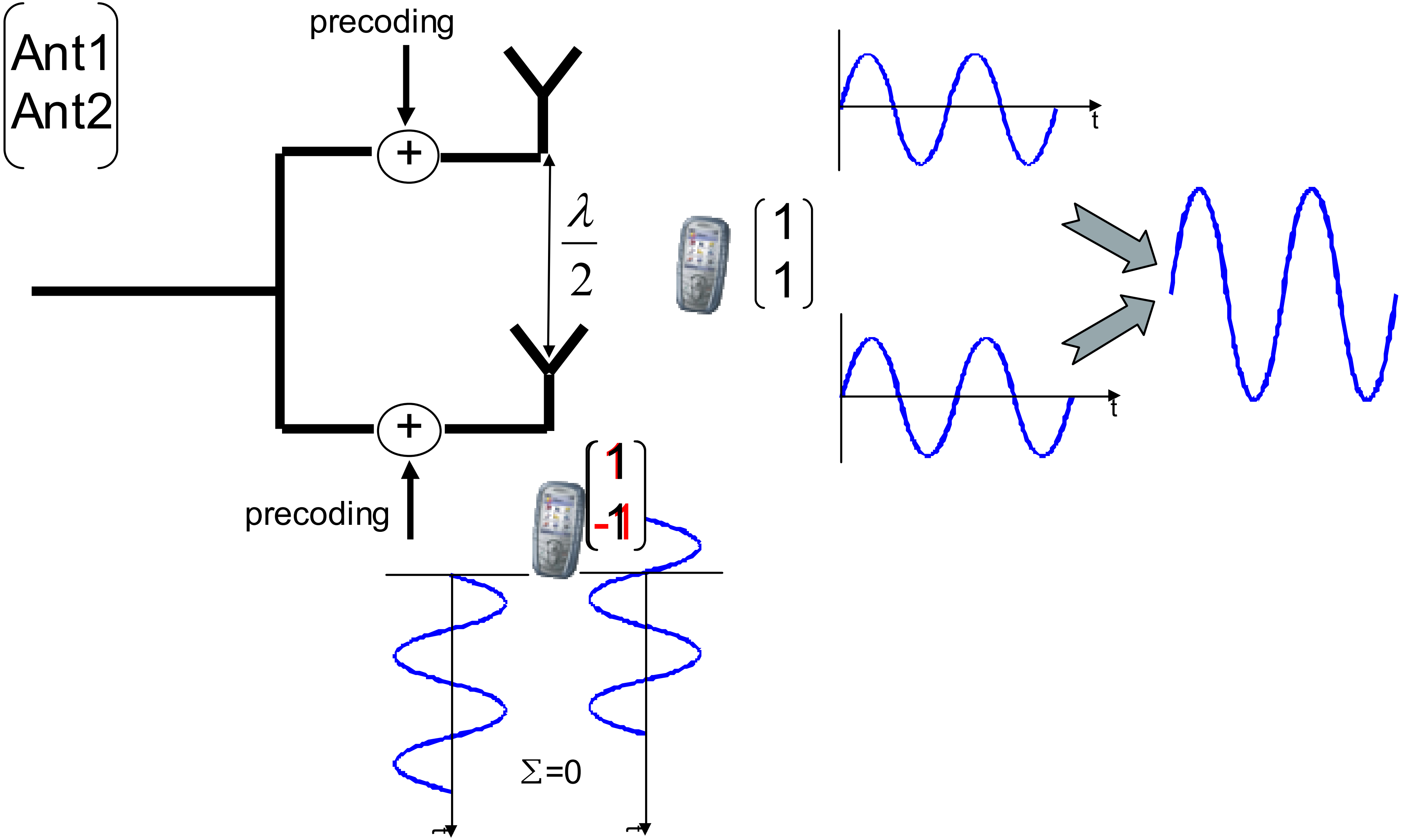
Spatial multiplexing – Code book for precoding

Code book for 2 Tx:

Codebook index	Number of layers υ 1	2
0	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$
1	$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$	$\frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ 1 \end{bmatrix}$	$\frac{1}{2}\begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}$
3	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -1 \end{bmatrix}$	-
4	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ j \end{bmatrix}$	-
5	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -j \end{bmatrix}$	-

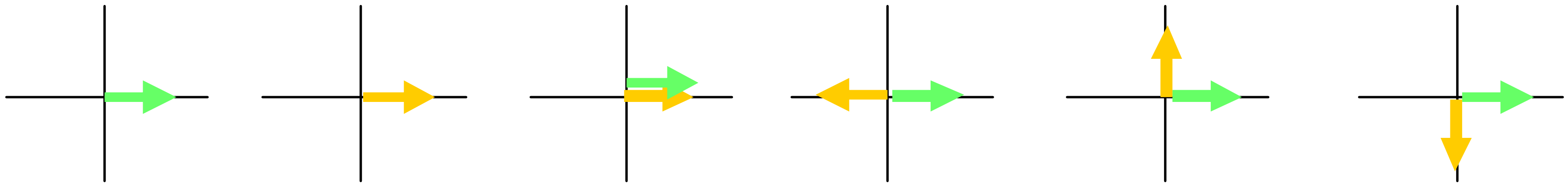
Additional multiplication of the layer symbols with codebook entry

MIMO precoding



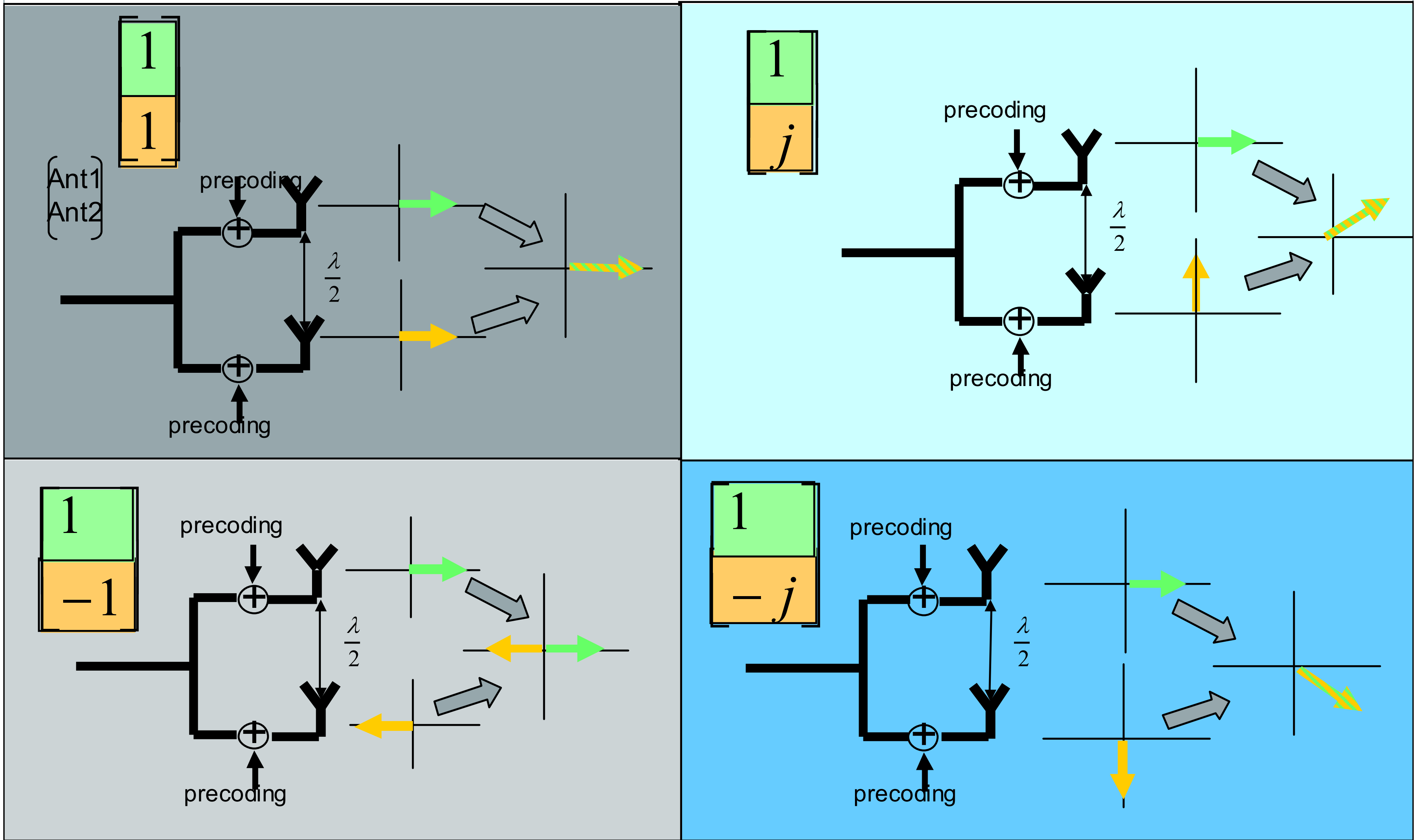
LTE precoding

$$\begin{bmatrix}1\\0\end{bmatrix} \quad \begin{bmatrix}0\\1\end{bmatrix} \quad \begin{bmatrix}1\\1\end{bmatrix} \quad \begin{bmatrix}1\\-1\end{bmatrix} \quad \begin{bmatrix}1\\j\end{bmatrix} \quad \begin{bmatrix}1\\-j\end{bmatrix}$$

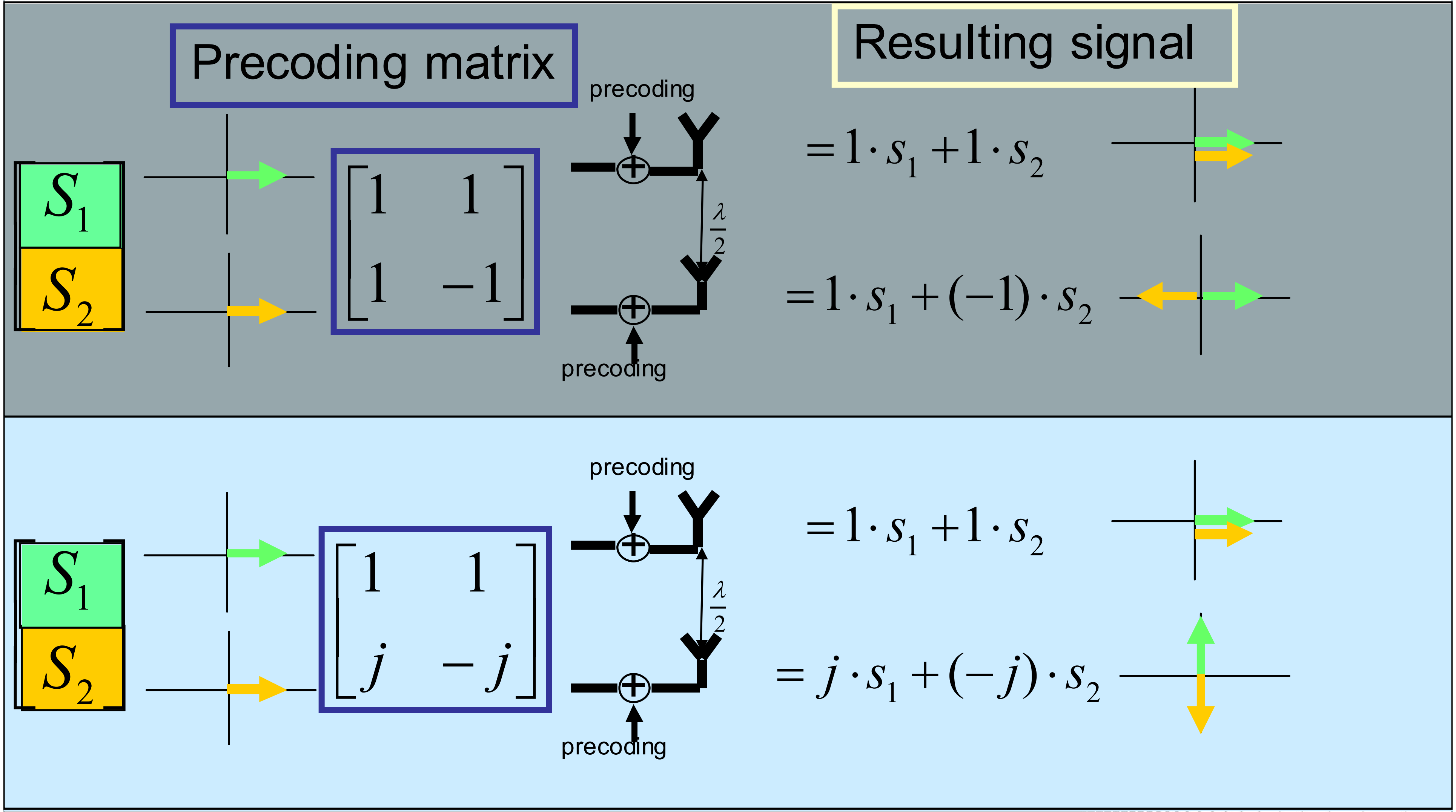


What does the codebook entry mean?

LTE precoding for 1 layer



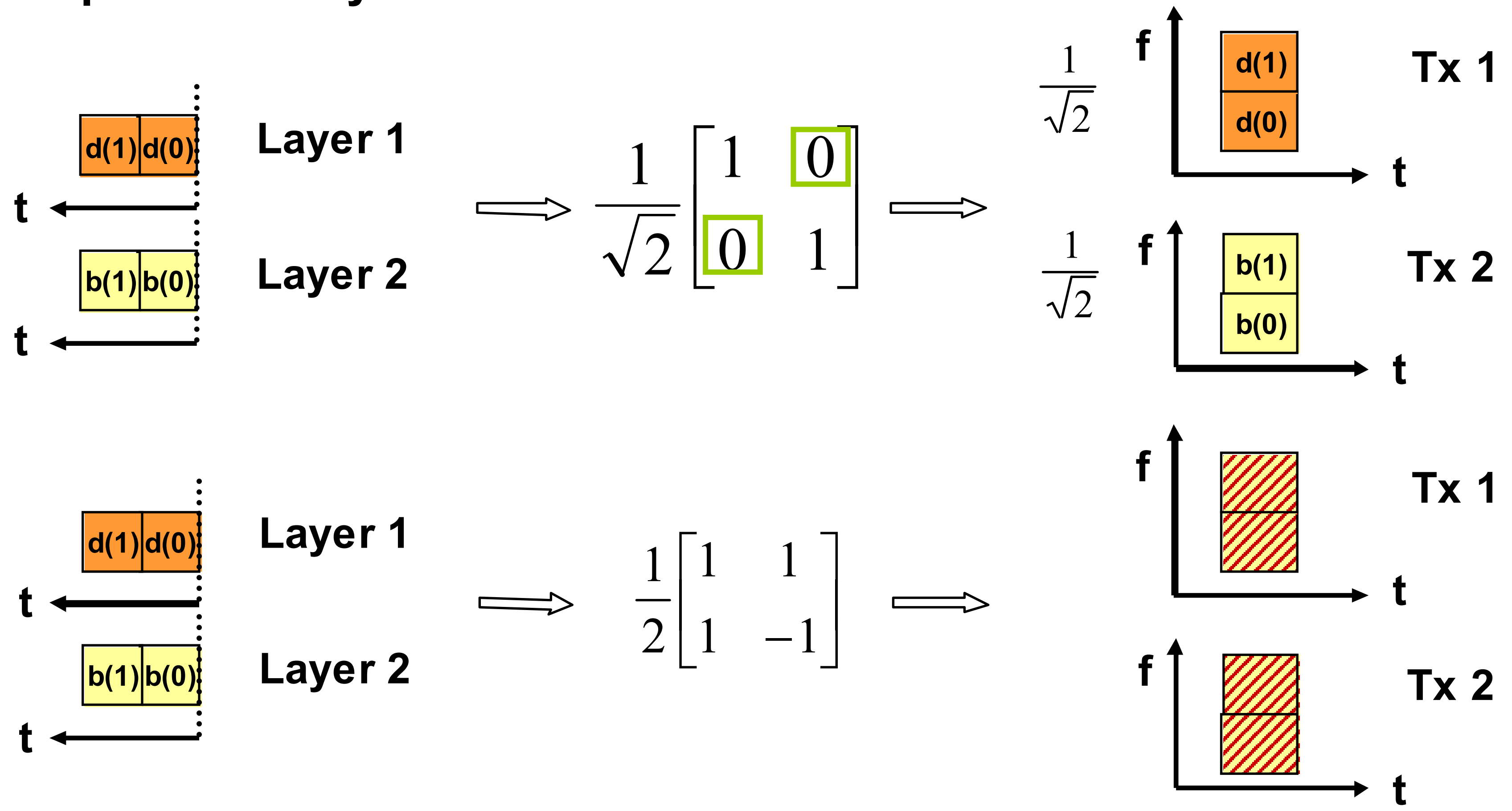
LTE precoding for 2 layers



MIMO Precoding in LTE (DL)

Spatial multiplexing – Code book for precoding

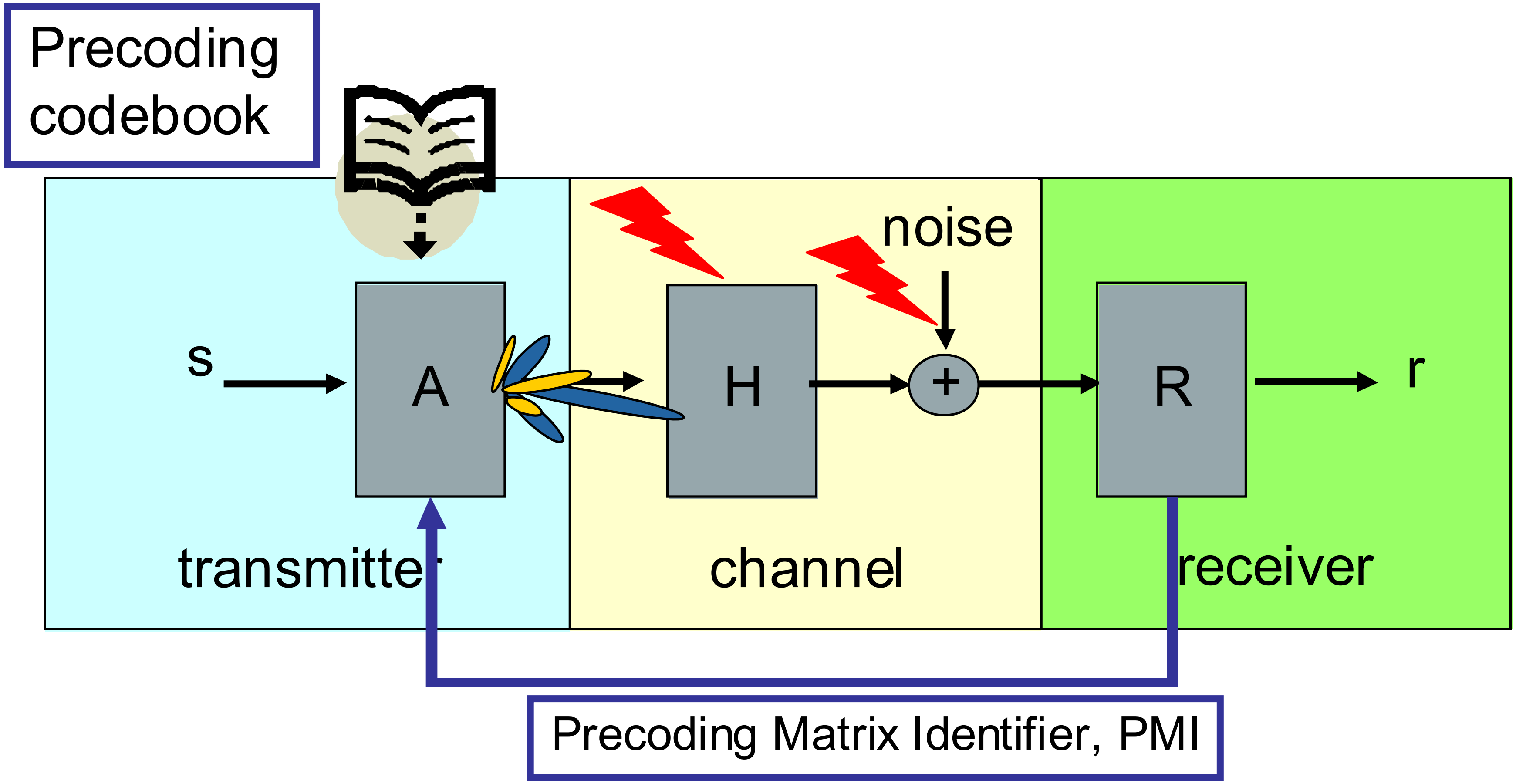
2 examples for 2 layers and 2 Tx antennas



$$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & \boxed{0} \\ \boxed{0} & 1 \end{bmatrix}$$

$$\frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

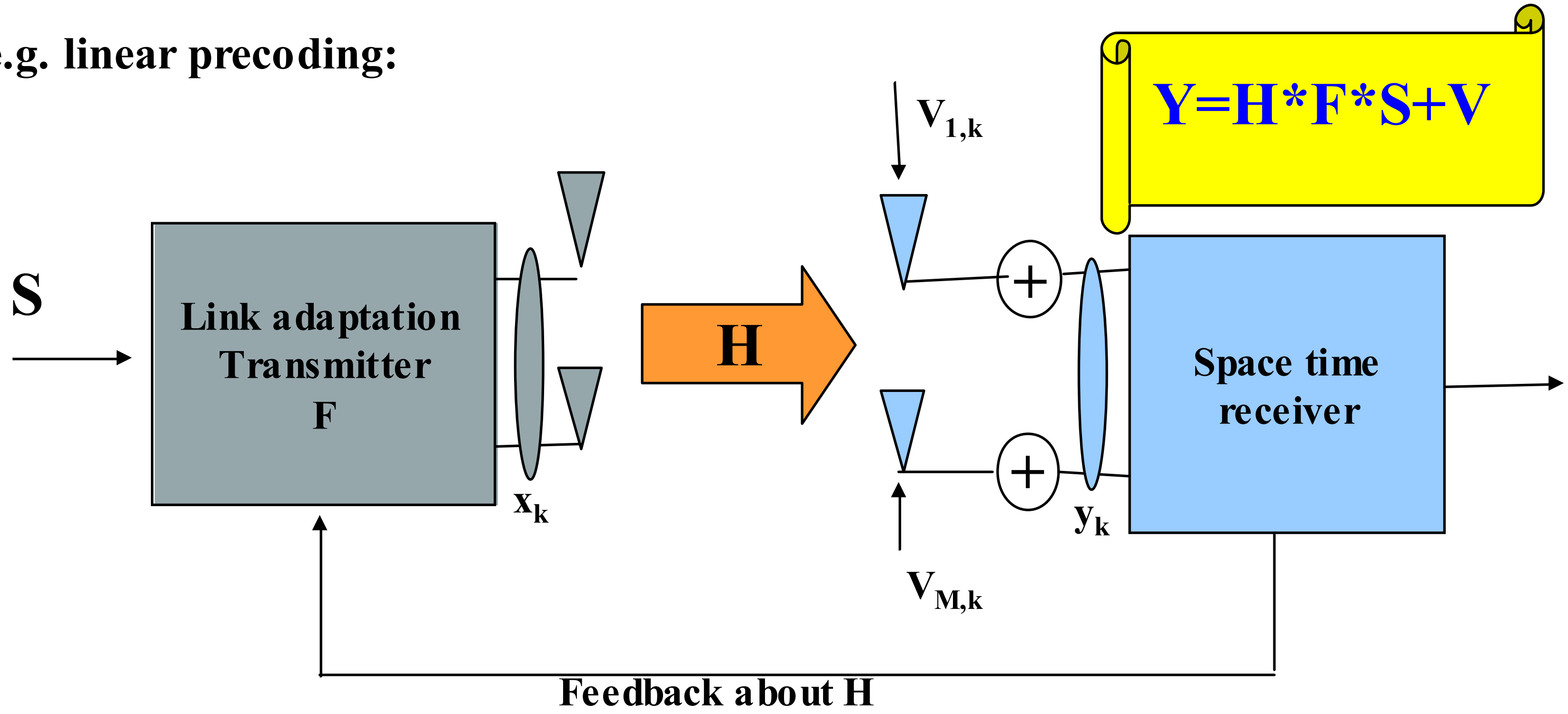
MIMO – codebook based precoding



Codebook based precoding creates some kind of „beamforming light“

MIMO: avoid inter-channel interference

e.g. linear precoding:

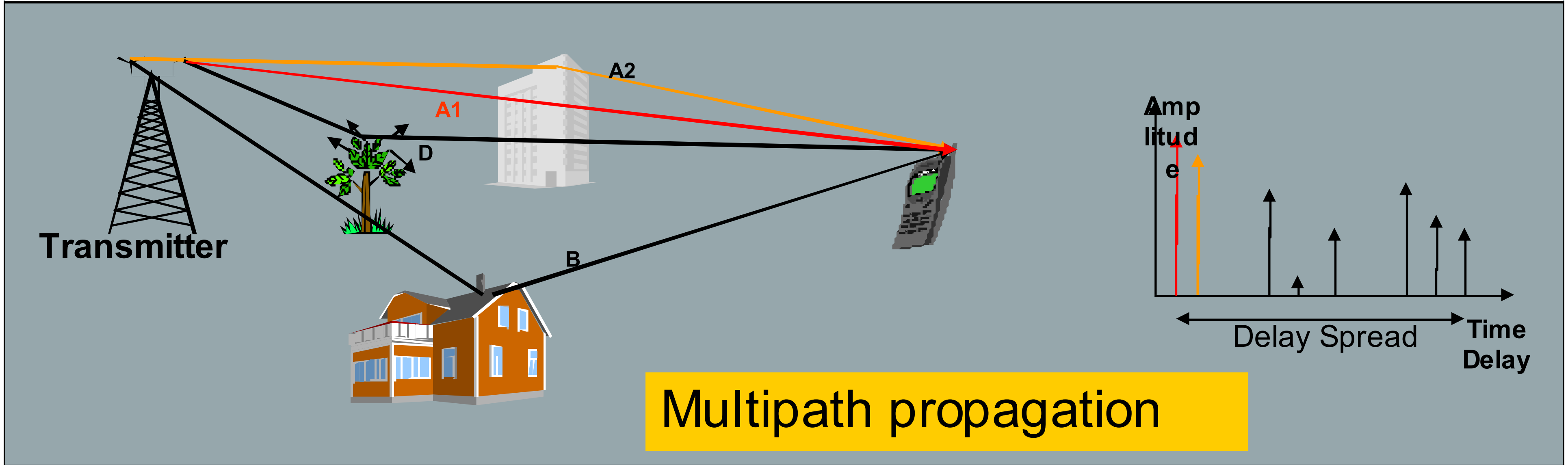


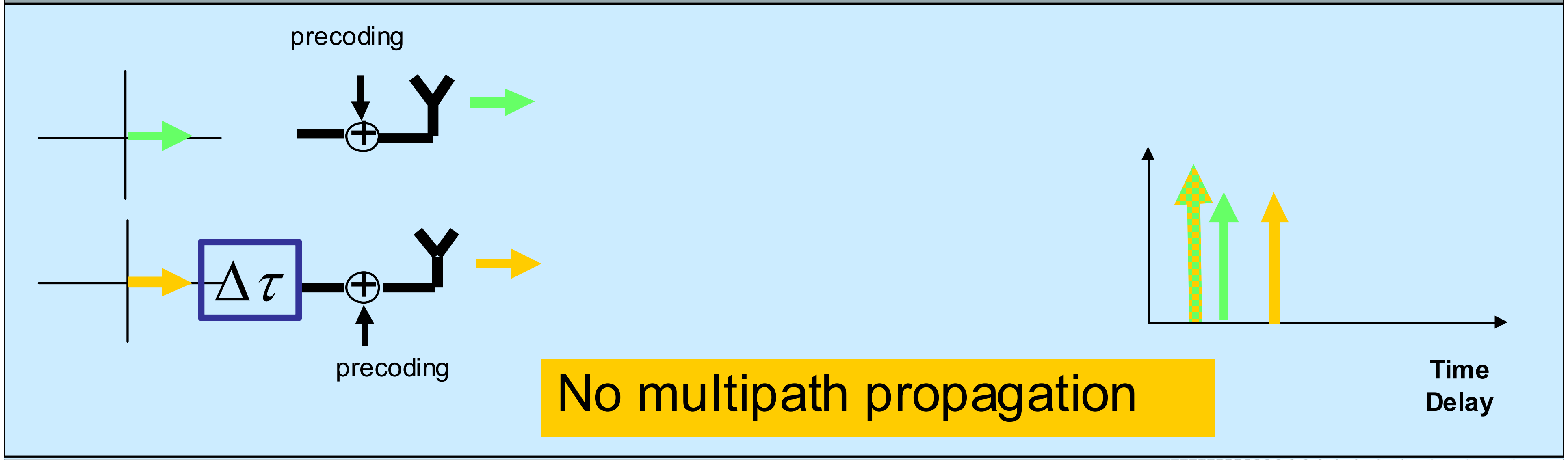
Idea: F adapts transmitted signal to current channel conditions

MAS: „Dirty Paper“ Coding

- **Multiple Antenna Signal Processing: „Known Interference“**
  - Is like NO interference
  - Analogy to writing on „dirty paper“ by changing ink color accordingly

Cyclic Delay Diversity, CDD





„Open loop“ und „closed loop“ MIMO

Open loop (No channel knowledge at transmitter)

$$r = Hs + n$$

Closed loop (With channel knowledge at transmitter

$$r = HWs + n$$

Adaptive Precoding matrix („Pre-equalisation“)

Feedback from receiver needed (closed loop)

MIMO transmission modes

Transmission mode1
SISO

Transmission mode2
TX diversity

Transmission mode3
Open-loop spatial multiplexing

Transmission mode4
Closed-loop spatial multiplexing

7 transmission modes are defined

Transmission mode7
SISO, port 5
= beamforming in TDD

Transmission mode5
Multi-User MIMO

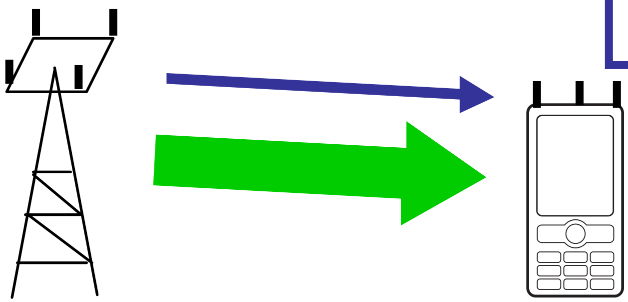
Transmission mode6
Closed-loop spatial multiplexing, using 1 layer

MIMO transmission modes

Transmission mode 1
SISO

the classic:
1Tx + 1RX
antenna

PDCCH indication via DCI format 1 or 1A



PDSCH transmission via single antenna port 0

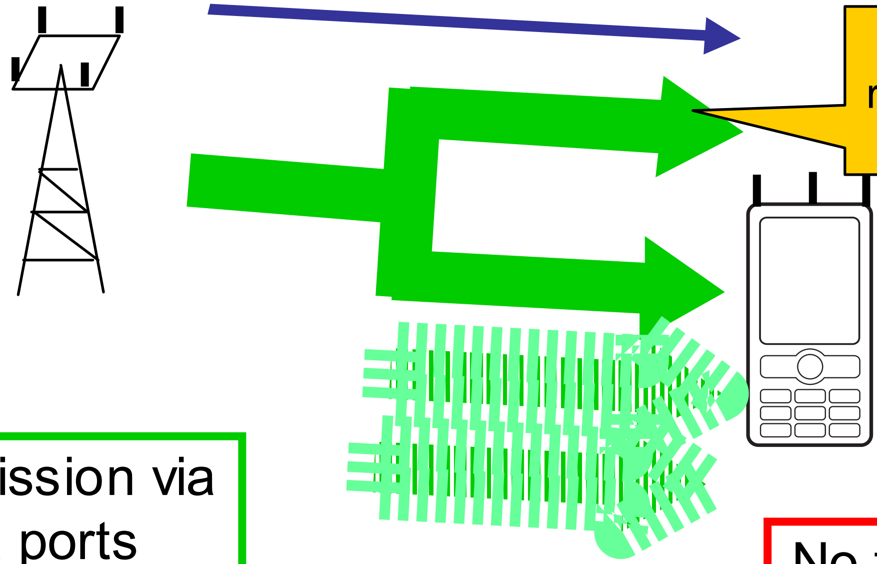
No feedback regarding antenna selection or precoding needed

MIMO transmission modes

Transmission mode 2
Transmit diversity

PDCCH indication via DCI format 1 or 1A

1 codeword



Codeword is sent redundantly over several streams

PDSCH transmission via 2 Or 4 antenna ports

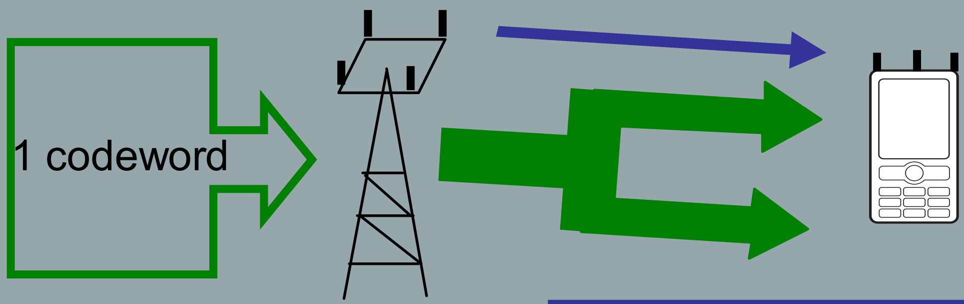
No feedback regarding antenna selection or precoding needed

MIMO transmission modes

Transmission mode 3
Transmit diversity or Open loop spatial multiplexing

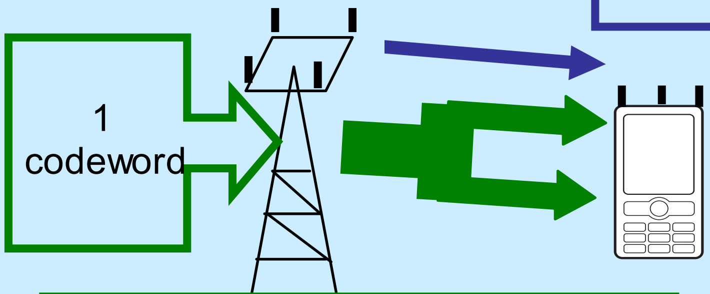
No feedback regarding antenna selection or precoding needed

PDCCH indication via DCI format 1A

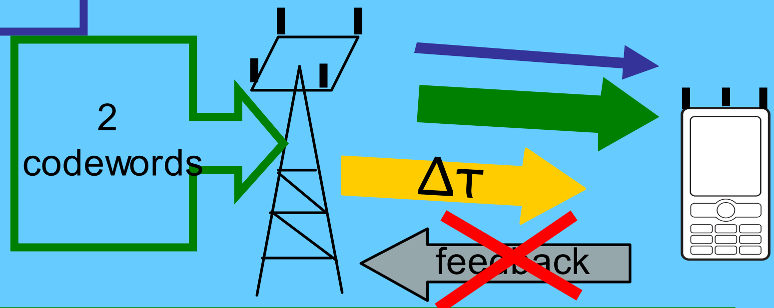


PDSCH transmission
Via 2 or 4 antenna ports

PDCCH indication via DCI format 2A



PDSCH transmission diversity

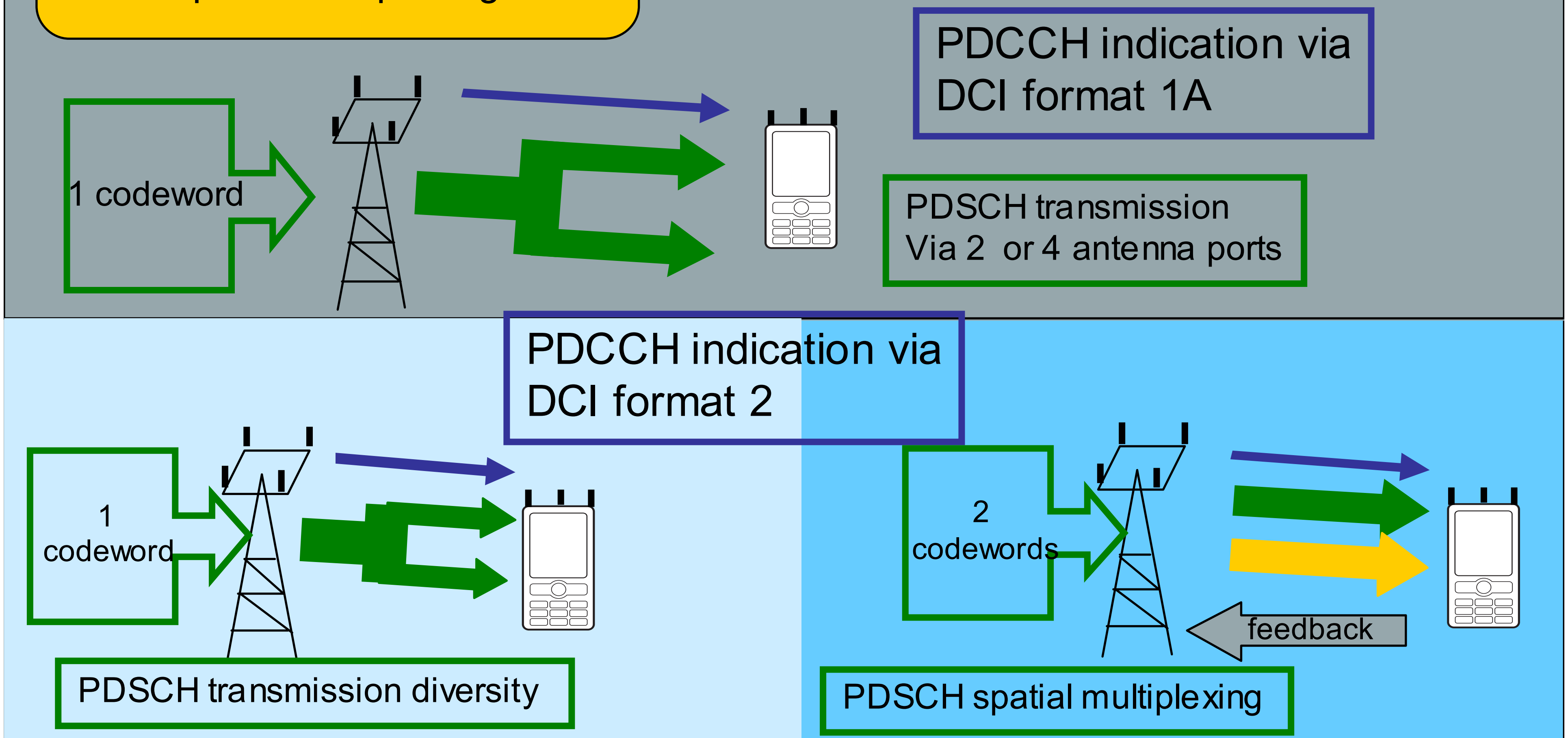


PDSCH spatial multiplexing, using CDD

MIMO transmission modes

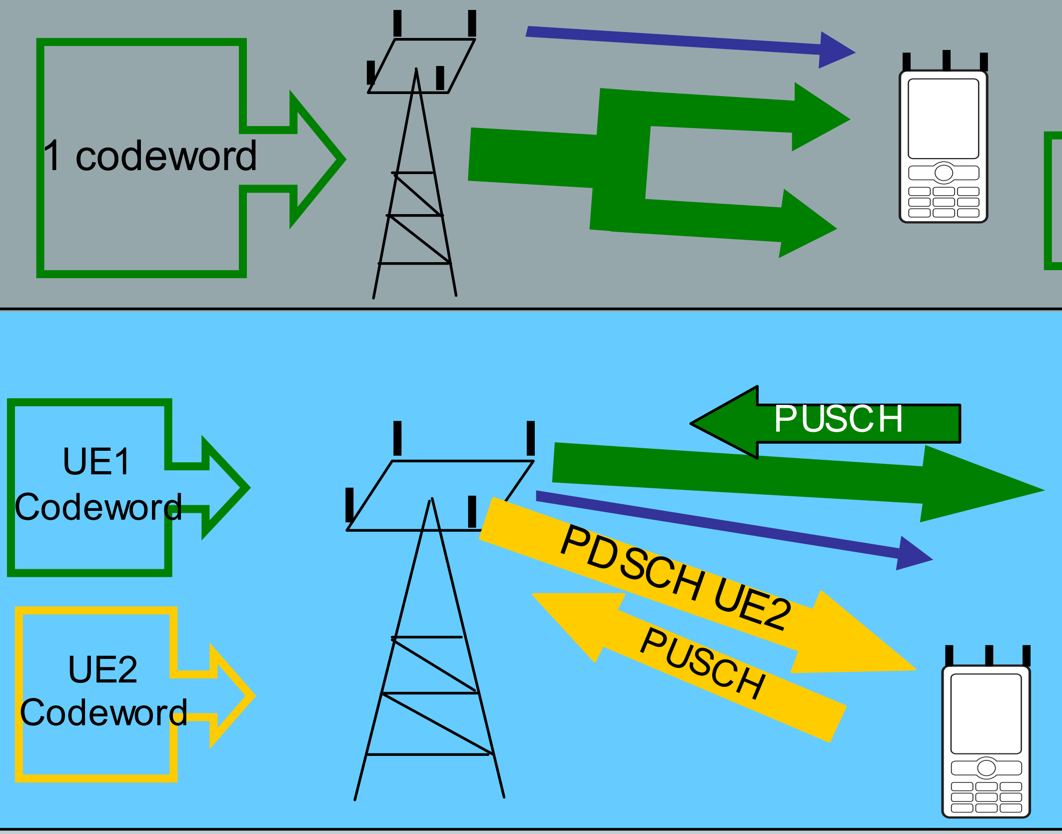
Transmission mode 4
Transmit diversity or Closed loop spatial multiplexing

Closed loop MIMO =
UE feedback needed regarding precoding and antenna selection



MIMO transmission modes

Transmission mode 5
Transmit diversity or
Multi User MIMO



PDCCH indication via DCI format 1A

PDSCH transmission
Via 2 or 4 antenna ports

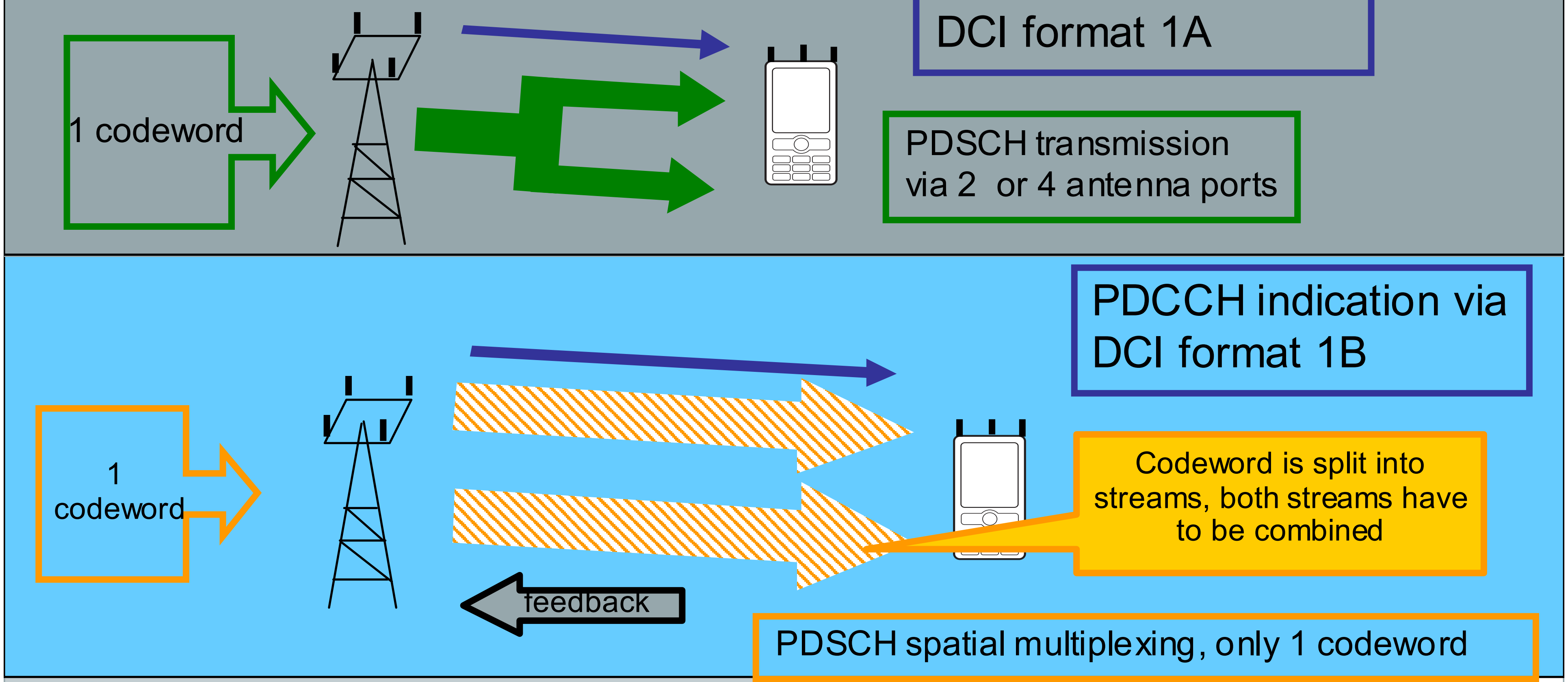
PDCCH indication via DCI format 1D

PDSCH multiplexing to several UEs.
PUSCH multiplexing in Uplink

MIMO transmission modes

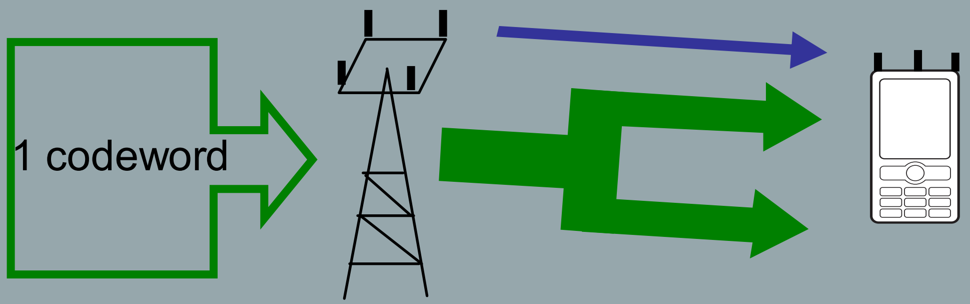
Closed loop MIMO =
UE feedback needed regarding precoding and antenna selection

Transmission mode 6
Transmit diversity or Closed loop spatial multiplexing with 1 layer



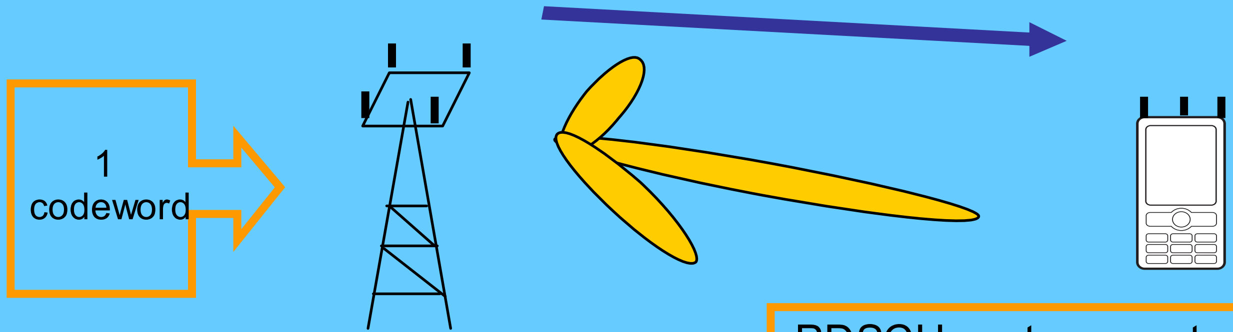
MIMO transmission modes

Transmission mode 7
Transmit diversity or beamforming



PDCCH indication via DCI format 1A

PDSCH transmission via 1, 2 or 4 antenna ports



PDCCH indication via DCI format 1

PDSCH sent over antenna port 5 = beamforming

Beamforming

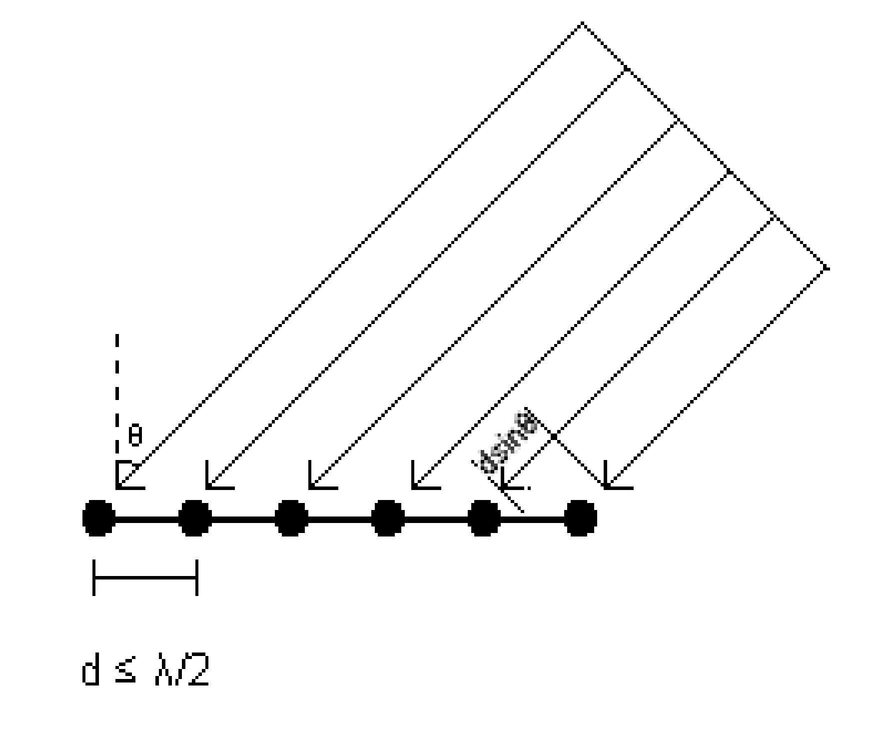
Adaptive Beamforming

- Classic way
- Antenna weights to adjust beam
- Directional characteristics
- Specific antenna array geometrie
- Dedicated pilots required

Closed loop precoded beamforming

- Kind of MISO with channel knowledge at transmitter
- Precoding based on feedback
- No specific antenna array geometrie
- Common pilots are sufficient

Adaptive Beamforming



$$s_0(t) = s(t)$$
$$s_1(t) = s(t-\tau) \approx s(t)e^{-j\theta}$$
$$s_1(t) = s(t-2\tau) \approx s(t)e^{-j2\theta}$$
$$s_1(t) = s(t-3\tau) \approx s(t)e^{-j3\theta}$$
$$\vdots$$
$$s_{M-1}(t) = s(t-(M-1)\tau) \approx s(t)e^{-j(M-1)\theta}$$

Signal at each antenna

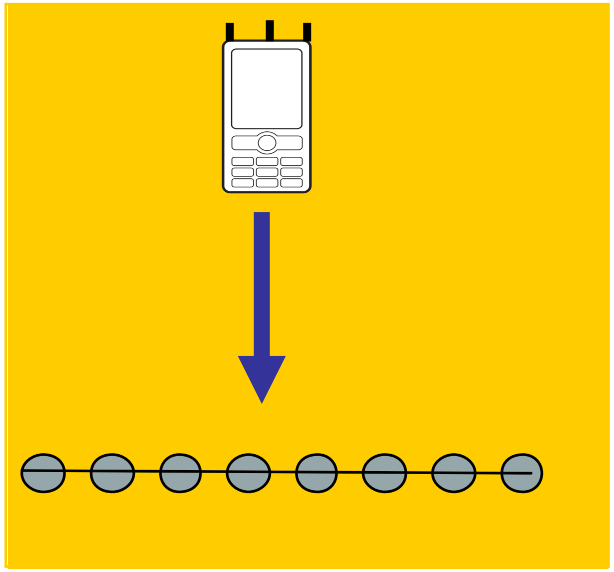
$$\boxed{\tau_i = \frac{(i-1)d\sin\theta}{c} = (i-1)\tau} \leftarrow \boxed{\tau = \frac{d\sin\theta}{c}}$$

Delay at each antenna

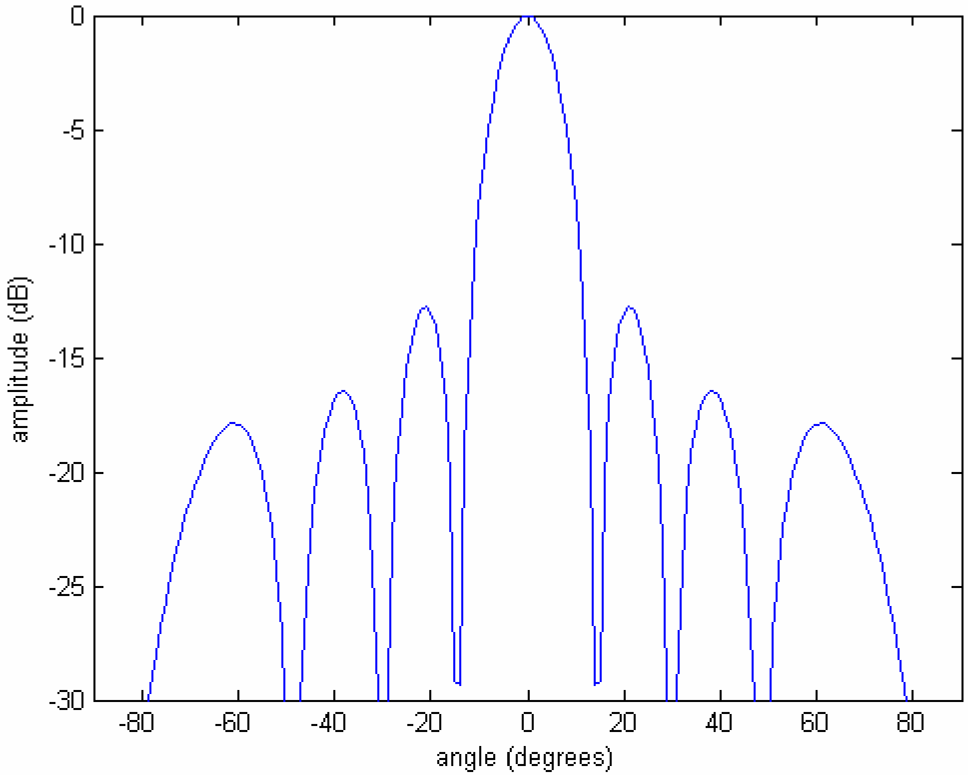
$$\mathbf{d}(t) = \begin{bmatrix} 1 \\ e^{-j\theta} \\ e^{-j2\theta} \\ e^{-j3\theta} \\ \vdots \\ e^{-j(M-1)\theta} \end{bmatrix} \cdot s(t) = \mathbf{a}(\theta) \cdot s(t),$$

Vector format

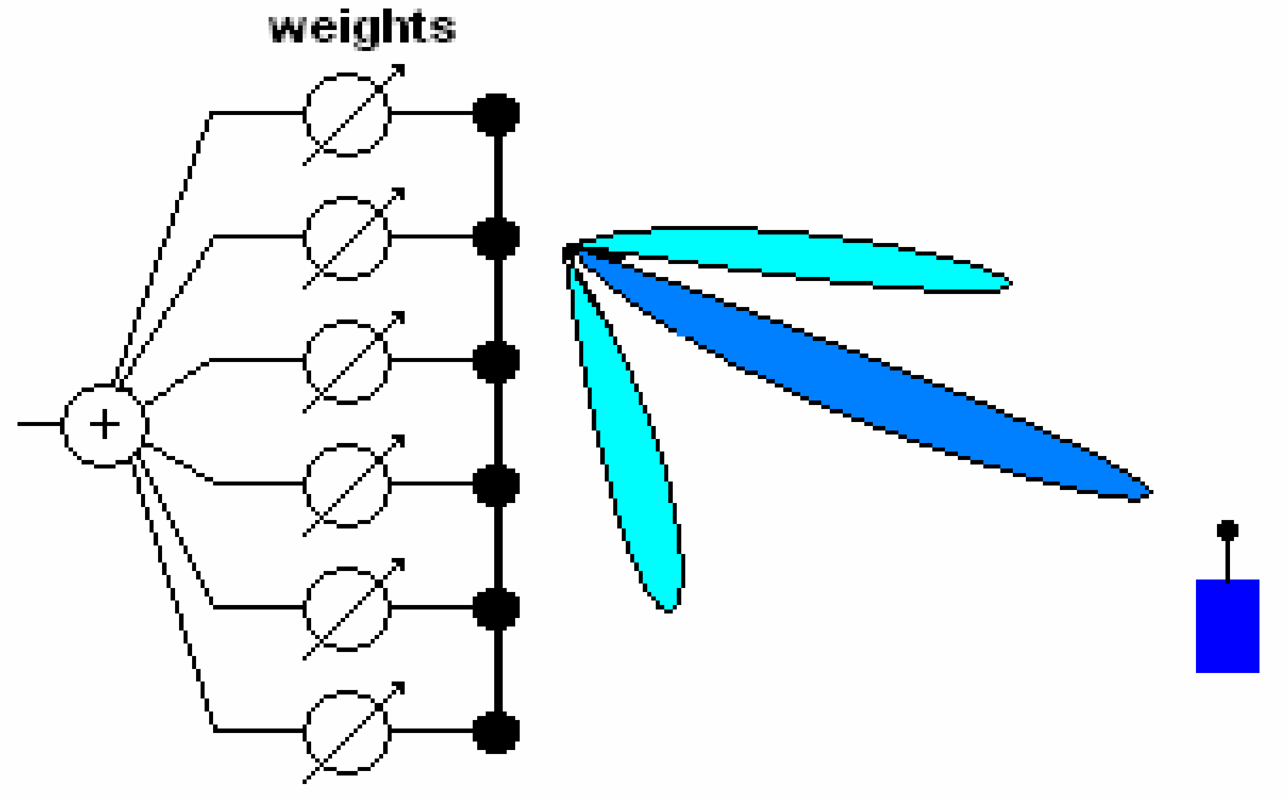
Adaptive Beamforming



Example:
8 antenna ULA,
Uniform antenna array



Adaptive Beamforming

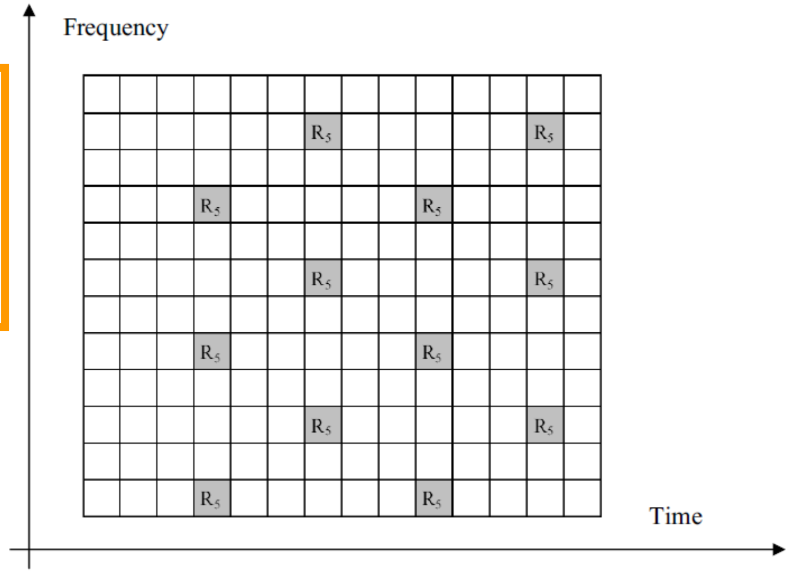


$$y(t) = \mathbf{w}^H \cdot \mathbf{d}(t) = \mathbf{w}^H \cdot \mathbf{a}(q) \cdot s(t),$$

Idea: Adding a weight vector and optimize e.g: $\mathbf{w}^H \cdot \mathbf{a}(q) = 1$

Adaptive beamforming

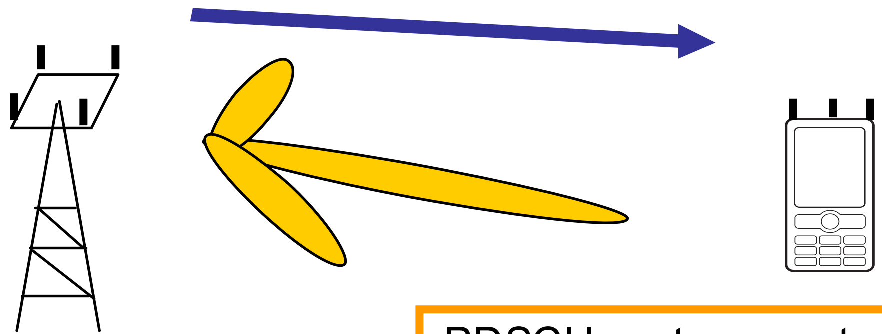
Node B sends
UE specific
Reference symbols



Transmission mode 7

PDCCH indication via
DCI format 1

1
codeword

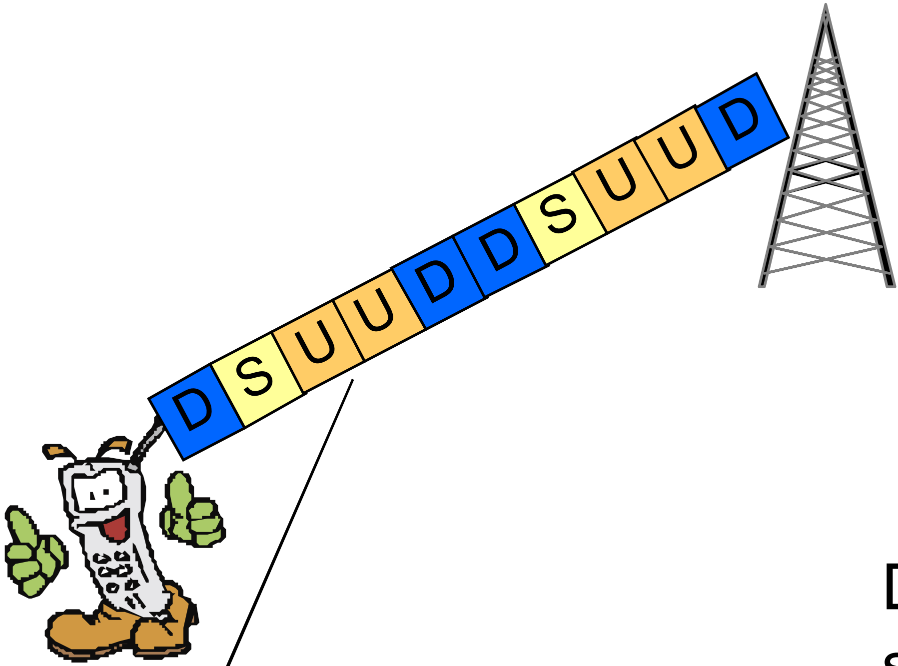


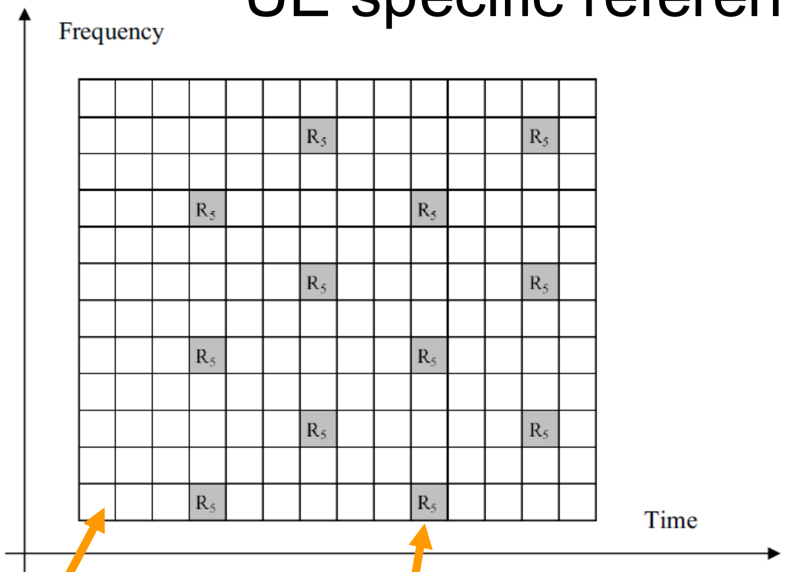
PDSCH sent over antenna port 5 = beamforming

Adaptive beamforming: transmission mode 7

Used only in TD-LTE mode

UE specific reference





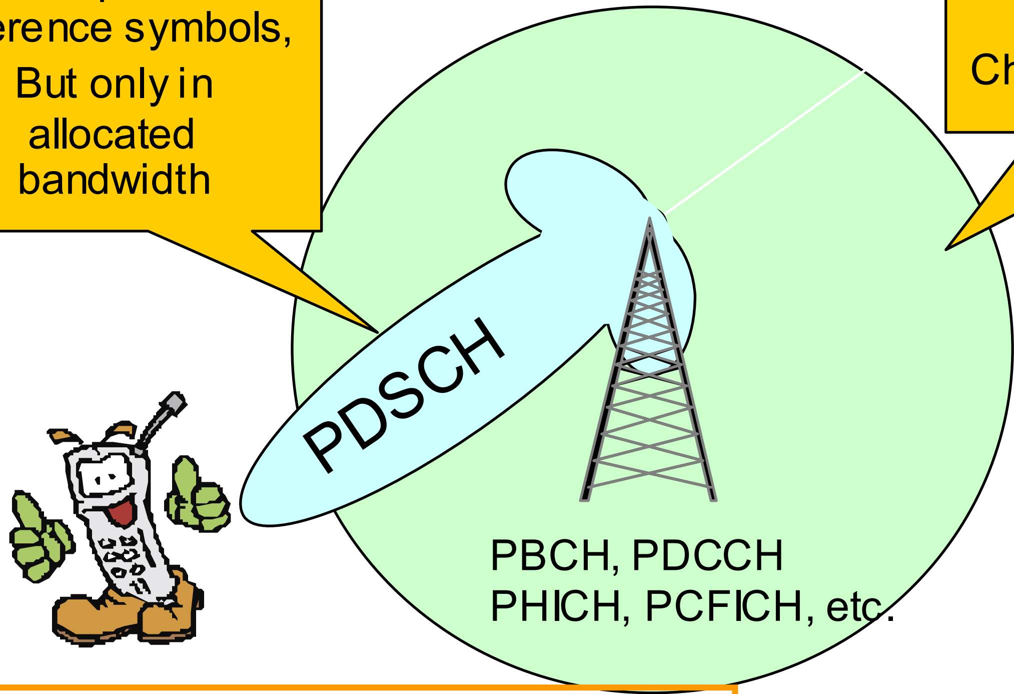
UL can be used by eNodeB for Channel Status Information inquiry

Data and reference symbols use the same precoding

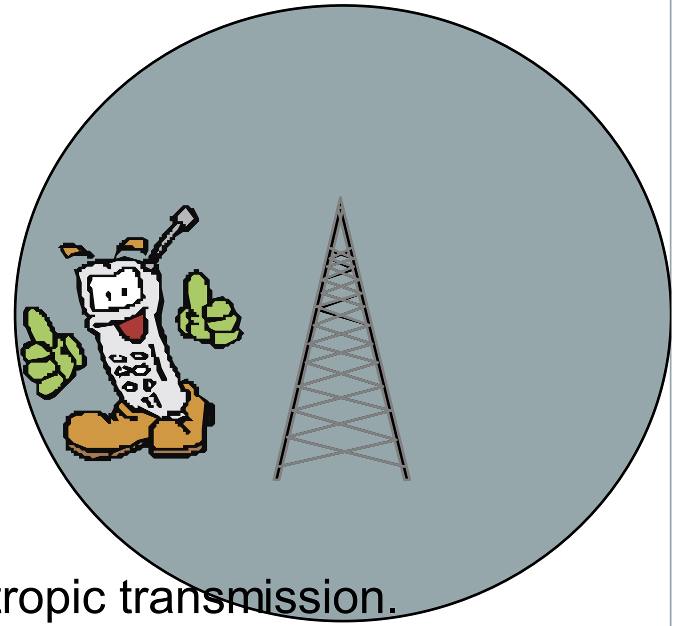
Adaptive beamforming. Transmission mode 7

UE specific reference symbols, But only in allocated bandwidth

eNode B sends common reference symbols for Channel status information



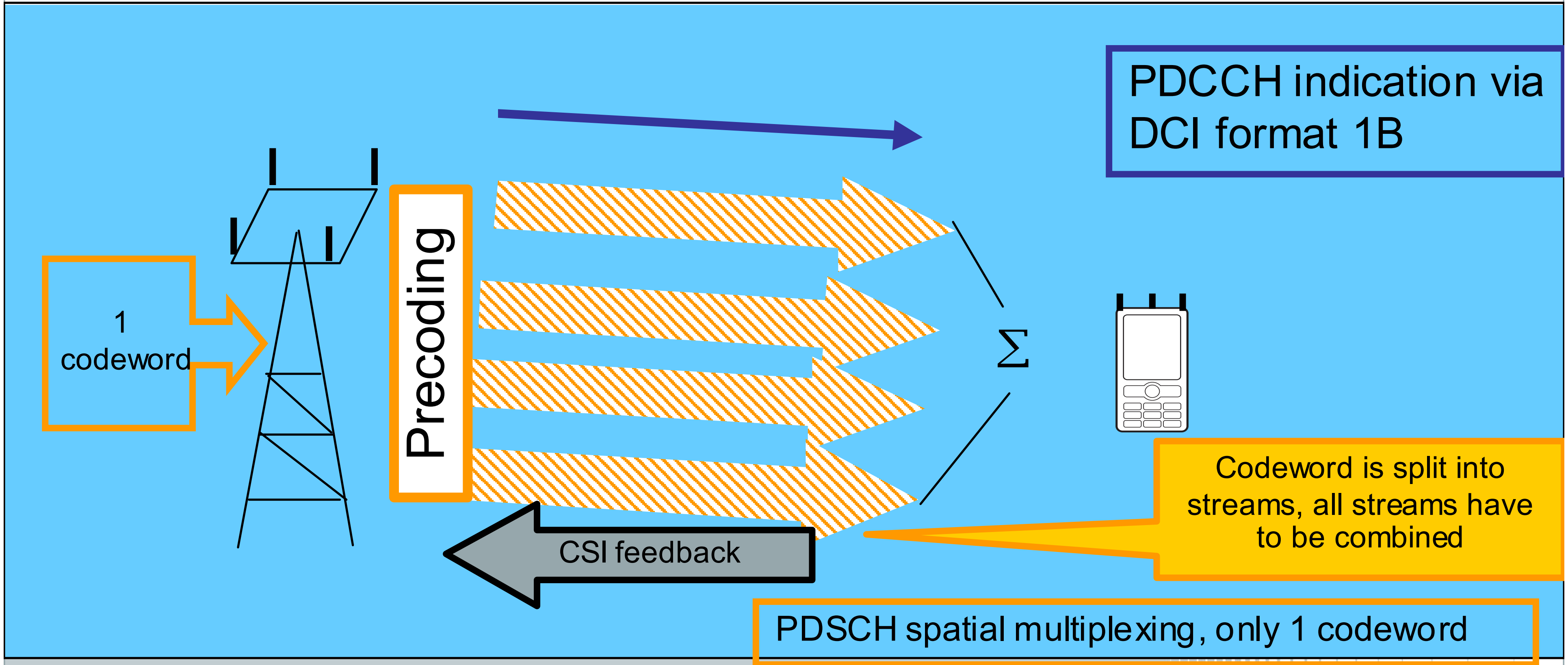
Antenna port 5 = from UE perspective, the eNode B looks like as only 1 antenna Transmits ☺



Here: isotropic transmission.
UE would not see difference between this and adaptive beamforming

Closed loop precoded beamforming

•UE has to send channel status information as feedback.
•Based on CSI, node B selects appropriate precoding matrix



Closed loop precoded beamforming

Codebook index	Number of layers υ	
	1	2
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 1\\j & -j\end{bmatrix}$
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	-

Possible precoding values for 1- 2 antennas

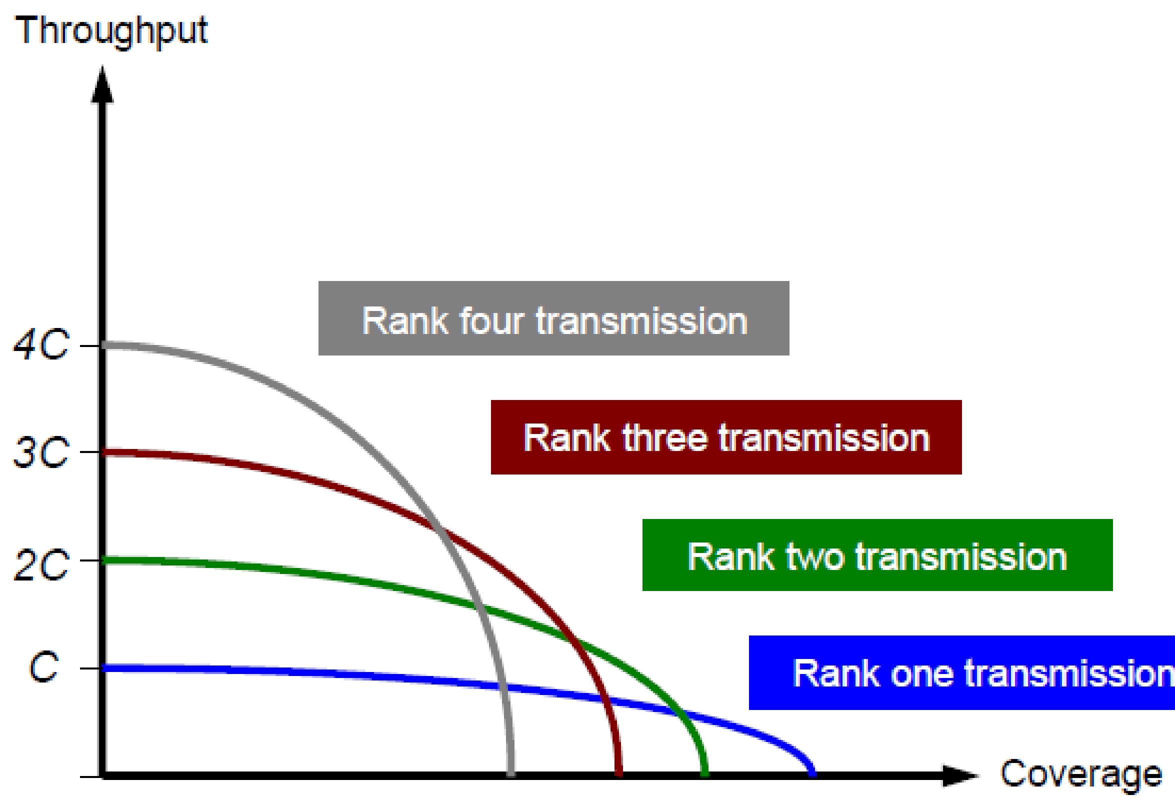
Closed loop precoded beamforming

Codebook index	u_n	Number of layers υ 1	2	3	4
0	$u_0 = [1 \quad -1 \quad -1 \quad -1]^T$	$W_0^{\{1\}}$	$W_0^{\{14\}}/\sqrt{2}$	$W_0^{\{124\}}/\sqrt{3}$	$W_0^{\{1234\}}/2$
1	$u_1 = [1 \quad -j \quad 1 \quad j]^T$	$W_1^{\{1\}}$	$W_1^{\{12\}}/\sqrt{2}$	$W_1^{\{123\}}/\sqrt{3}$	$W_1^{\{1234\}}/2$
2	$u_2 = [1 \quad 1 \quad -1 \quad 1]^T$	$W_2^{\{1\}}$	$W_2^{\{12\}}/\sqrt{2}$	$W_2^{\{123\}}/\sqrt{3}$	$W_2^{\{3214\}}/2$
3	$u_3 = [1 \quad j \quad 1 \quad -j]^T$	$W_3^{\{1\}}$	$W_3^{\{12\}}/\sqrt{2}$	$W_3^{\{123\}}/\sqrt{3}$	$W_3^{\{3214\}}/2$
4	$u_4 = [1 \quad (-1-j)/\sqrt{2} \quad -j \quad (1-j)/\sqrt{2}]^T$	$W_4^{\{1\}}$	$W_4^{\{14\}}/\sqrt{2}$	$W_4^{\{124\}}/\sqrt{3}$	$W_4^{\{1234\}}/2$
5	$u_5 = [1 \quad (1-j)/\sqrt{2} \quad j \quad (-1-j)/\sqrt{2}]^T$	$W_5^{\{1\}}$	$W_5^{\{14\}}/\sqrt{2}$	$W_5^{\{124\}}/\sqrt{3}$	$W_5^{\{1234\}}/2$
6	$u_6 = [1 \quad (1+j)/\sqrt{2} \quad -j \quad (-1+j)/\sqrt{2}]^T$	$W_6^{\{1\}}$	$W_6^{\{13\}}/\sqrt{2}$	$W_6^{\{134\}}/\sqrt{3}$	$W_6^{\{1324\}}/2$
7	$u_7 = [1 \quad (-1+j)/\sqrt{2} \quad j \quad (1+j)/\sqrt{2}]^T$	$W_7^{\{1\}}$	$W_7^{\{13\}}/\sqrt{2}$	$W_7^{\{134\}}/\sqrt{3}$	$W_7^{\{1324\}}/2$
8	$u_8 = [1 \quad -1 \quad 1 \quad 1]^T$	$W_8^{\{1\}}$	$W_8^{\{12\}}/\sqrt{2}$	$W_8^{\{124\}}/\sqrt{3}$	$W_8^{\{1234\}}/2$
9	$u_9 = [1 \quad -j \quad -1 \quad -j]^T$	$W_9^{\{1\}}$	$W_9^{\{14\}}/\sqrt{2}$	$W_9^{\{134\}}/\sqrt{3}$	$W_9^{\{1234\}}/2$
10	$u_{10} = [1 \quad 1 \quad 1 \quad -1]^T$	$W_{10}^{\{1\}}$	$W_{10}^{\{13\}}/\sqrt{2}$	$W_{10}^{\{123\}}/\sqrt{3}$	$W_{10}^{\{1324\}}/2$
11	$u_{11} = [1 \quad j \quad -1 \quad j]^T$	$W_{11}^{\{1\}}$	$W_{11}^{\{13\}}/\sqrt{2}$	$W_{11}^{\{134\}}/\sqrt{3}$	$W_{11}^{\{1324\}}/2$
12	$u_{12} = [1 \quad -1 \quad -1 \quad 1]^T$	$W_{12}^{\{1\}}$	$W_{12}^{\{12\}}/\sqrt{2}$	$W_{12}^{\{123\}}/\sqrt{3}$	$W_{12}^{\{1234\}}/2$
13	$u_{13} = [1 \quad -1 \quad 1 \quad -1]^T$	$W_{13}^{\{1\}}$	$W_{13}^{\{13\}}/\sqrt{2}$	$W_{13}^{\{123\}}/\sqrt{3}$	$W_{13}^{\{1324\}}/2$
14	$u_{14} = [1 \quad 1 \quad -1 \quad -1]^T$	$W_{14}^{\{1\}}$	$W_{14}^{\{13\}}/\sqrt{2}$	$W_{14}^{\{123\}}/\sqrt{3}$	$W_{14}^{\{3214\}}/2$
15	$u_{15} = [1 \quad 1 \quad 1 \quad 1]^T$	$W_{15}^{\{1\}}$	$W_{15}^{\{12\}}/\sqrt{2}$	$W_{15}^{\{123\}}/\sqrt{3}$	$W_{15}^{\{1234\}}/2$

Possible precoding values for 4 antennas

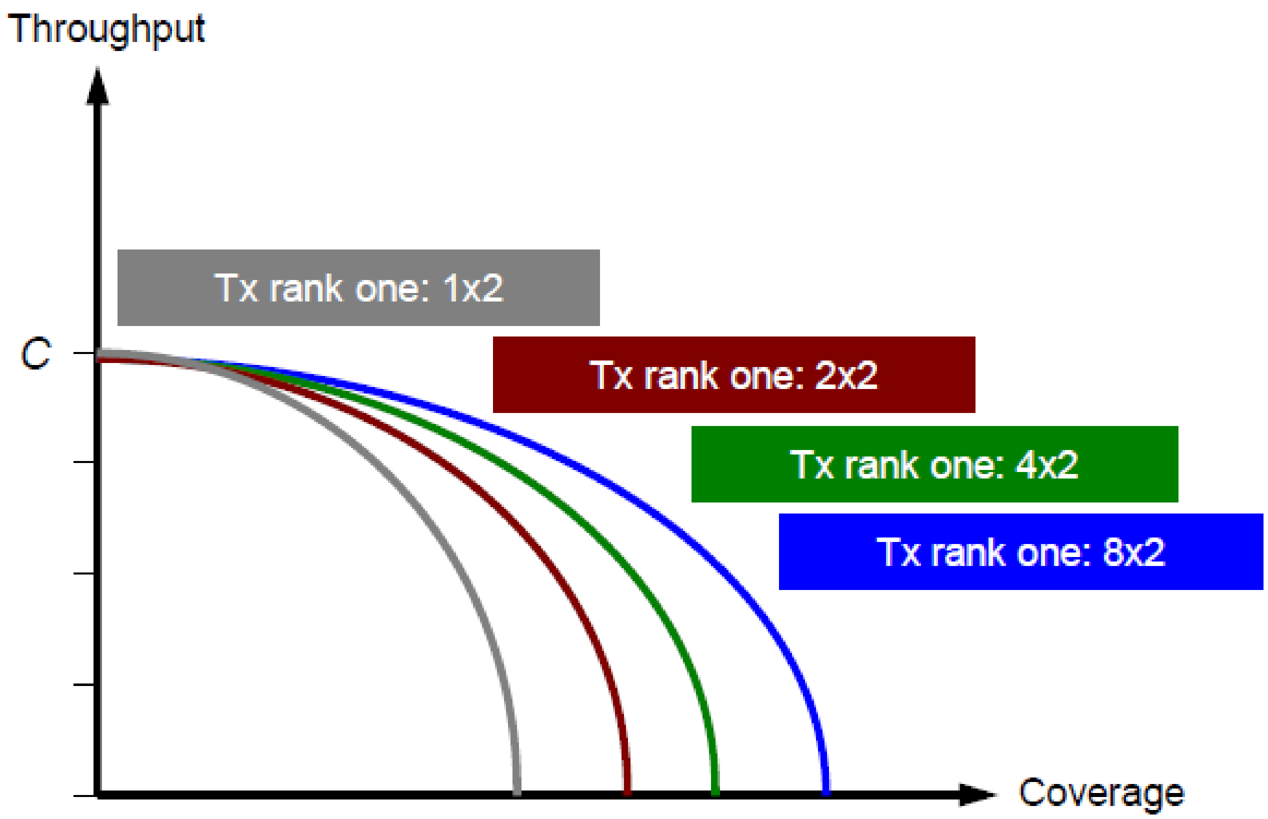
$$W_n = I - 2u_n u_n^H / u_n^H u_n$$

Spatial multiplexing vs beamforming



Spatial multiplexing increases throughput, but looses coverage

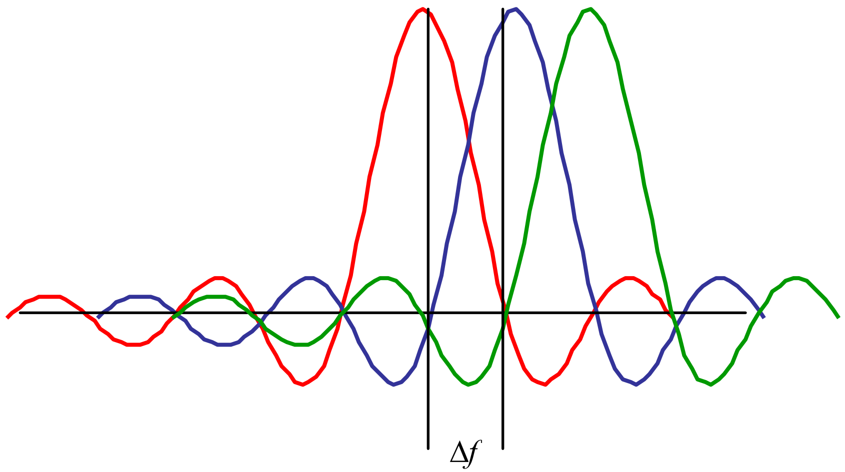
Spatial multiplexing vs beamforming



Beamforming increases coverage

Some technical details of LTE / EUTRA

Basic OFDM parameter



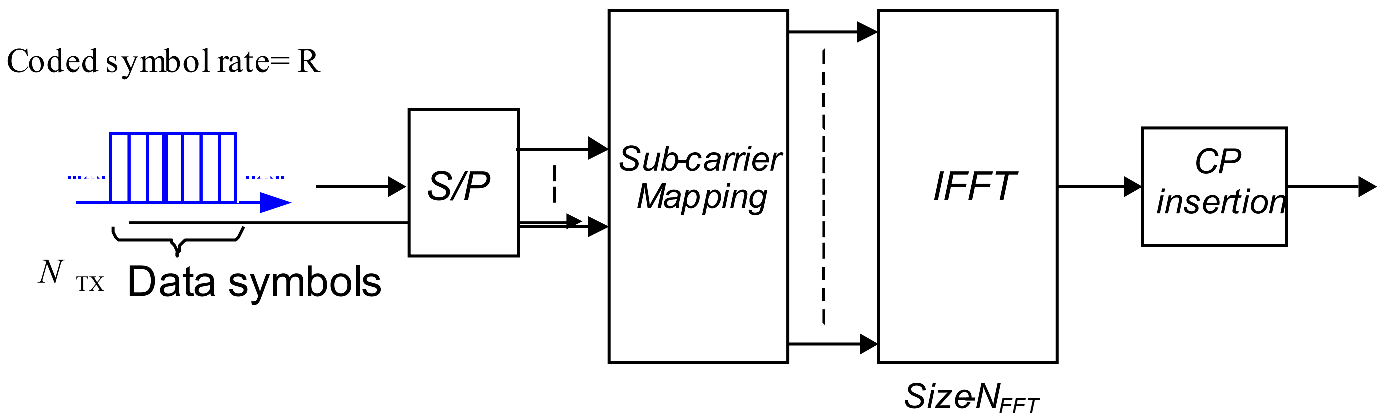
LTE

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

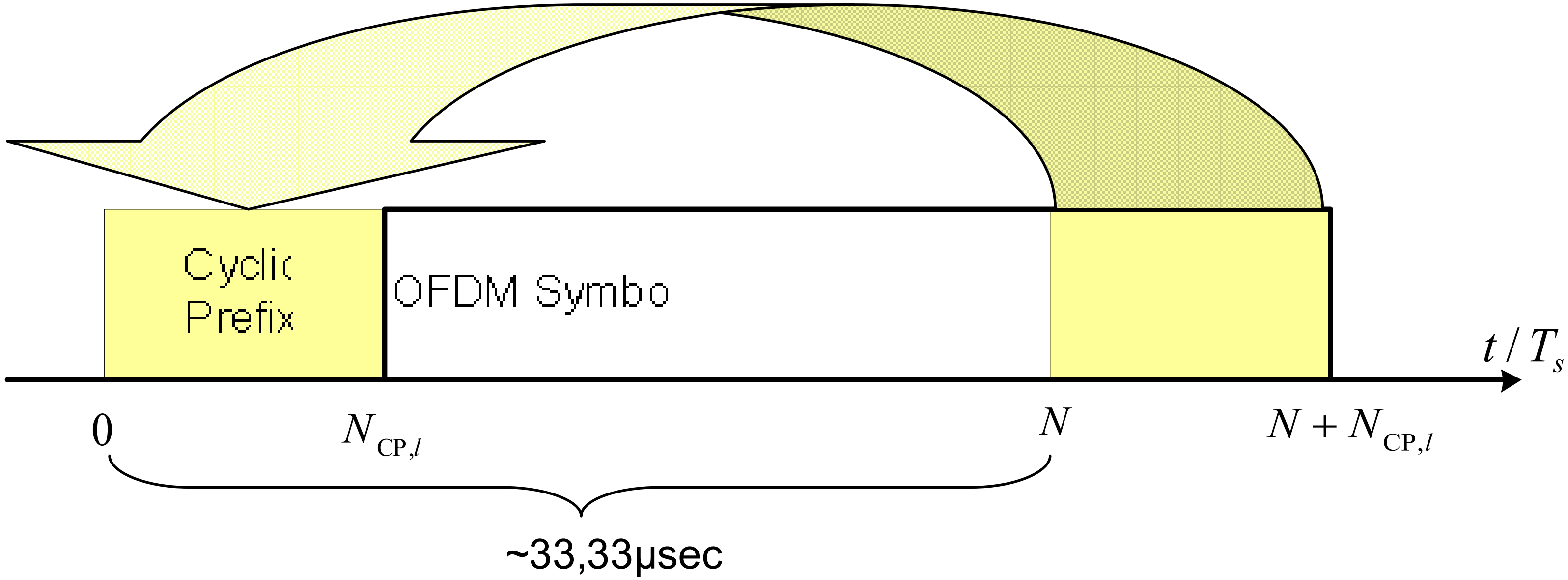
$$F_s = N_{FFT} \cdot \Delta f$$

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

$$N_{FFT} = 2048$$



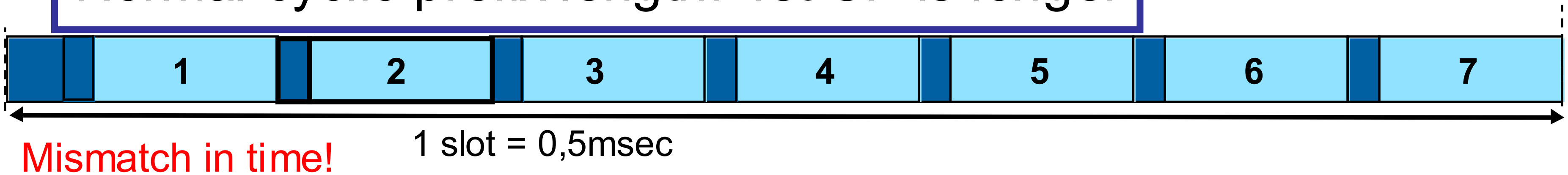
Cyclic Prefix



$N_{CP,l}$ is different for 1st (*l=0*) and residual symbols (*l = 1..6*) in each slot!
CP ratio $^1/_{14}$ resp. ¼ is mean value across one slot length!
Example with normal cyclic prefix (CP = $^1/_{14}$):
$N = 1024$, $N_{CP,0} = 160$, $N_{CP,1..6} = 144$
$7 \cdot N + N_{CP,0} + 6 \cdot N_{CP,1..6} = 7 \cdot 1024 + 1024$

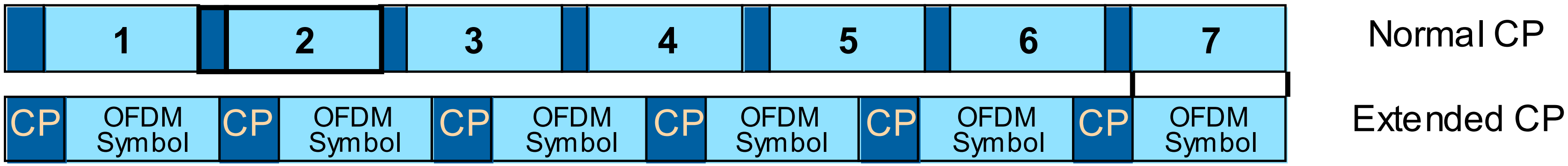
Cyclic prefix length

Normal cyclic prefix length: 1st CP is longer



Mismatch in time!

1st Cyclic prefix is longer



2 different Cyclic prefix lengths are defined

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

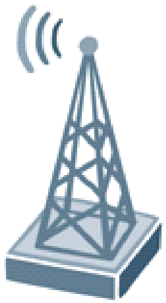
$$T_s = \frac{1}{15kHz \cdot 2048} = \frac{1}{25 * 1.2288}$$

LTE Physical Layer

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

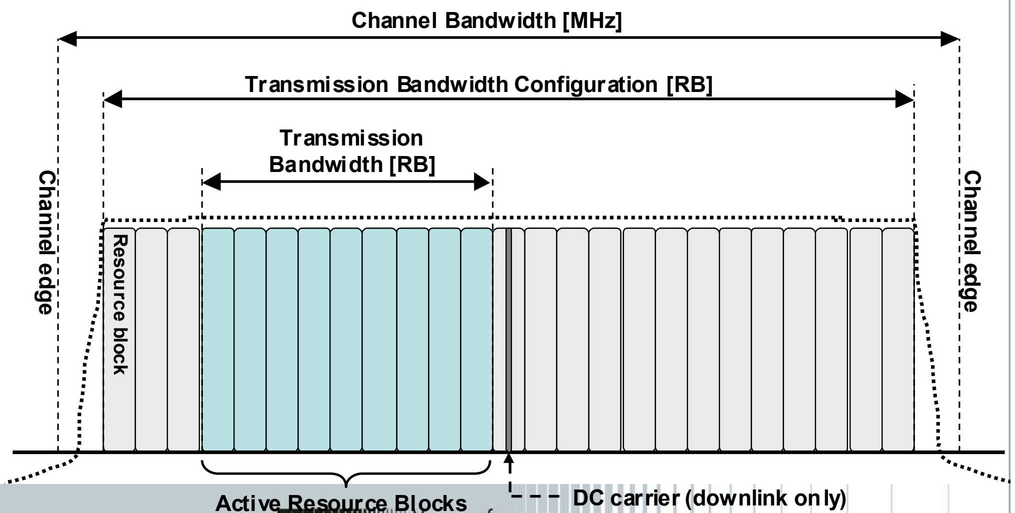
Physical Uplink Control Channel PUCCH:
ACK/NACK for downlink packets, scheduling requests, channel quality info

LTE – spectrum flexibility

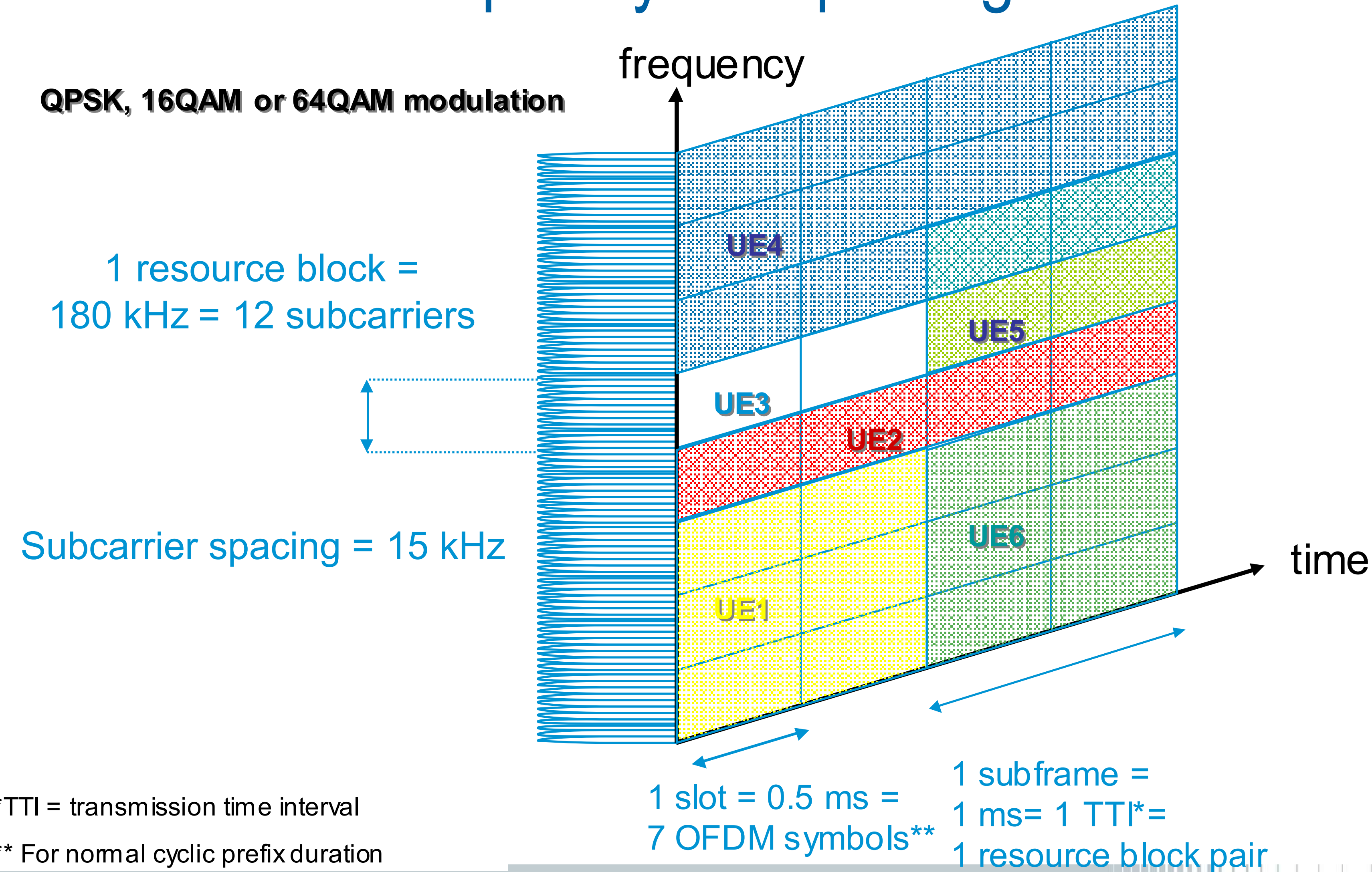
- LTE physical layer supports any bandwidth from 1.4 MHz to 20 MHz in steps of 180 kHz (resource block)
- Current LTE specification supports only a subset of 6 different system bandwidths
- All UEs must support the maximum bandwidth of 20 MHz

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



LTE Downlink
OFDMA time-frequency multiplexing



*TTI = transmission time interval

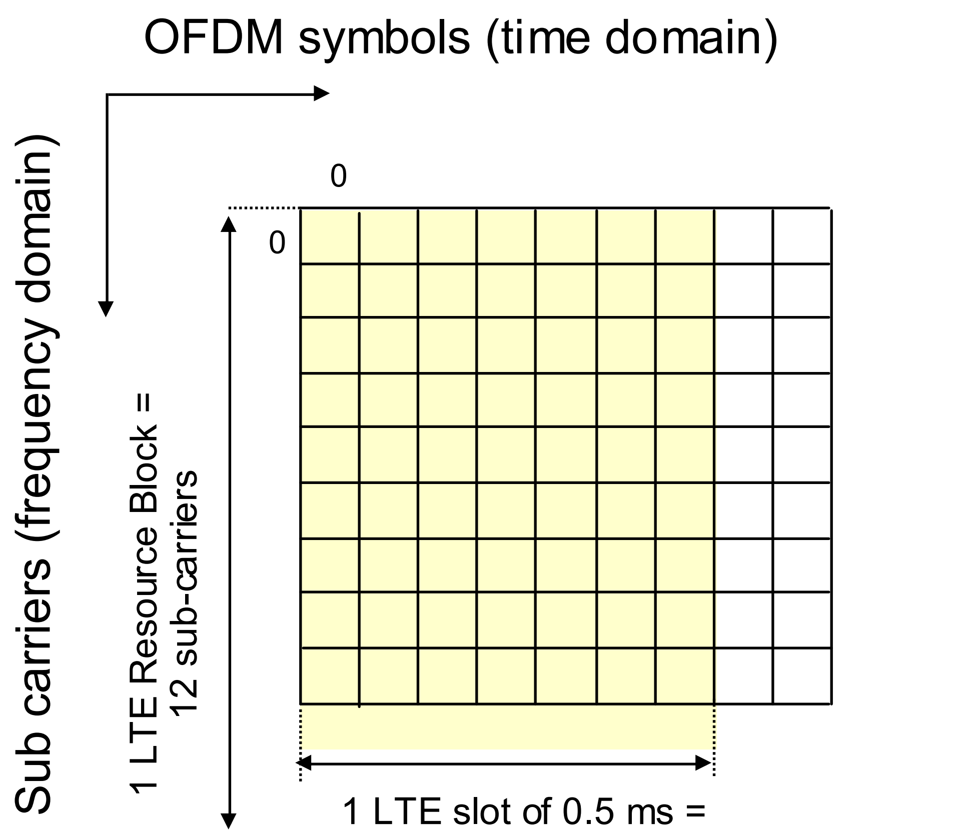
** For normal cyclic prefix duration

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

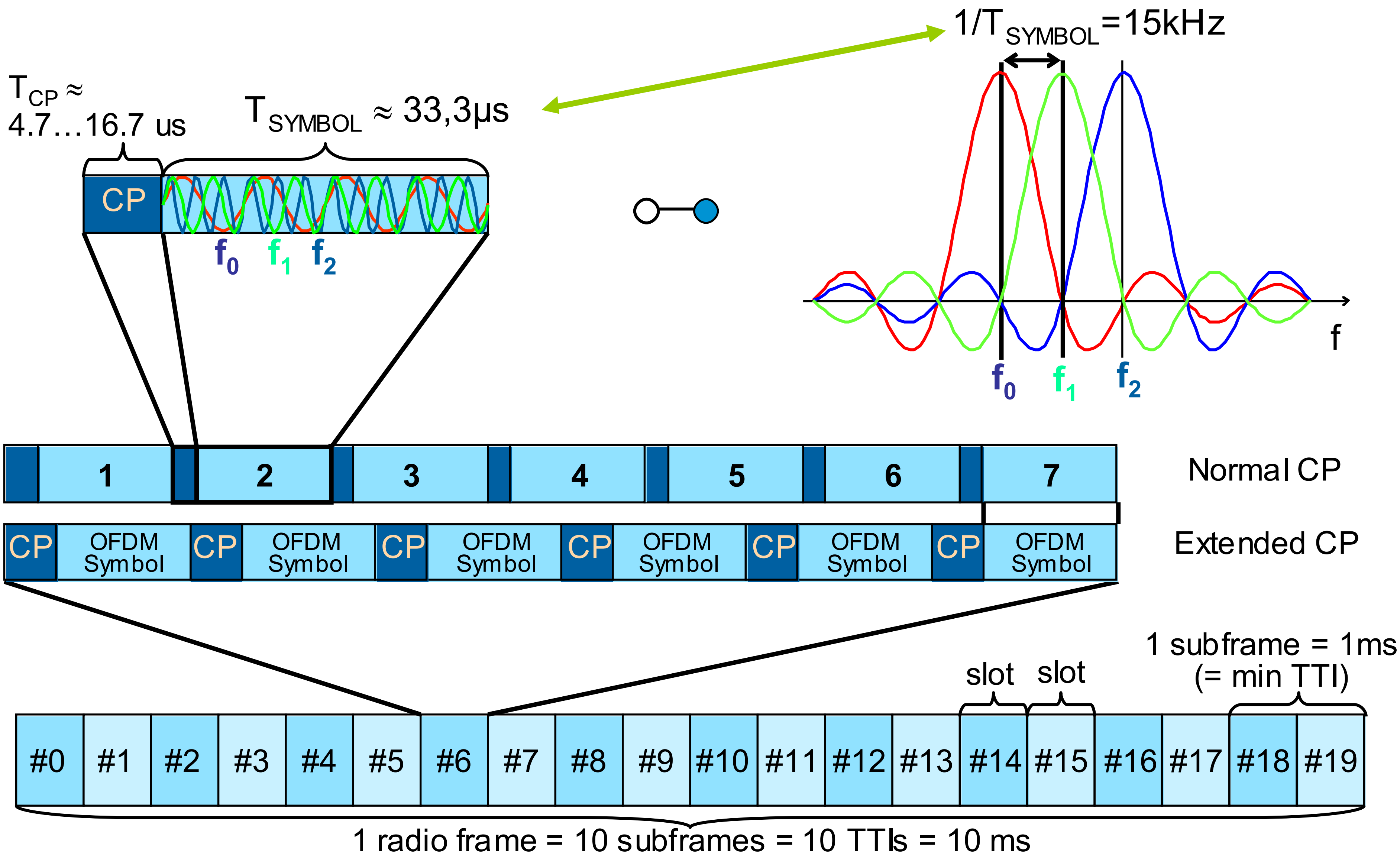
Normal scenario: carrier spacing of 15 kHz
Big cell scenario: 7,5 kHz + extended guard time



6 / 7 OFDM symbols dep. on cyclic prefix length

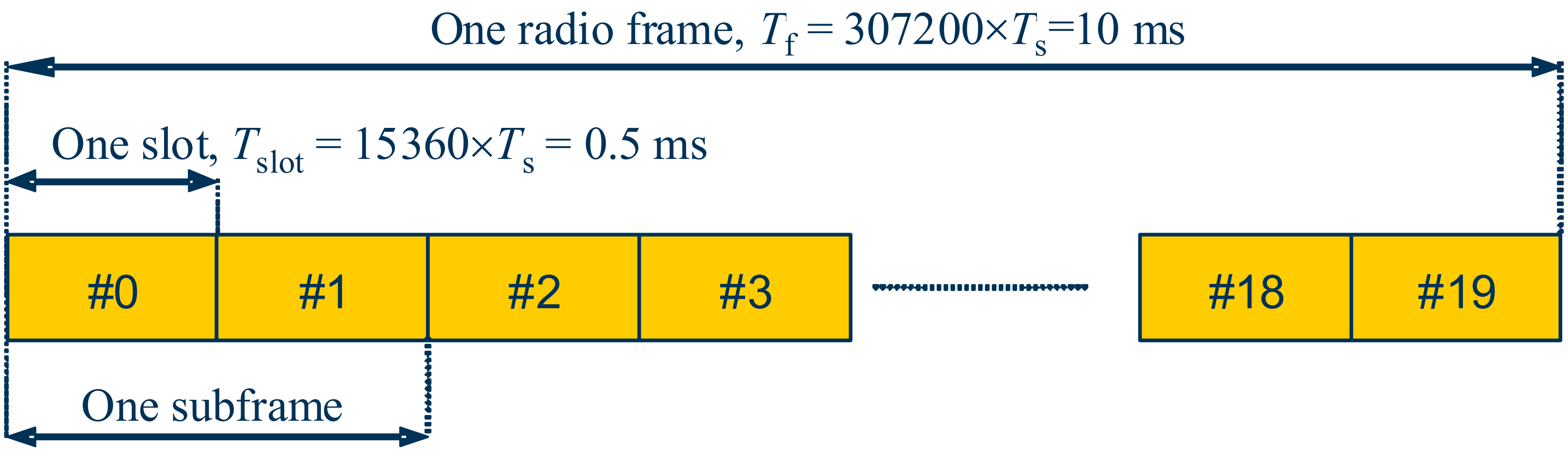
(3 symbols for 7.5 kHz spacing / MBMS scenarios)

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

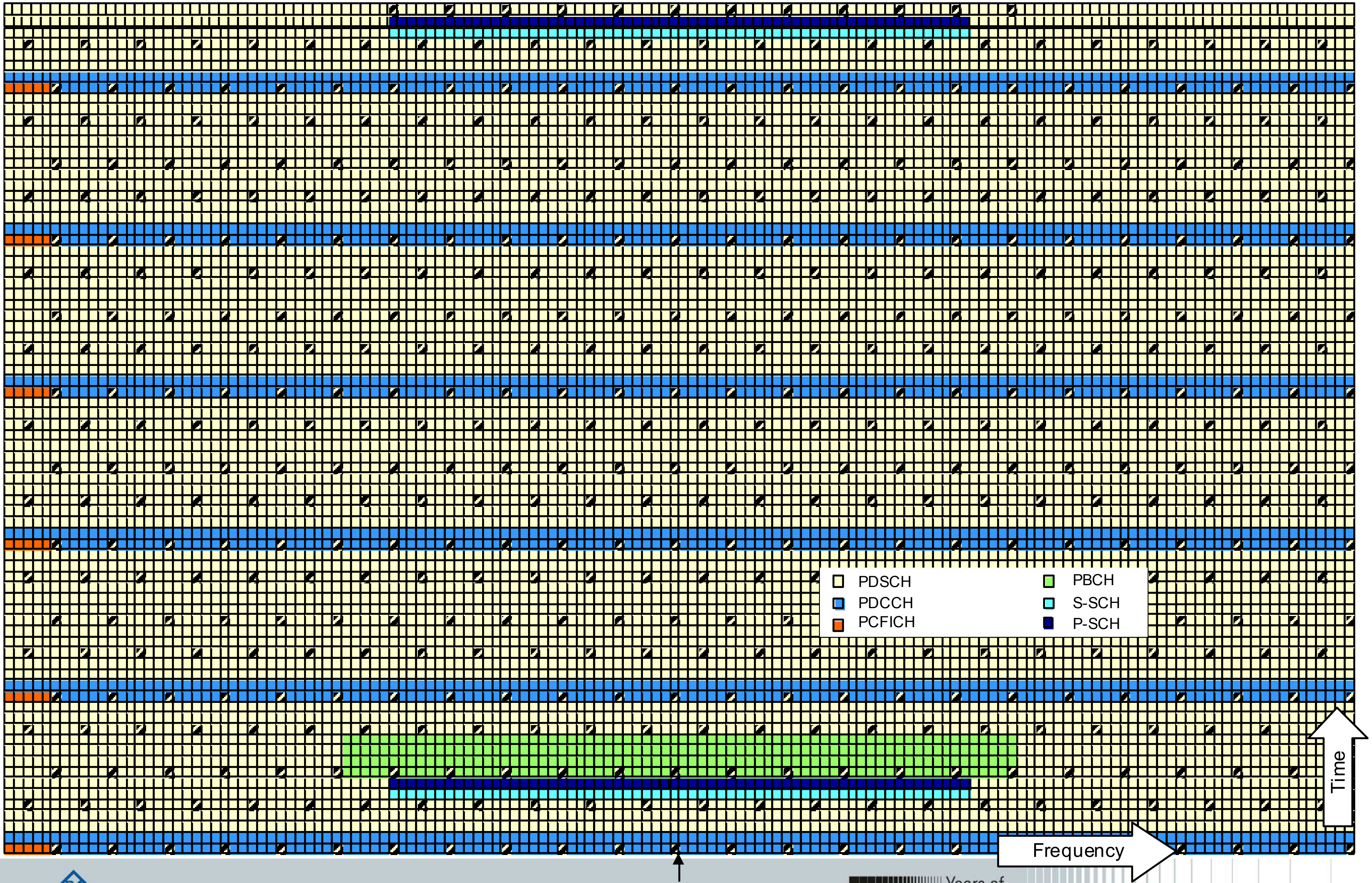


We talk about 1 slot, but the minimum resource is 1 subframe = 2 slots !!!!!

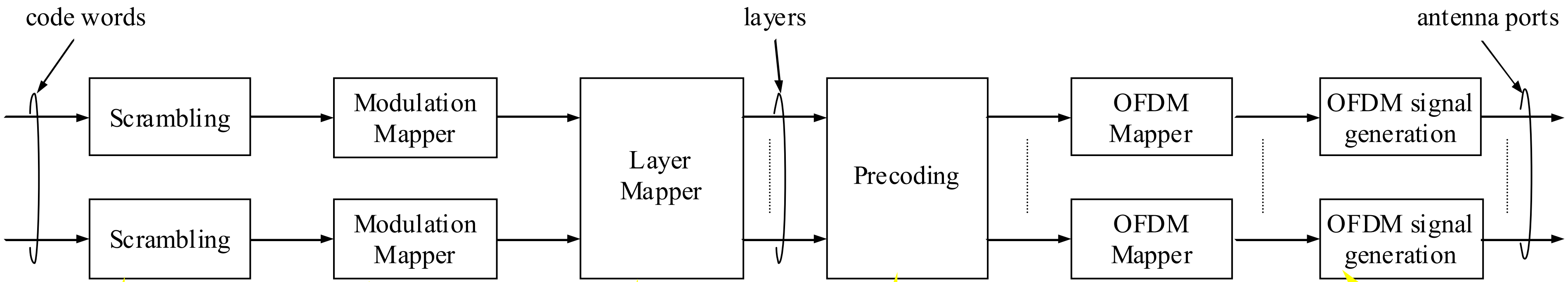
Ts = 32.522 ns

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

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

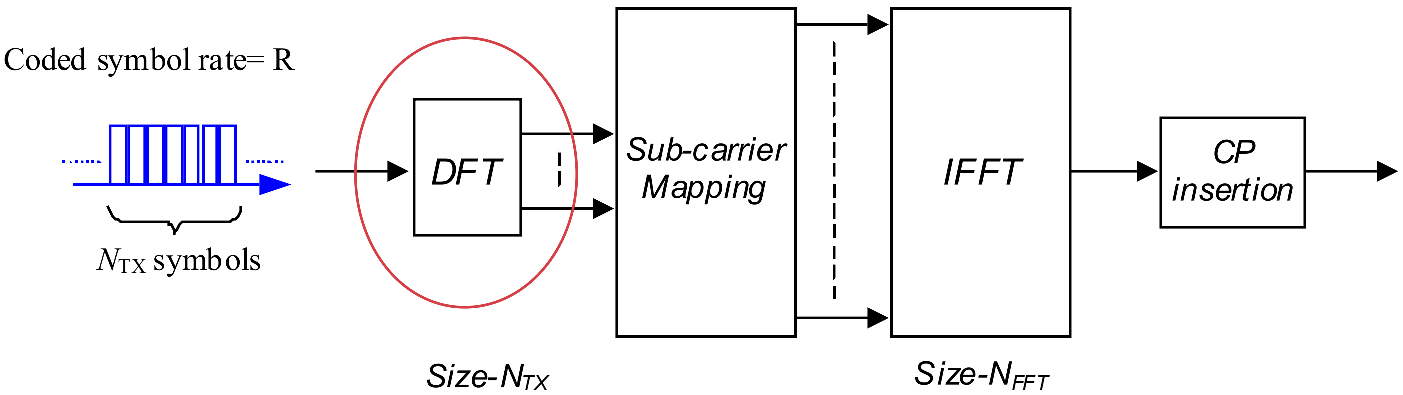
Weighting data streams for MIMO

1 OFDM symbol per stream

1 stream = several subcarriers, based on Physical ressource blocks

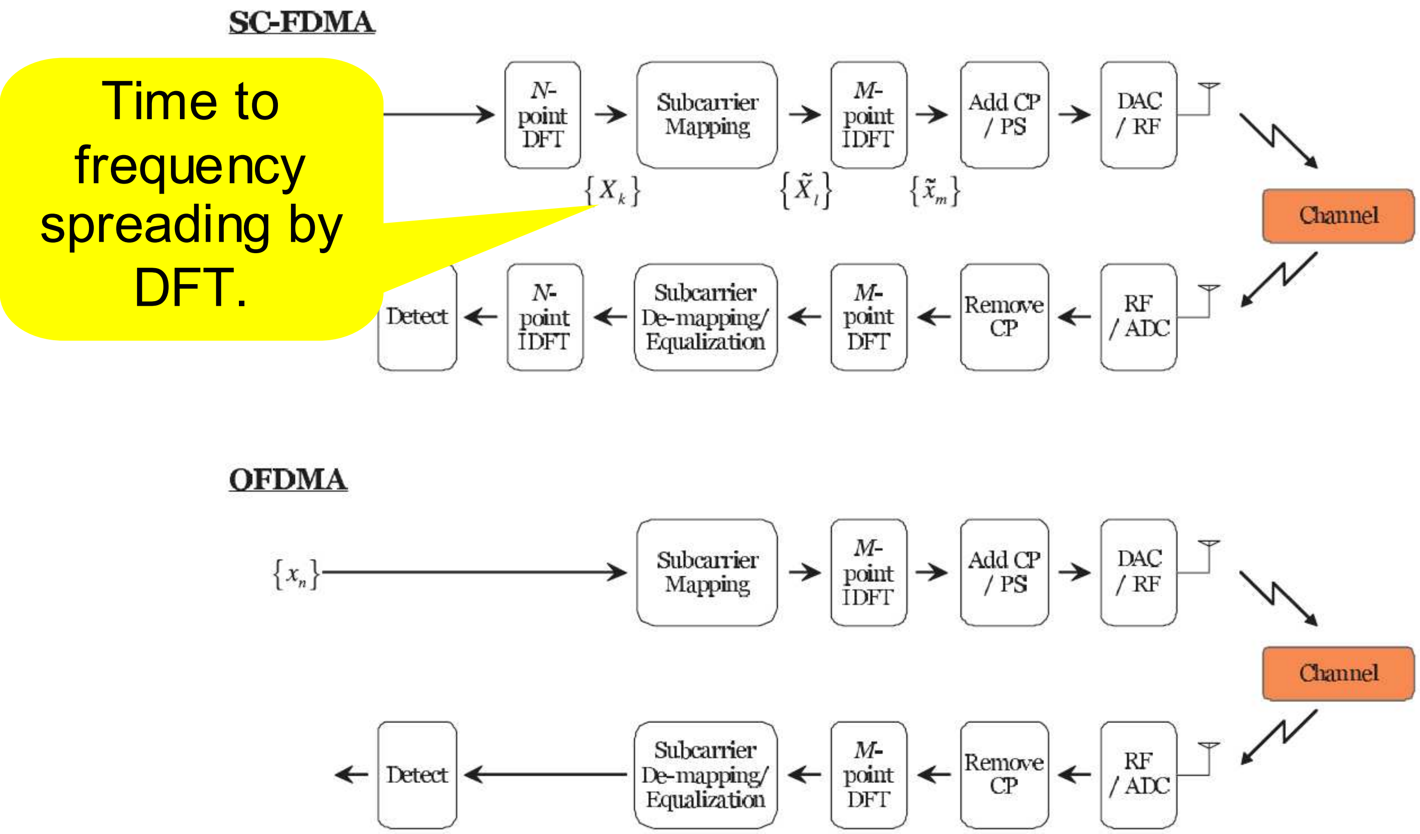
LTE Physical Layer:
SC-FDMA in uplink

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**"

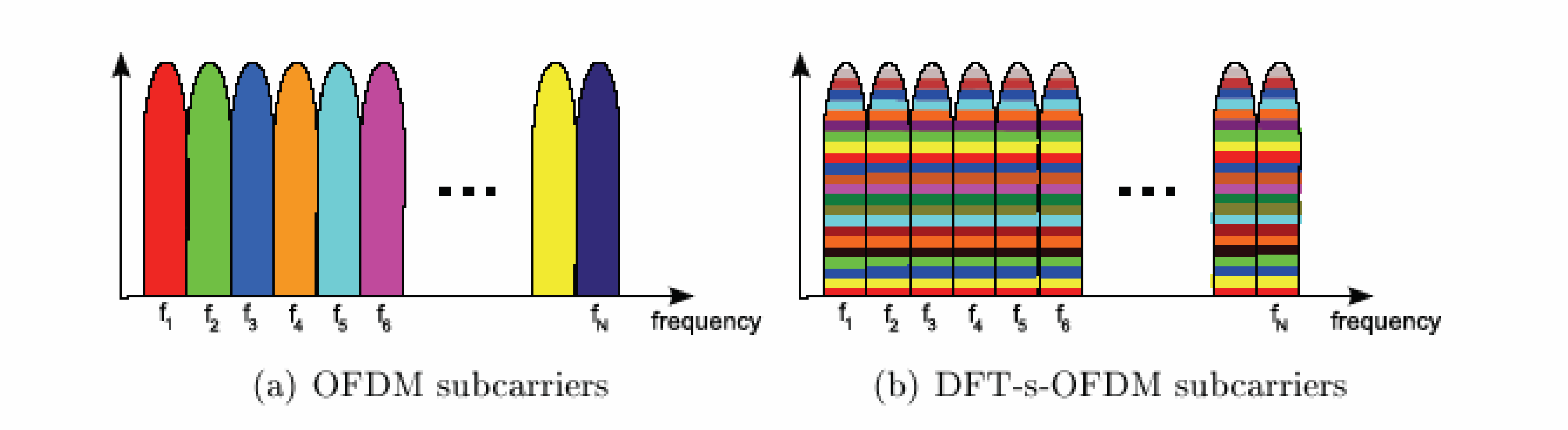
SC-FDMA and OFDMA - differences



* CP: Cyclic Prefix, PS: Pulse Shaping

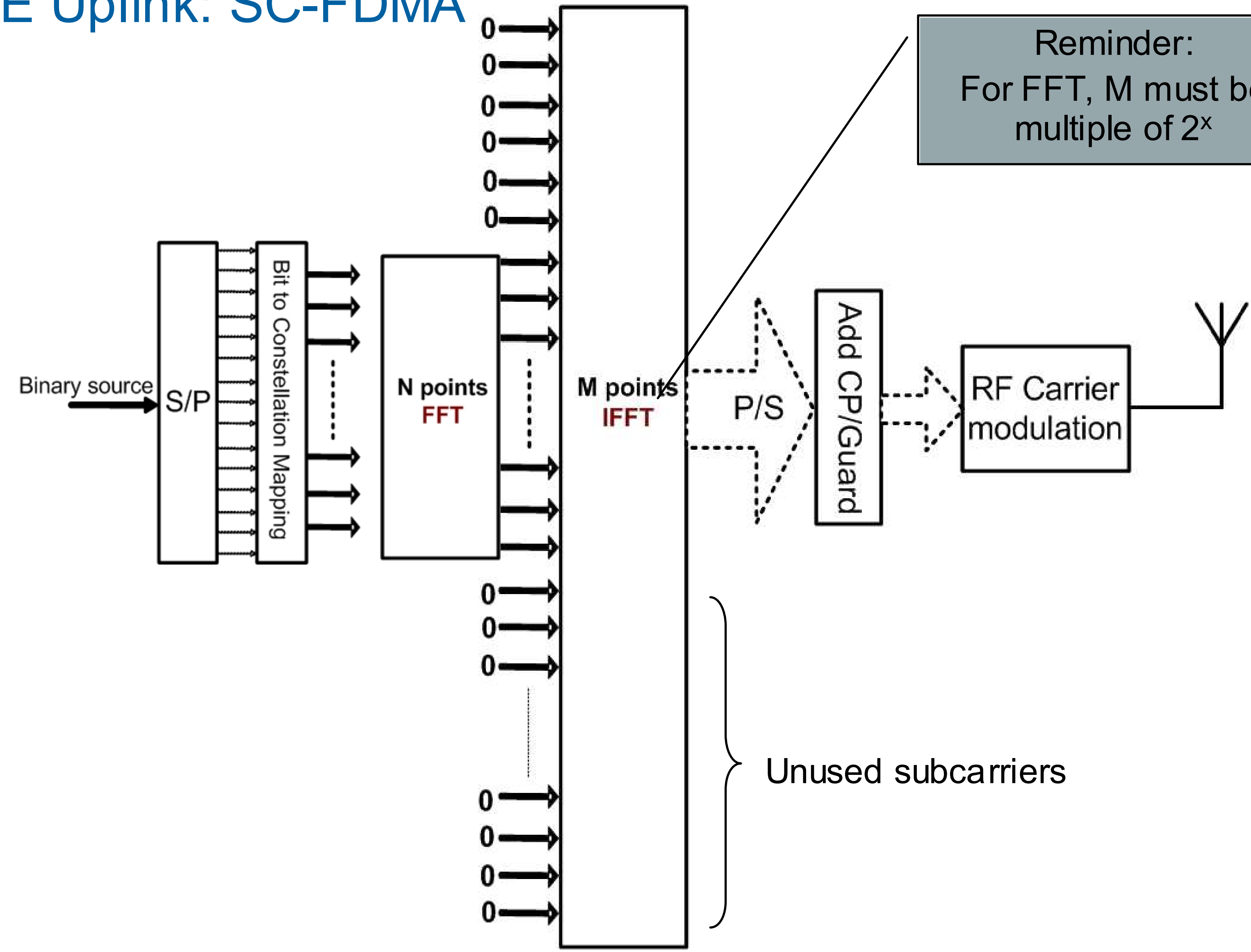
LTE Uplink: How does the SC-FDMA signal look like?

- 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

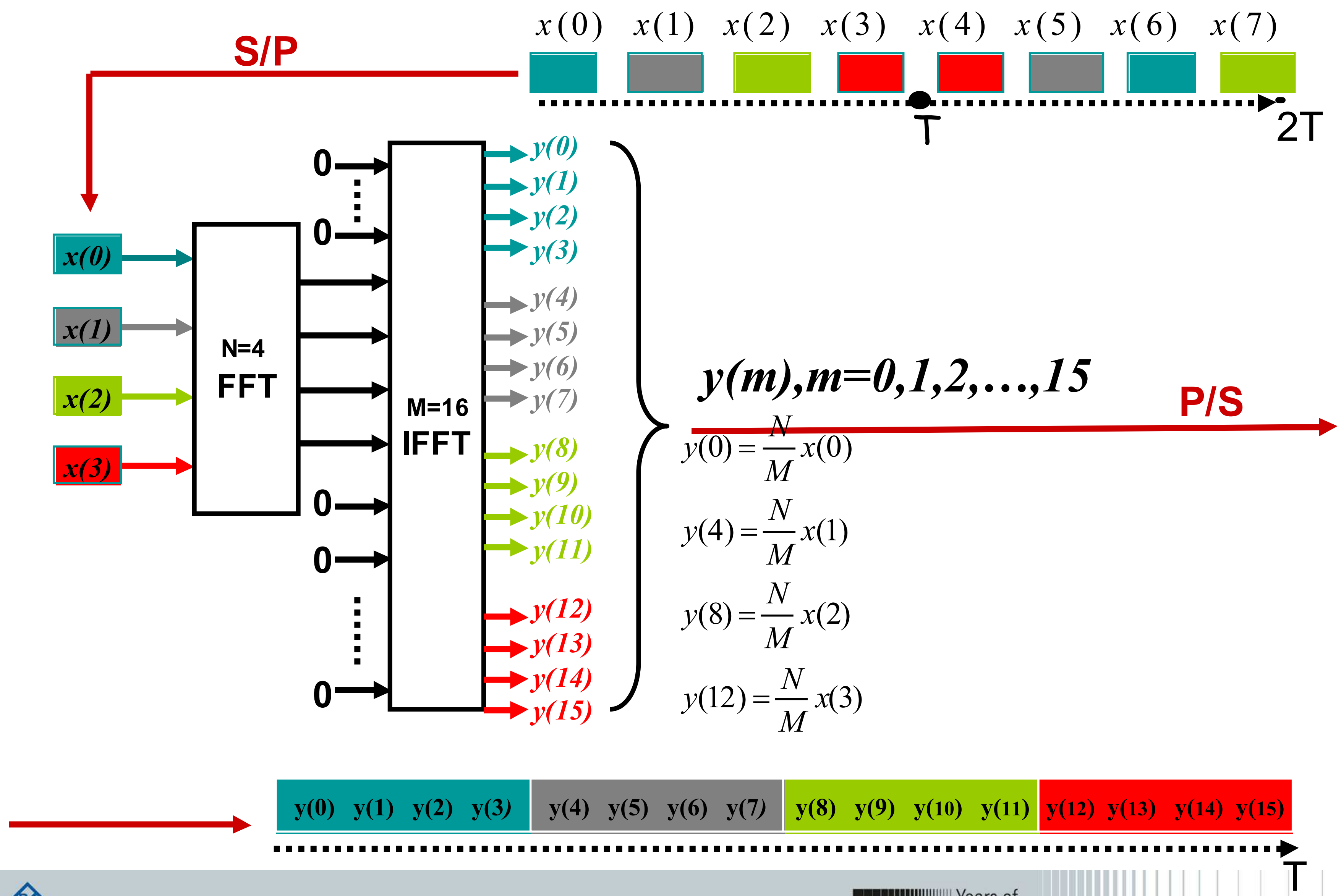


LTE Uplink: SC-FDMA

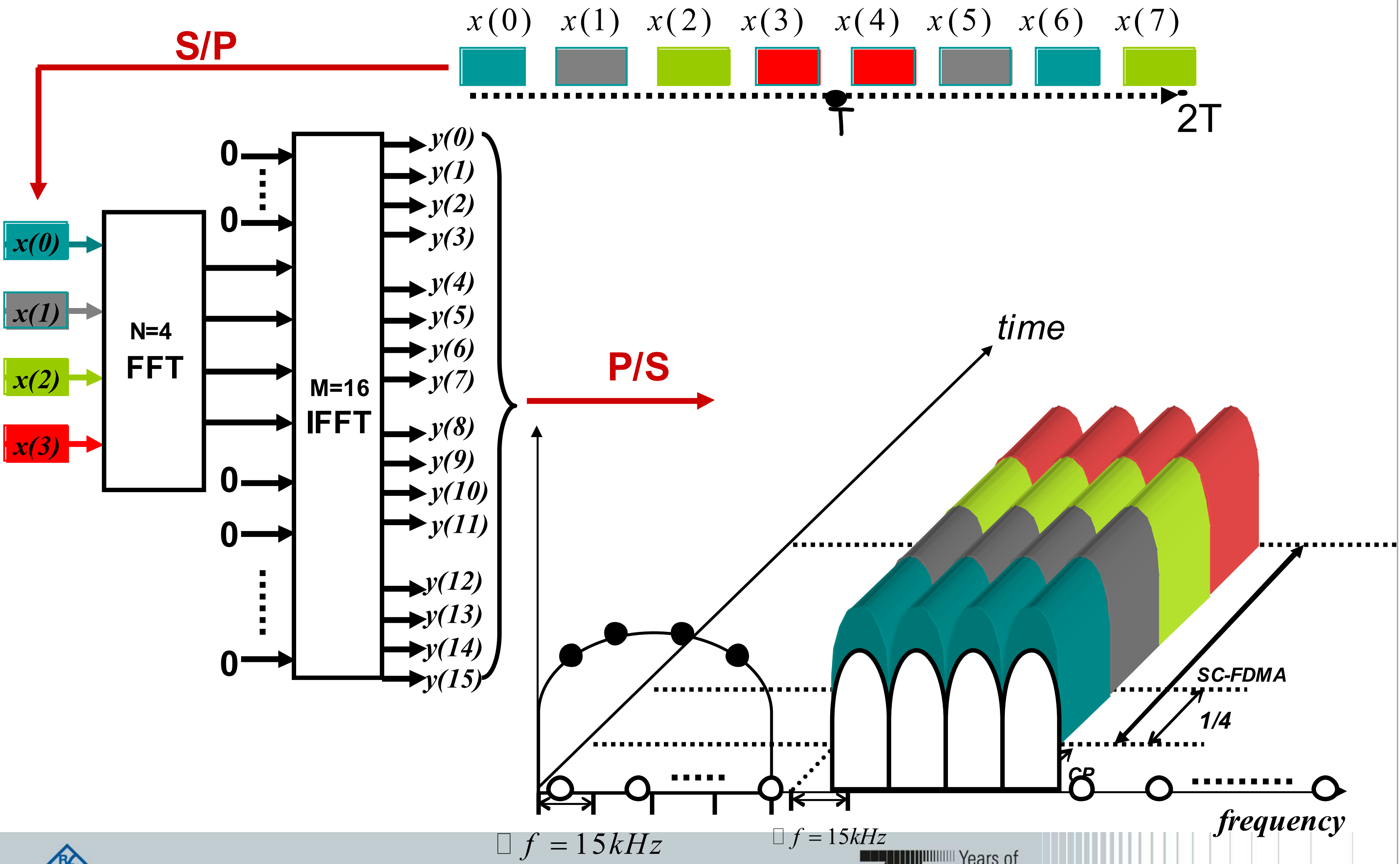
Reminder:
For FFT, M must be multiple of 2^x



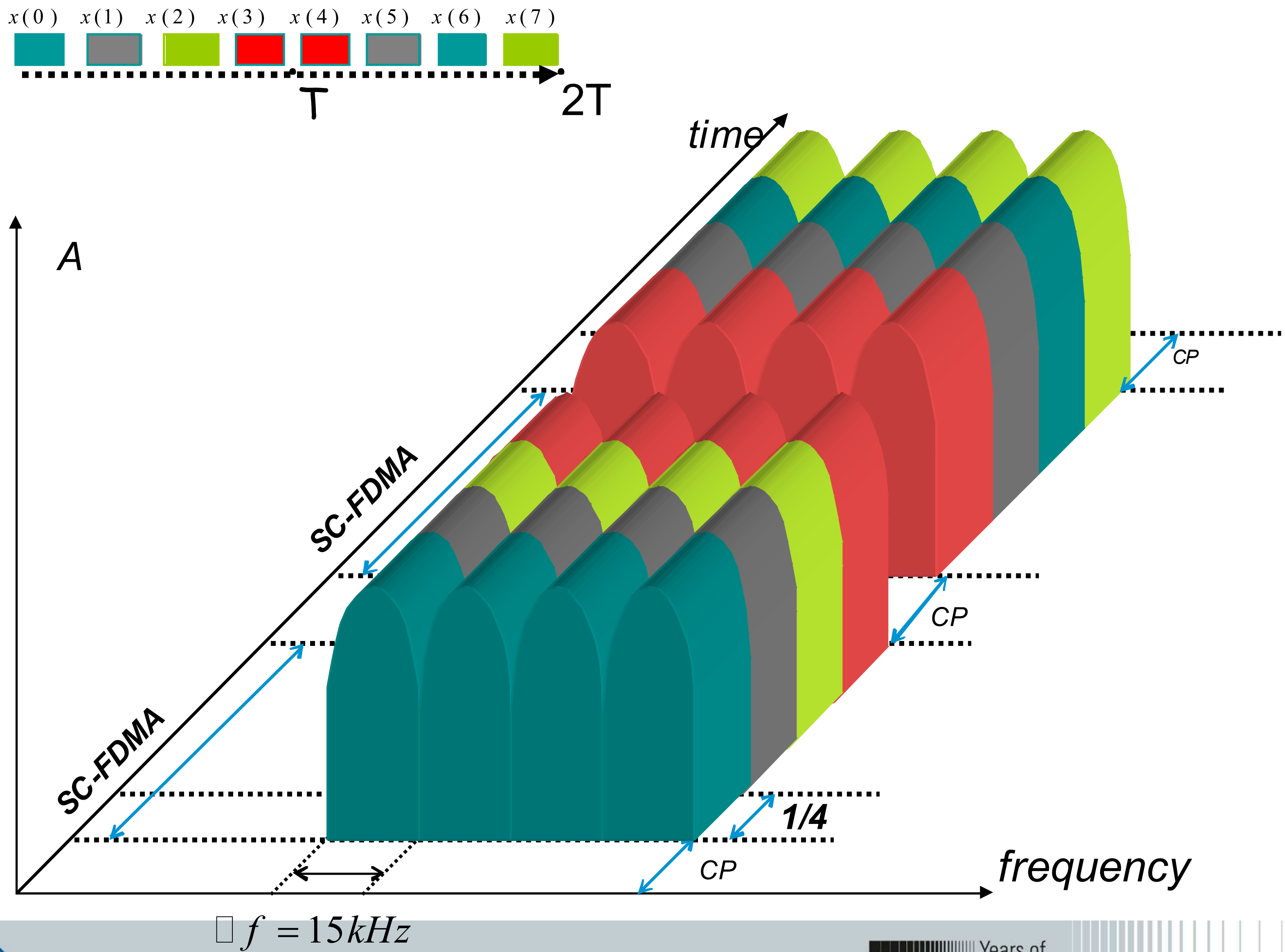
SC-FDMA example



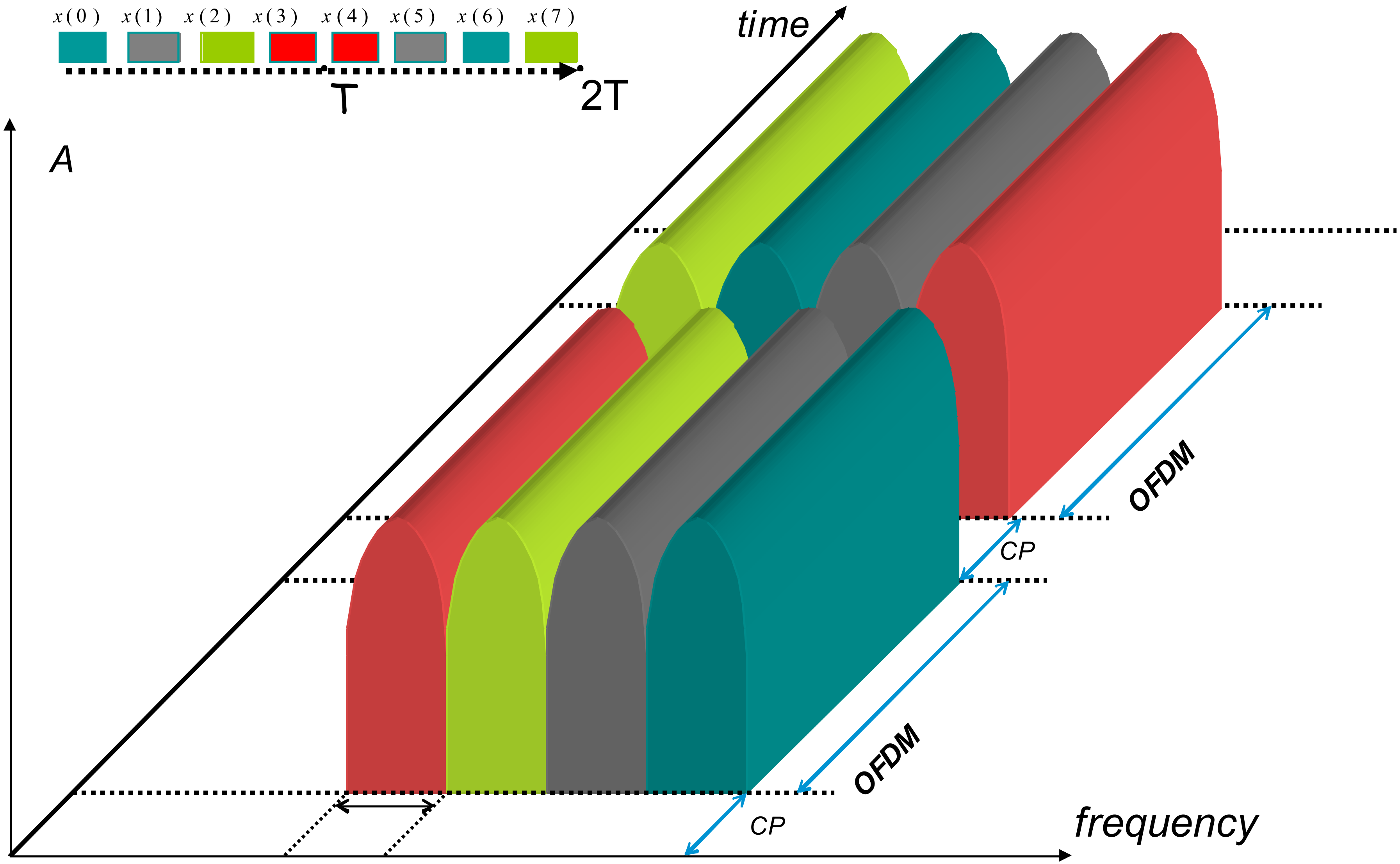
SC-FDMA example



SC-FDMA example



SC-FDMA example

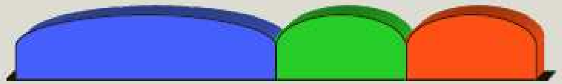


$$\Delta f = 15kHz$$

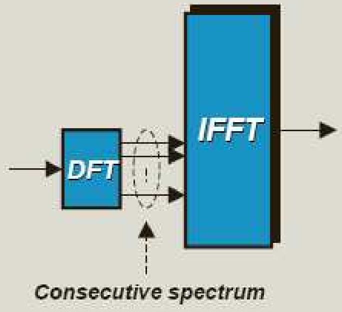
Localized versus Distributed FDMA

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



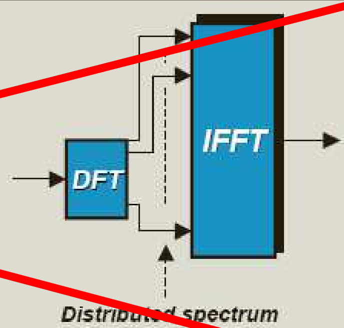
- *Each user transmission localized in the frequency domain*
- *Low-PAPR by single-carrier transmisssion*
- *Flexible transmission bandwidth*
- *Channel-dependent scheduling in frequency domain*



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*~~



SC-FDMA Peak to average

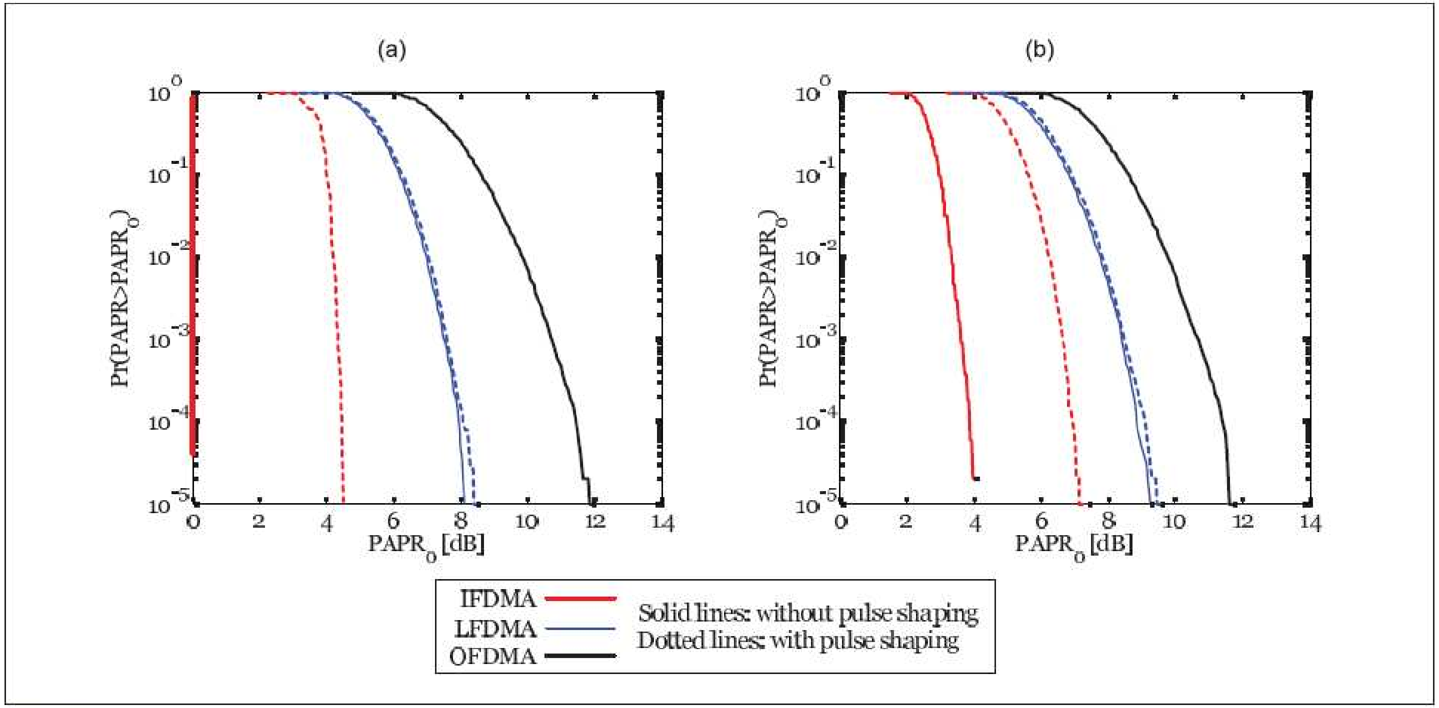
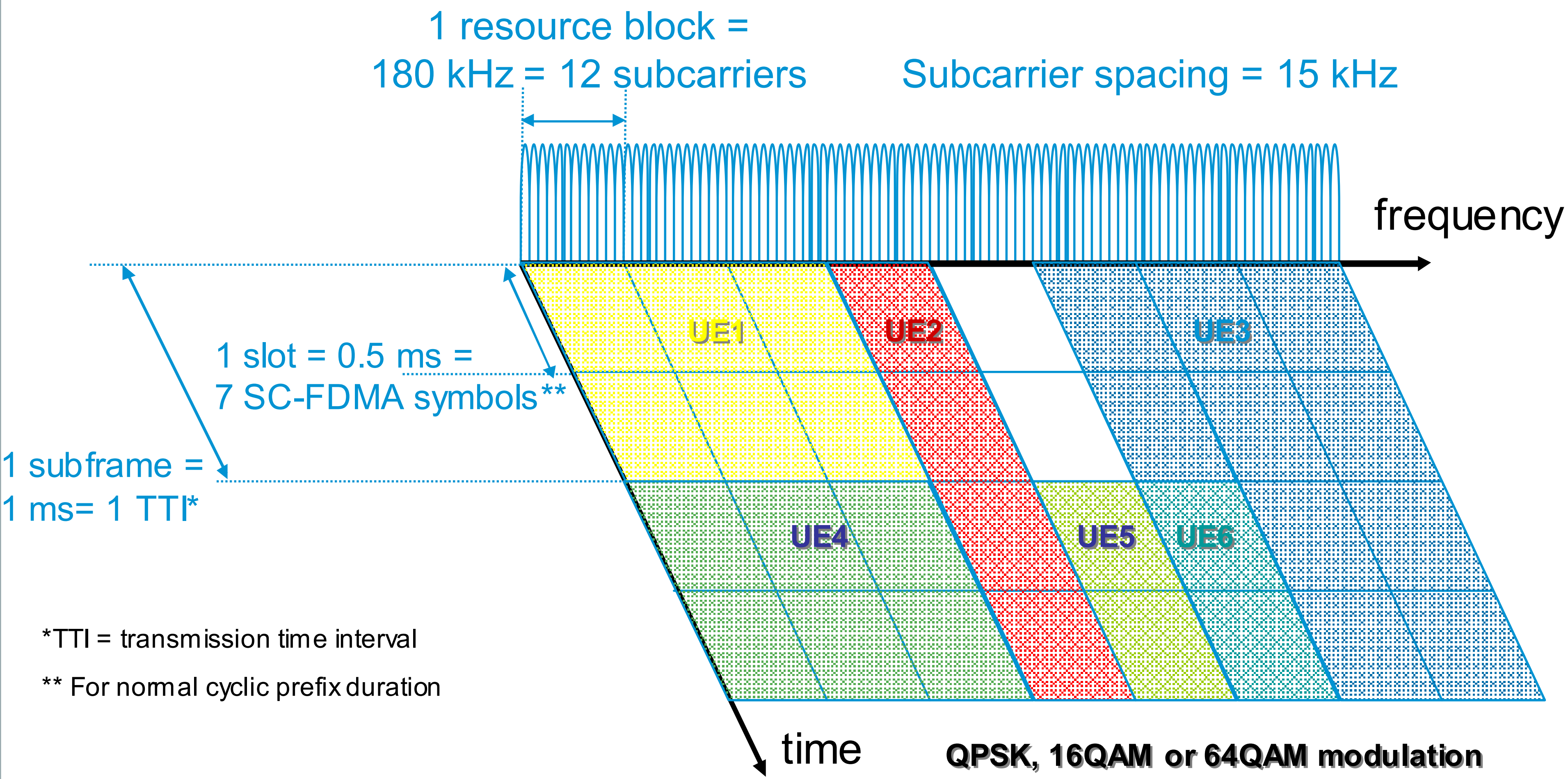


FIGURE 5 Comparison of CCDF of PAPR for IFDMA, LFDMA, and OFDMA with $M = 256$ system subcarriers, $N = 64$ subcarriers per user, and a = 0.5 rolloff factor; (a) QPSK; (b) 16-QAM.

75 Years of Driving Innovation

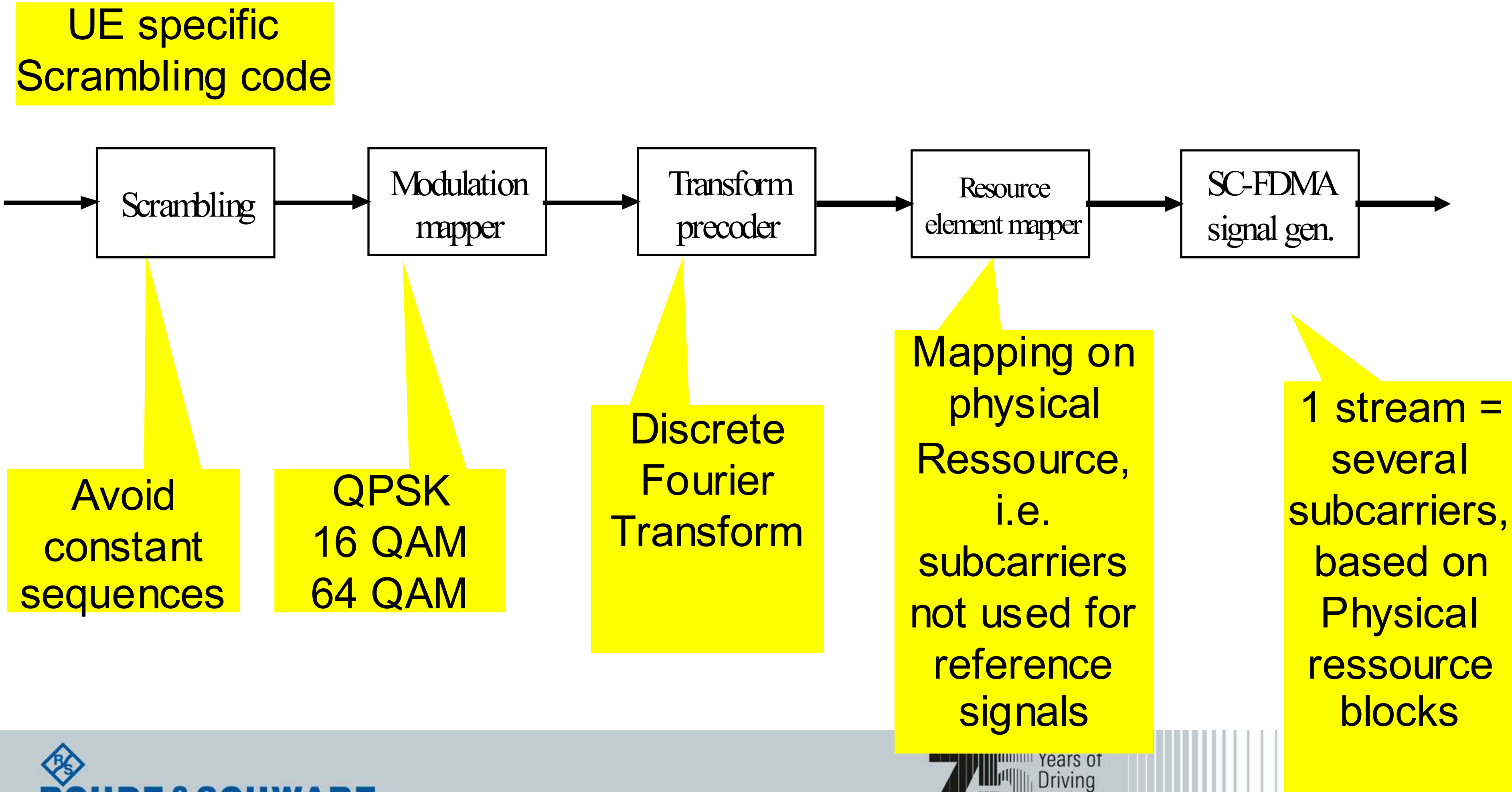
LTE uplink
SC-FDMA time-frequency multiplexing



*TTI = transmission time interval

** For normal cyclic prefix duration

LTE Uplink: baseband signal generation



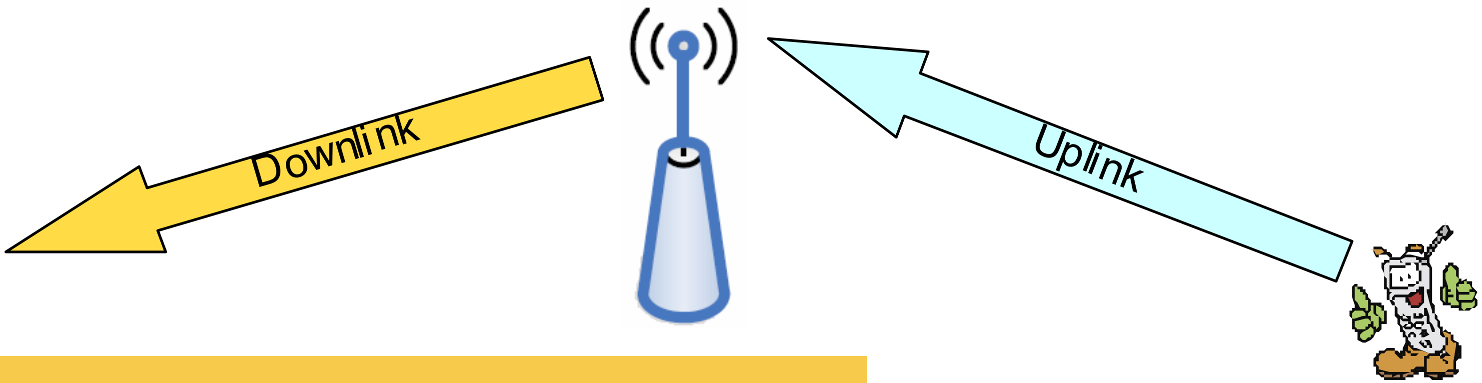
LTE Physical Layer:

Reference signals – general aspects

Reference signals in Downlink

Reference signals in Uplink

LTE Reference signals in UL and DL overview



Downlink reference signals:

- Primary synchronisation signal
- Secondary synchronisation signal
- Cell specific reference signals
- UE specific reference signals
- MBMS specific reference signals

Uplink reference signals:

- Random Access Preamble
- Uplink demodulation reference signal
- Sounding reference signal

= based on pseudo random bit sequences

= based on Zhadoff-Chu sequences

= only used for special applications

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

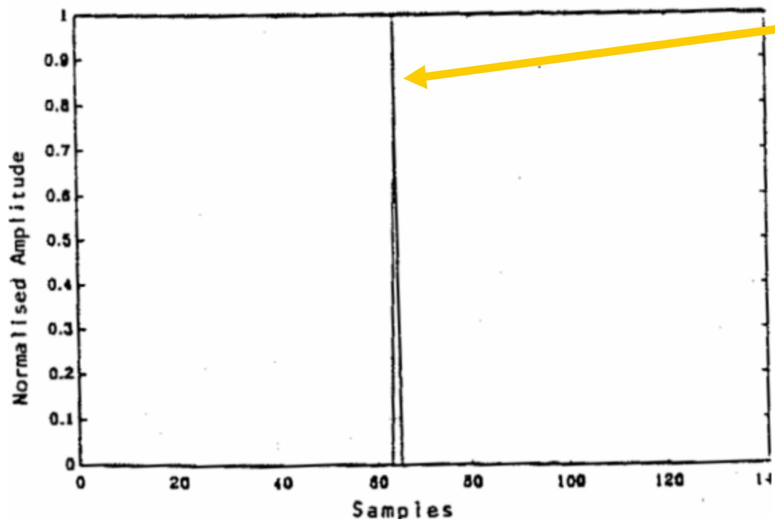
Primary synchronisation signal in downlink

CAZAC sequence characteristics – constellation diagram

Constant amplitude

Characteristics of Zadoff-Chu sequences

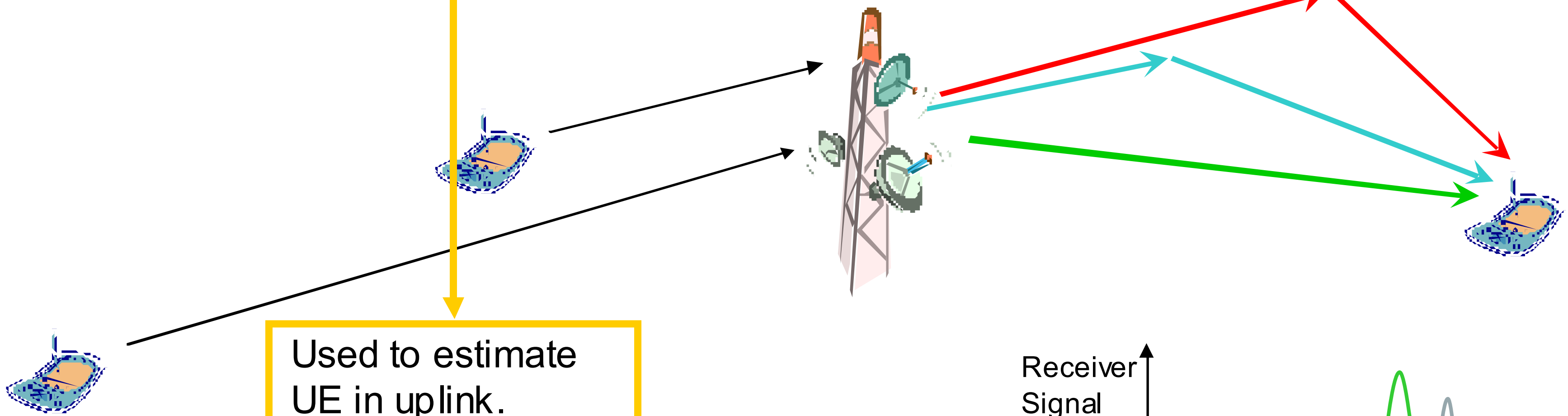
Zero autocorrelation



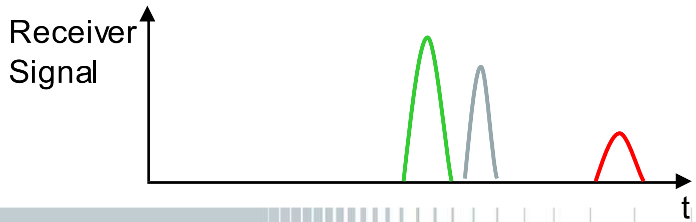
Zero Autocorrelation

e.g. here autocorrelation of length 64 sequence

Used to estimate Channel impulse response

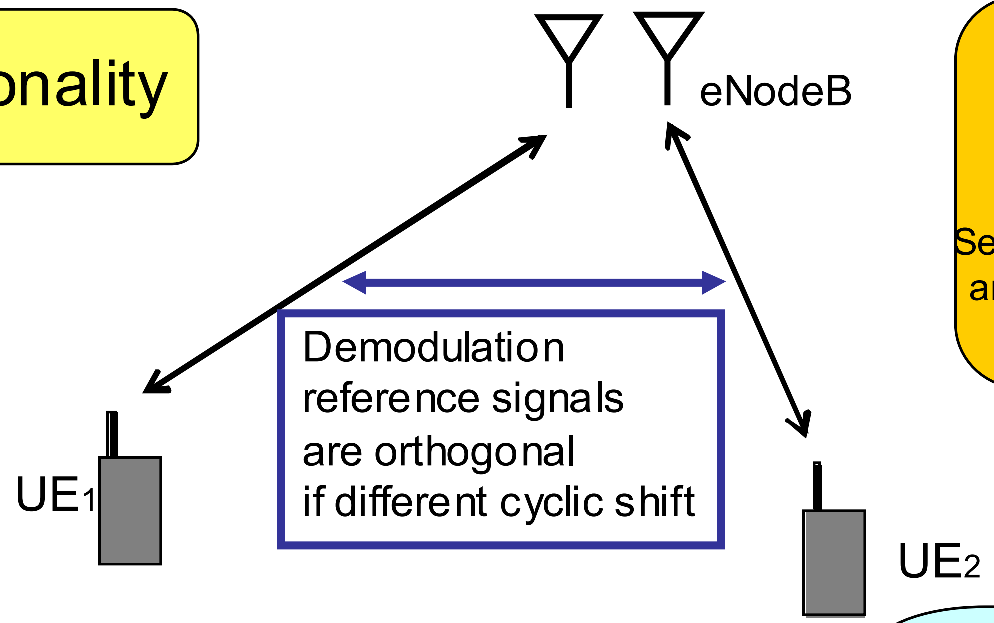


Used to estimate UE in uplink. Near – far situation



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

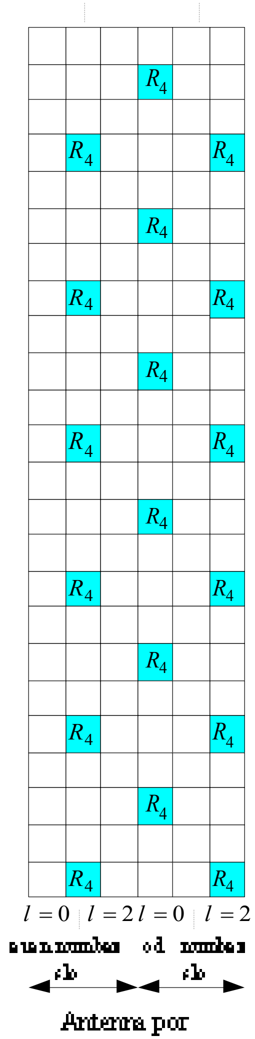
$$a_q(n) = e^{-j2\pi q \frac{n\frac{n+1}{2} + l \cdot n}{N_{ZC}}}$$

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: $\frac{1}{\sqrt{N_{ZC}}}$

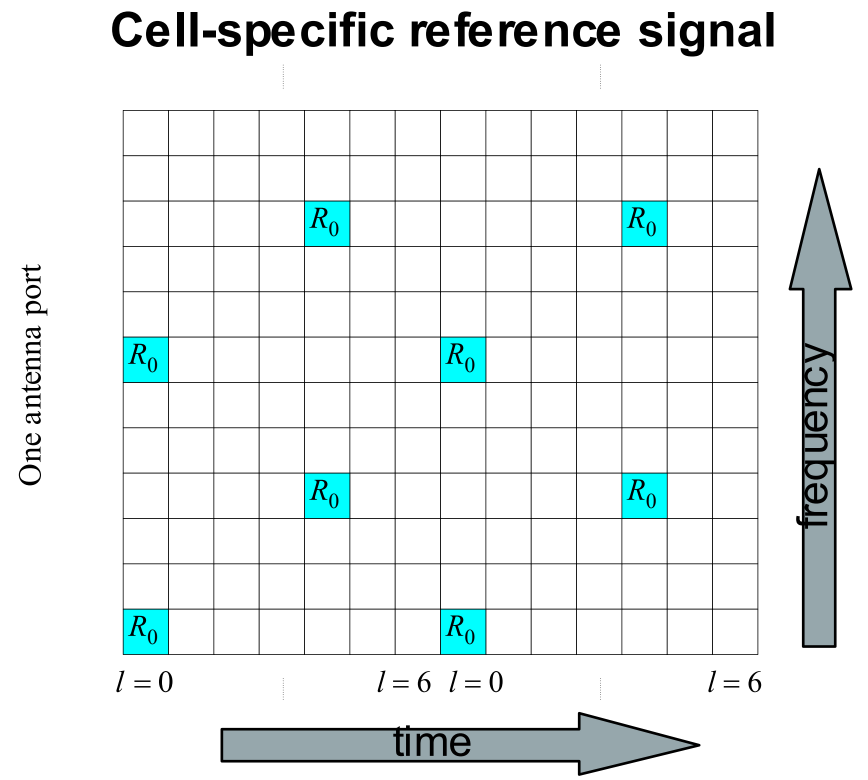
Downlink Reference Signals

- 3 downlink reference signals defined:
  - **Cell-specific reference signals, associated with non-MBSFN transmission**
    - Transmitted on one or several of antenna ports 0 to 3
    - Pseudo-random sequence defined by a length-31 Gold sequence
    - Mapped to physical resources with cell-specific frequency shift
    - Same resource element cannot be used by more than one antenna port
  - **MBSFN reference signals, associated with MBSFN transmission**
    - MBSFN reference signals are transmitted on antenna port 4
    - Defined for extended cyclic prefix only
    - Can be used with Δf=15kHz subcarrier spacing as well as in MBSFN-dedicated cells with Δf=7.5kHz (FFT_{SIZE}=4096)
    - Pseudo-random sequence defined by a length-31 Gold sequence
  - **UE-specific reference signals**
    - Supported for single-antenna-port transmission of PDSCH only
    - Phase reference for PDSCH demodulation
    - Pseudo-random sequence defined by a length-31 Gold sequence
    - UE-specific reference signals are transmitted only on the resource blocks upon which the corresponding PDSCH is mapped



MBSFN
Δf=7.5kHz

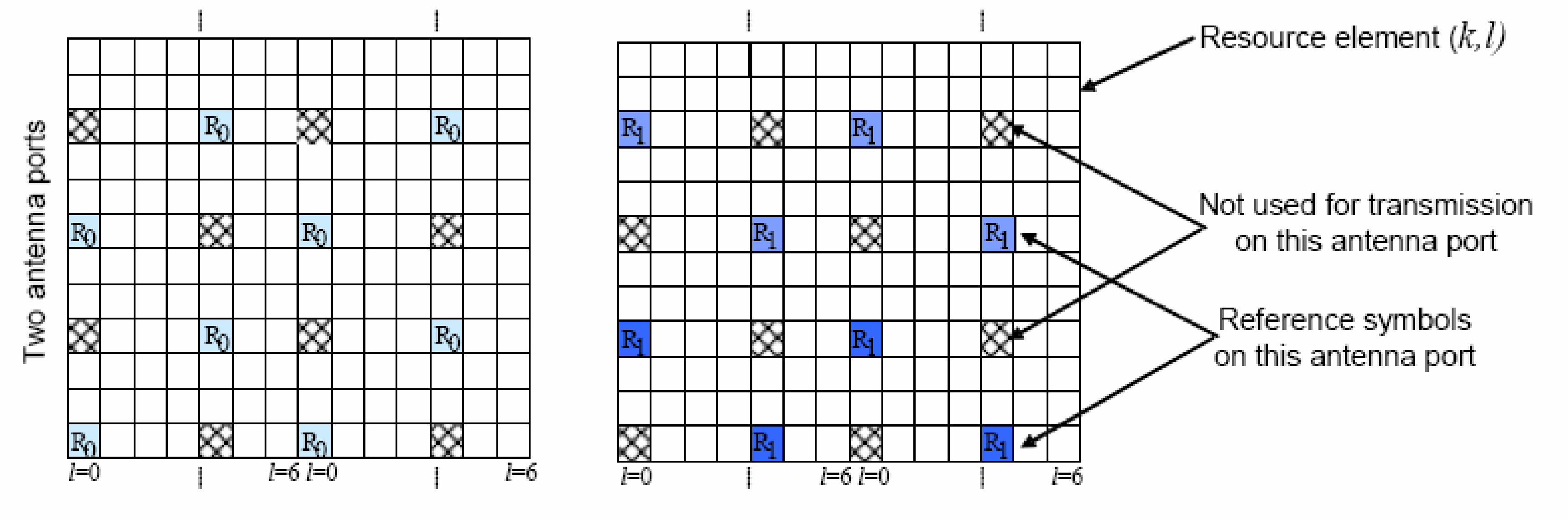
Downlink Reference Signals



- <u>Cell specific reference signals</u>
  - Pseudo random bit sequence, based on physical cell ID
  - Staggered in frequency + time
  - Distributed over channel bandwidth, always sent

MIMO in LTE (DL)
Reference Symbols / Pilots

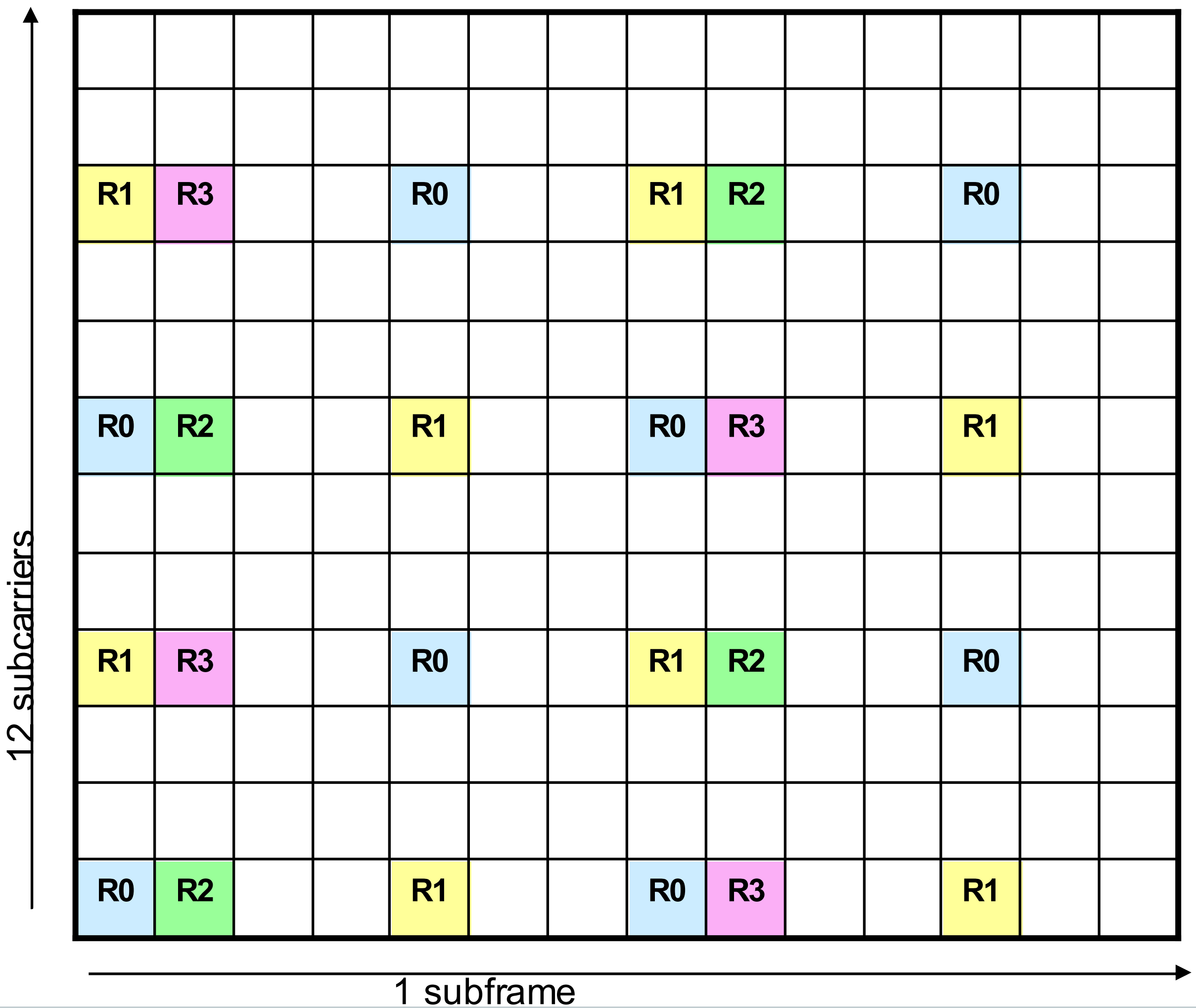
e.g.:



Antenna 1 Antenna 2

MIMO in LTE (DL)

Reference Symbols / Pilots



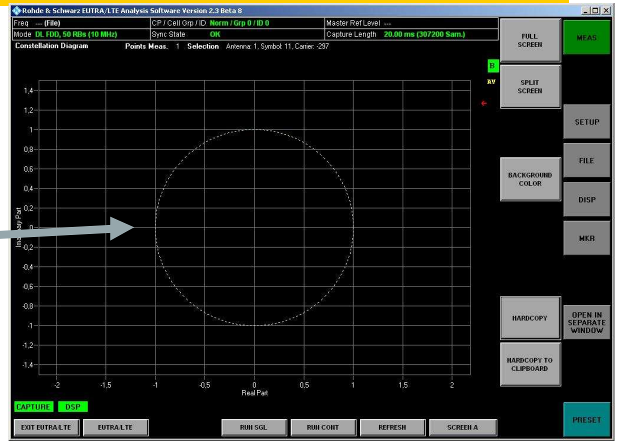
R0	Antenna 0
R1	Antenna 1
R2	Antenna 2
R3	Antenna 3

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

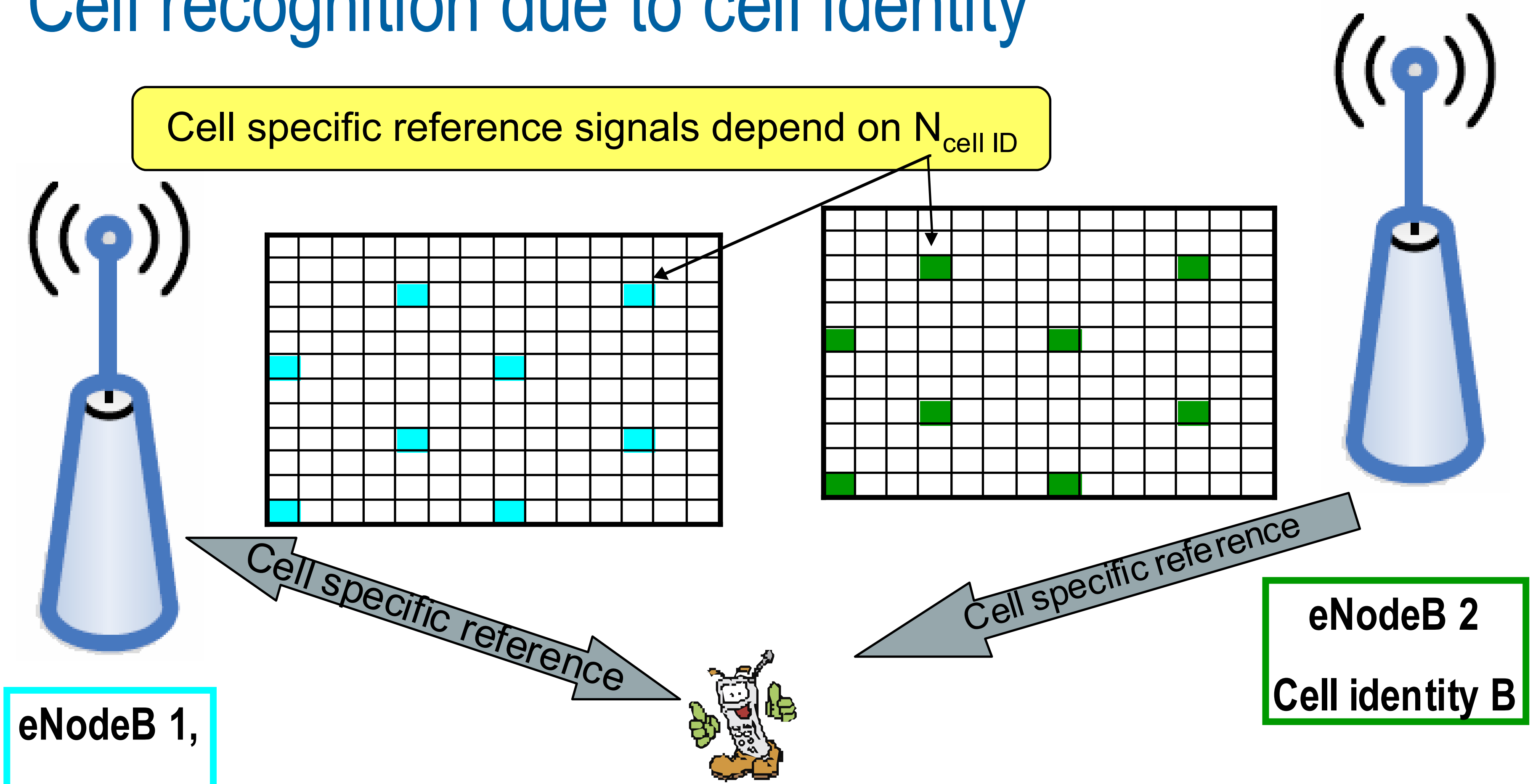


$$r_{l,n_s}(m) = \underbrace{\frac{1}{\sqrt{2}}\left(1-2\cdot c(2m)\right)}_{\text{Real part}} + j\underbrace{\frac{1}{\sqrt{2}}\left(1-2\cdot c(2m+1)\right)}_{\text{Imaginary part}}, \qquad m = 0,1,\ldots,2N_{\mathrm{RB}}^{\max,\mathrm{DL}}-1$$

Pseudo random sequence, based on cell identity and slot

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

Cell recognition due to cell identity



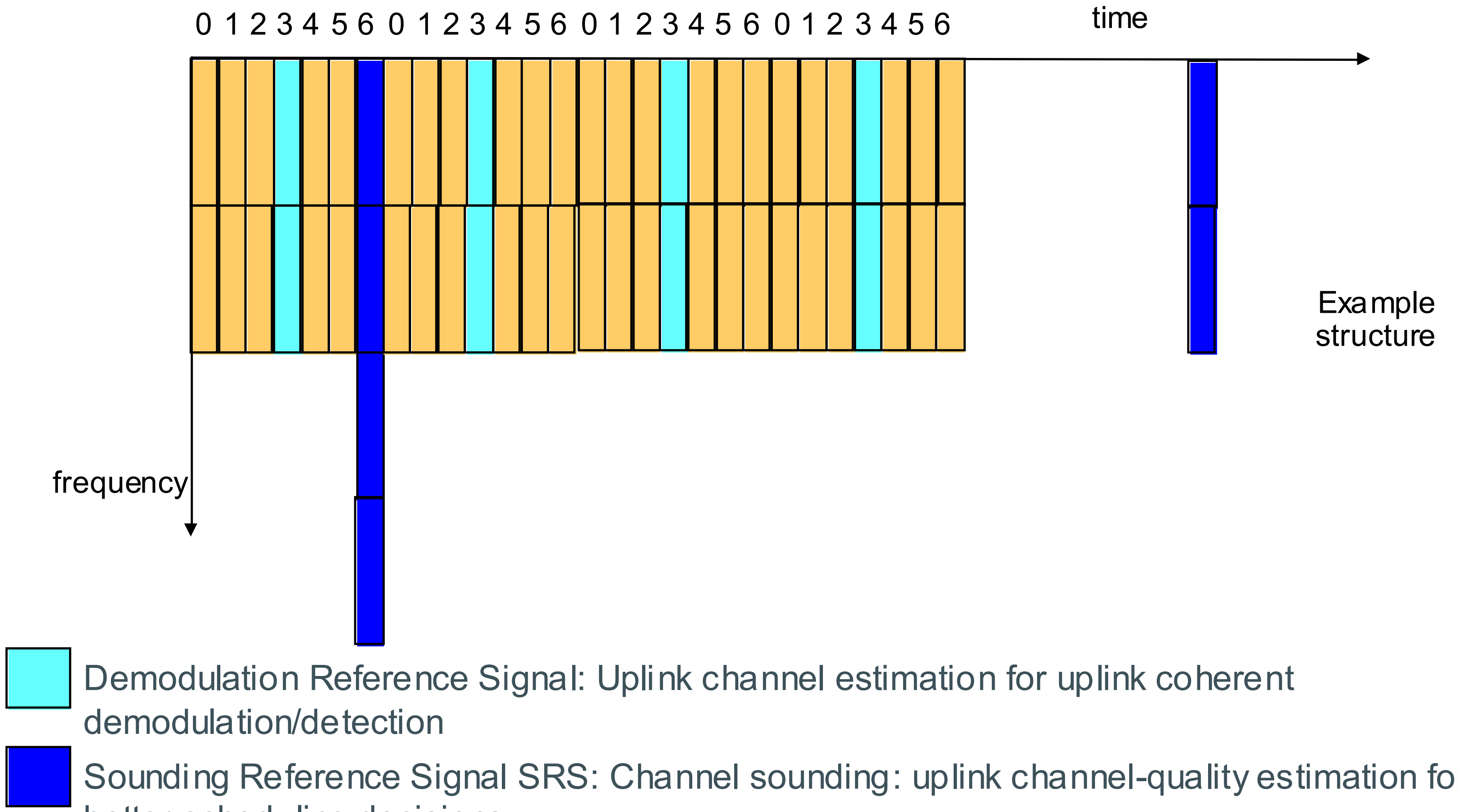
Neighbour cells should have different physical layer cell identities to be distinguished

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

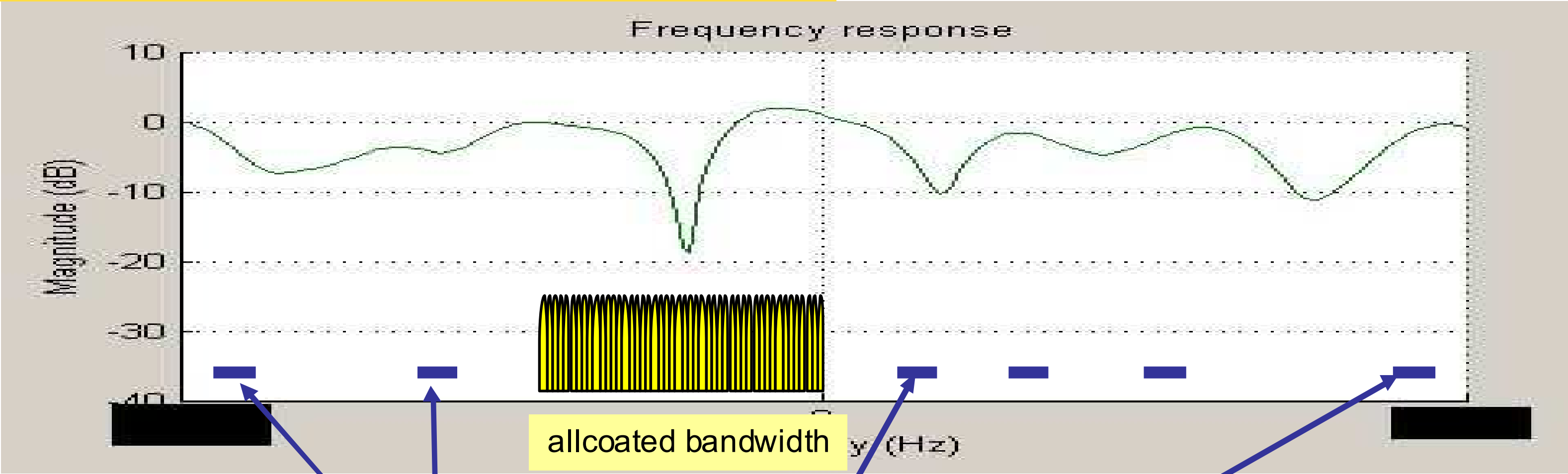


Demodulation Reference Signal: Uplink channel estimation for uplink coherent demodulation/detection

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

Sounding reference signal

Frequency selective channel



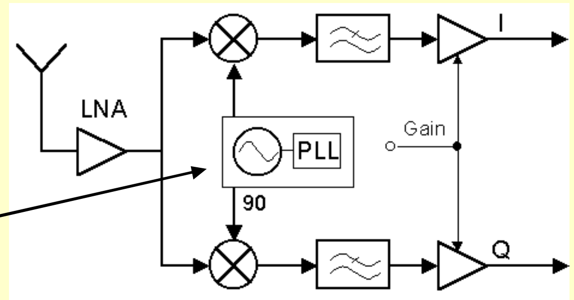
eNodeB configures the UE when and where to send sounding reference signals

Sounding reference signals in uplink may assist the eNodeB to investigate frequency selectivity

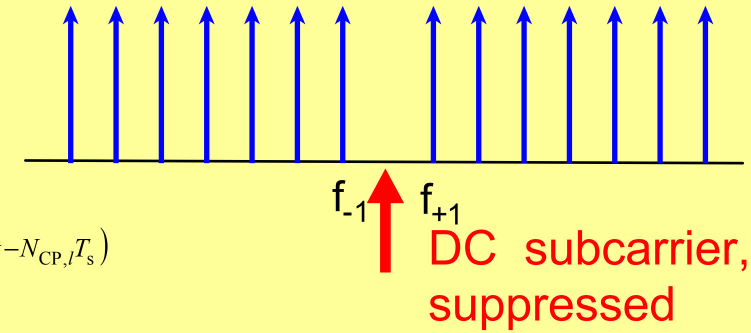
LTE Physical Layer Procedures

Subcarrier zero handling

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



Downlink:

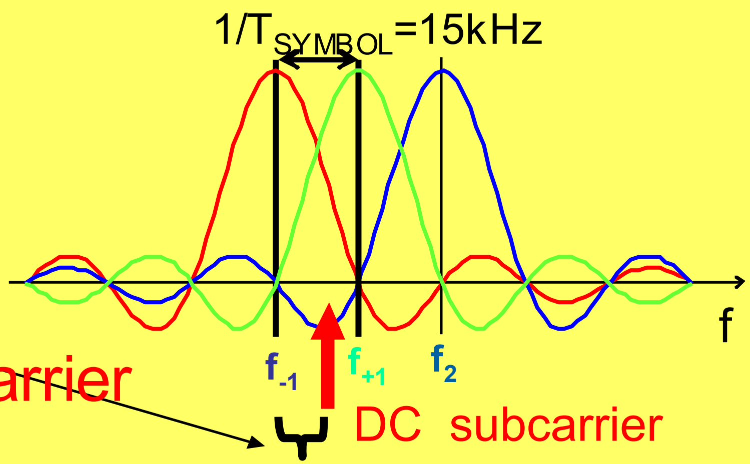


$$s_l^{(p)}(t)=\sum_{k=-\lfloor N_{\mathrm{RB}}^{\mathrm{DL}}N_{\mathrm{sc}}^{\mathrm{RB}}/2\rfloor}^{-1} a_{k^{(-)},l}^{(p)}\cdot e^{j2\pi k\Delta f(t-N_{\mathrm{CP},l}T_s)}+\sum_{k=1}^{\lceil N_{\mathrm{RB}}^{\mathrm{DL}}N_{\mathrm{sc}}^{\mathrm{RB}}/2\rceil} a_{k^{(+)},l}^{(p)}\cdot e^{j2\pi k\Delta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

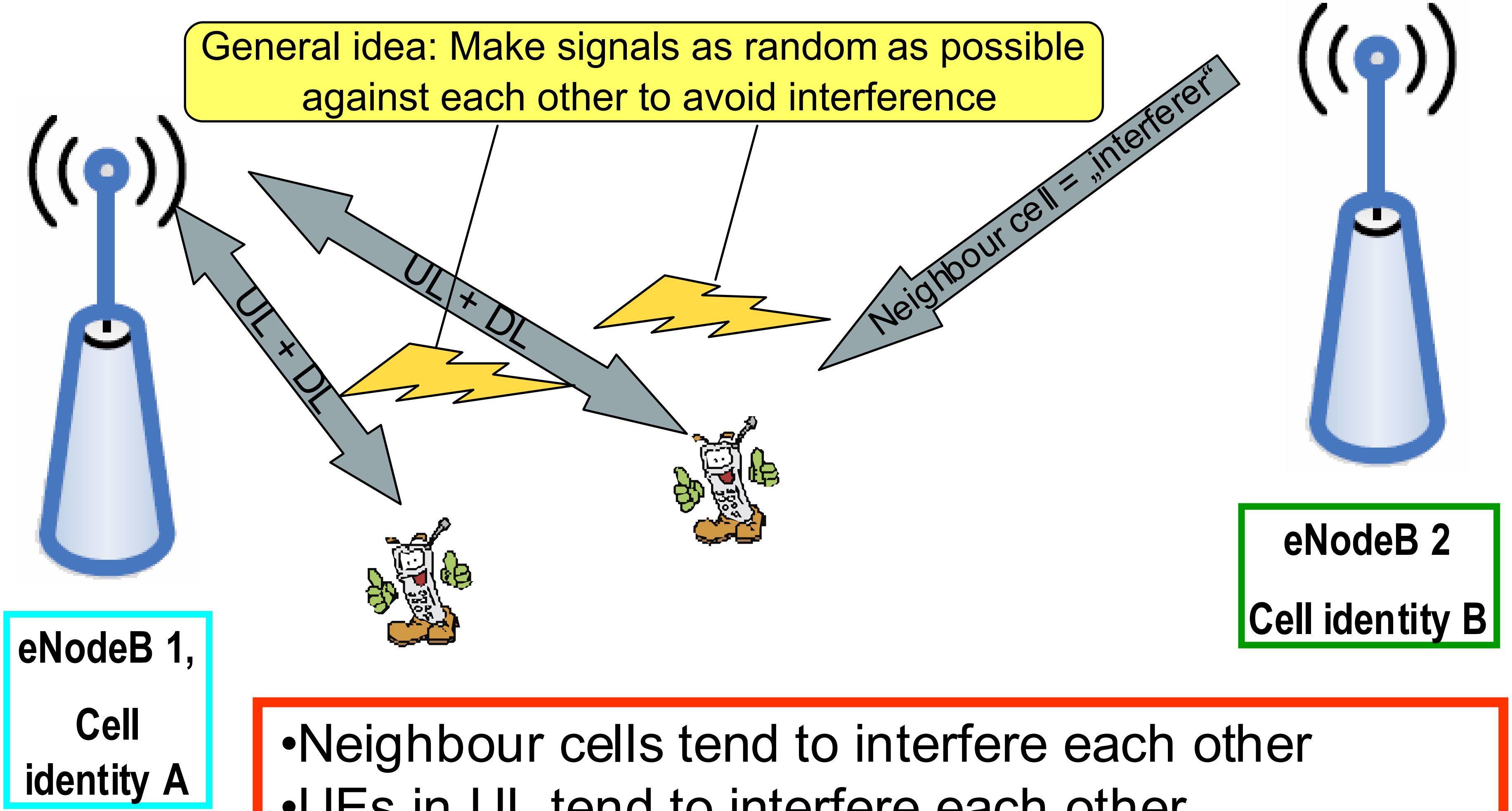
Uplink:

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

½ subcarrier offset

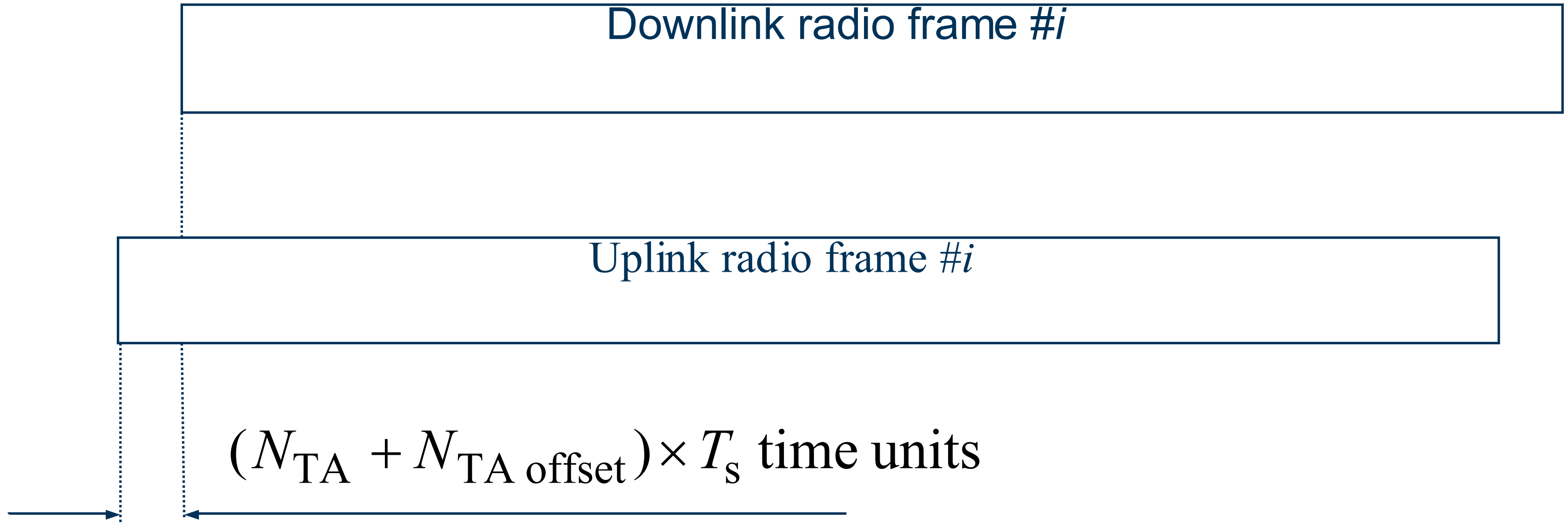


General aspect of PHY: interference avoidance



- Neighbour cells tend to interfere each other
- UEs in UL tend to interfere each other
- Reference + common channels tend to be „similar“

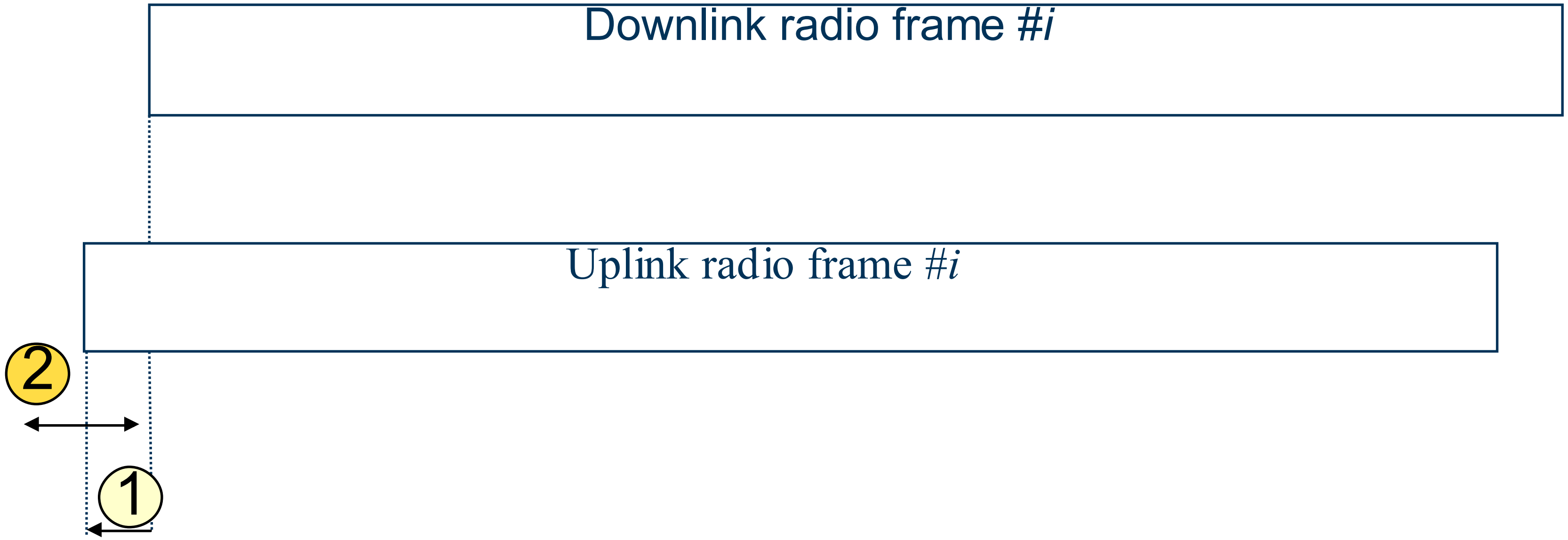
Uplink – Downlink Timing



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

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

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

LTE measurements

RSRP = Reference Signal Received Power

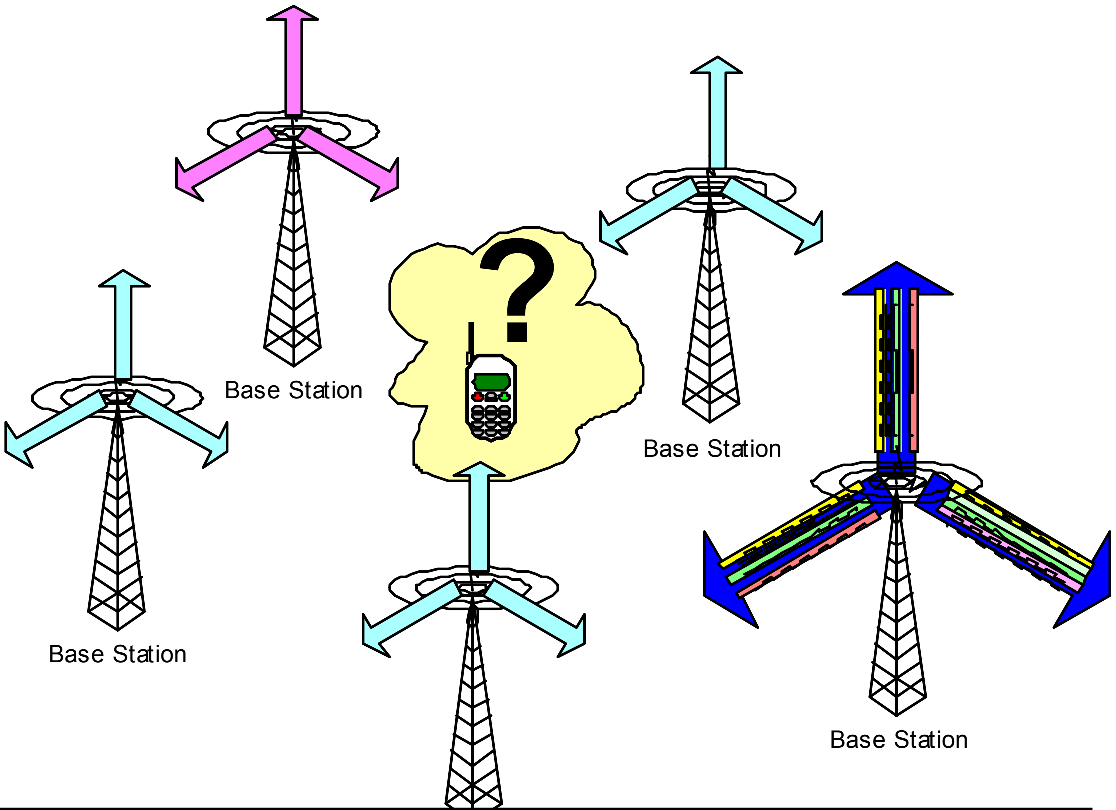
Definition	Reference signal received power, the mean measured power of the reference symbols during the measurement period.
Applicable for	TBD

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

Synchronisation Aspects in LTE

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

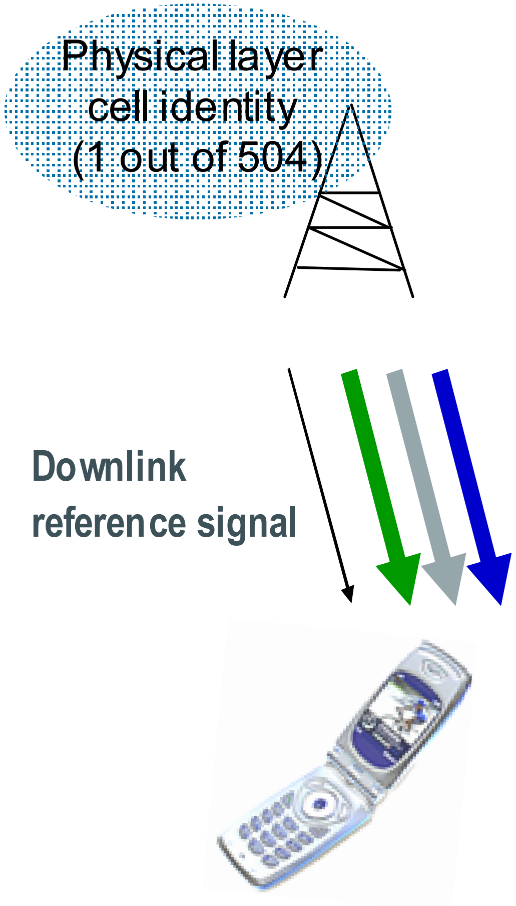
- 1. carrier frequency detection
- 2. primary synchronisation signal - > 5msec timing and $N_{\mathrm{ID}}^{(2)}$
- 3. secondary synchronisation signal -> 10msec timing and $N_{\mathrm{ID}}^{(1)}$
- 4. Derive physical layer cell identity out of PSS and SSS
- 5. Blind detect cyclic prefix duration (extended 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			Downlink (DL) BS transmit UE receive			Duplex Mode
	F_{UL_low}	–	F_{UL_high}	F_{DL_low}	–	F_{DL_high}	
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



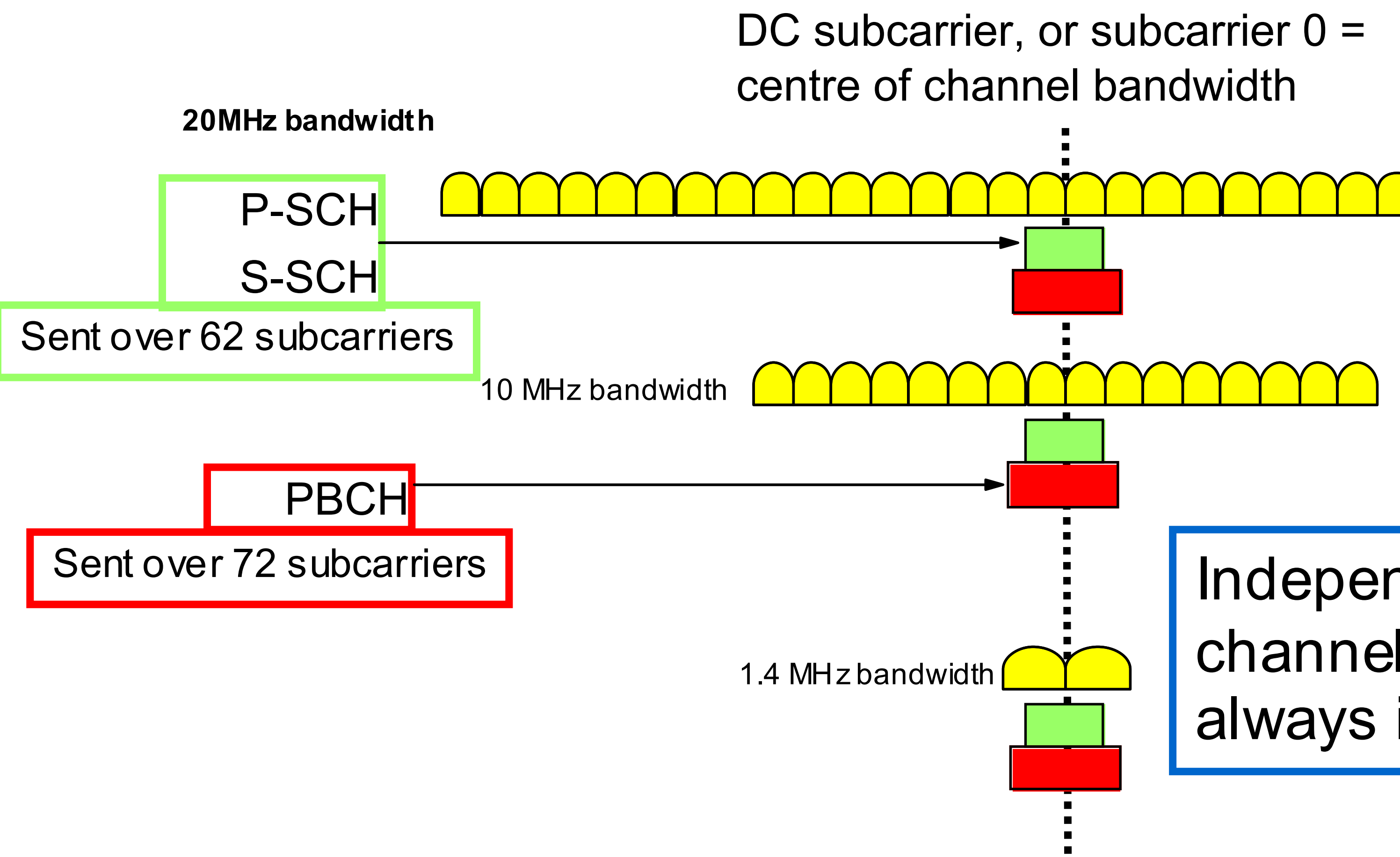
1. **Primary synchronization signal:**
   3 possible sequences to identify the cell's physical layer identity (0, 1, 2)
   Transmitted every 5 ms to identify 5 ms timing

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



Independent of channel bandwidth, always in the centre

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

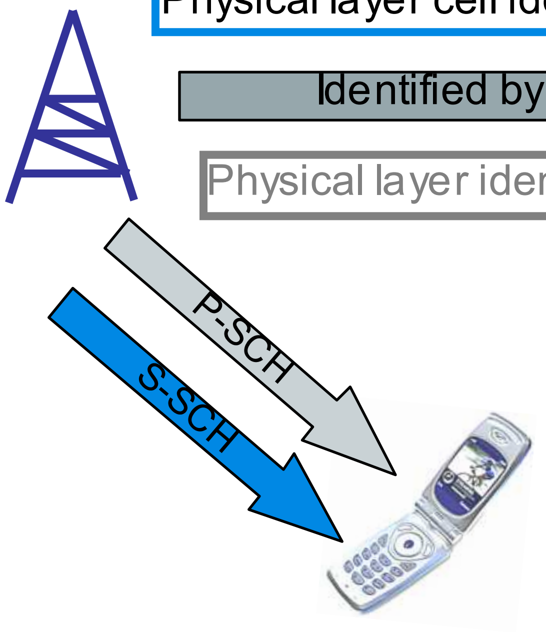
Physical layer identity

„Smith“ „Miller“ „Kennedy“

0 1 ………….. 167

0 1 2 0 1 2 0 1 2

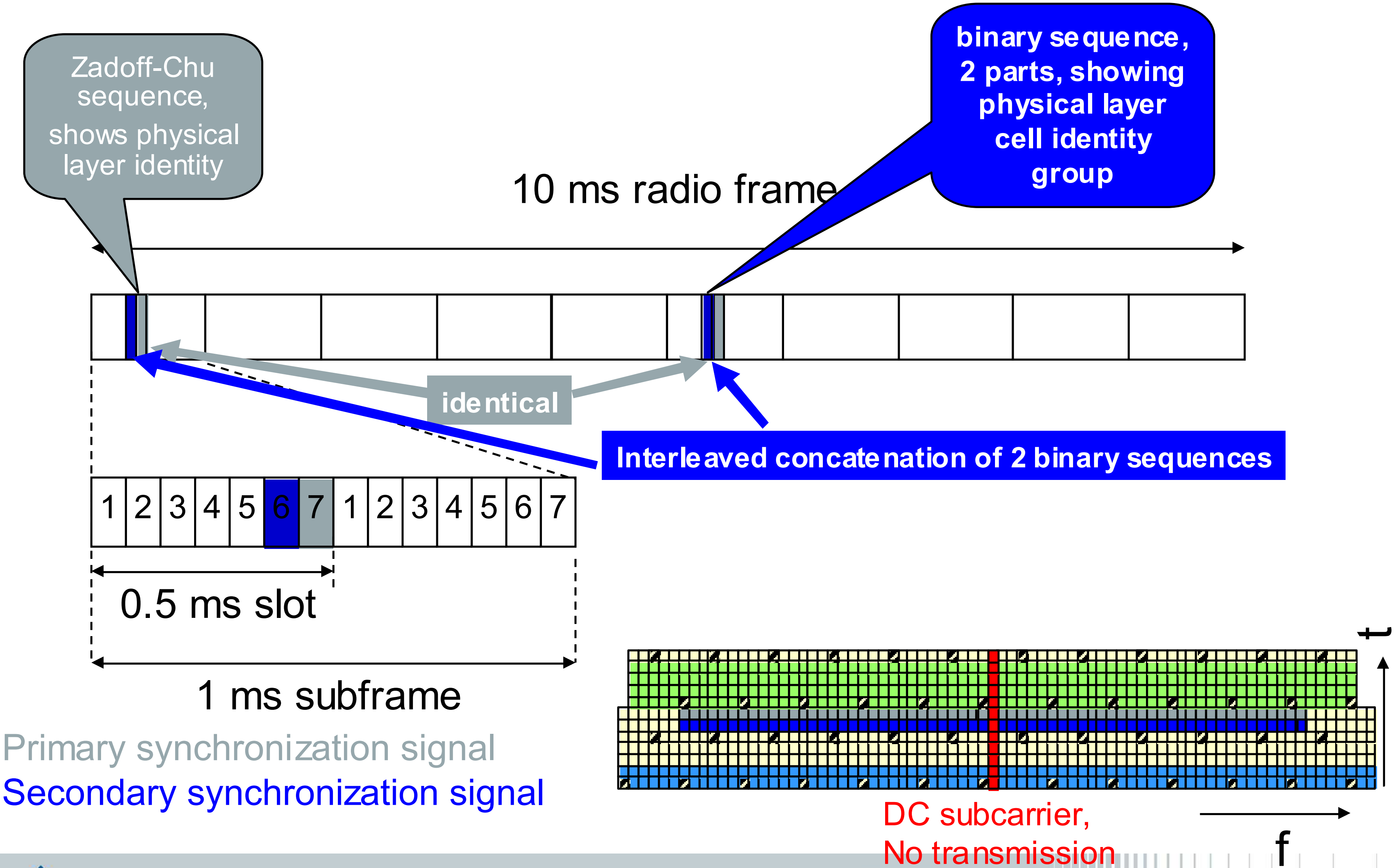
„Peter“ „Bob“ „John“ „Peter“ „Bob“ „John“ „Peter“ „Bob“ „John“



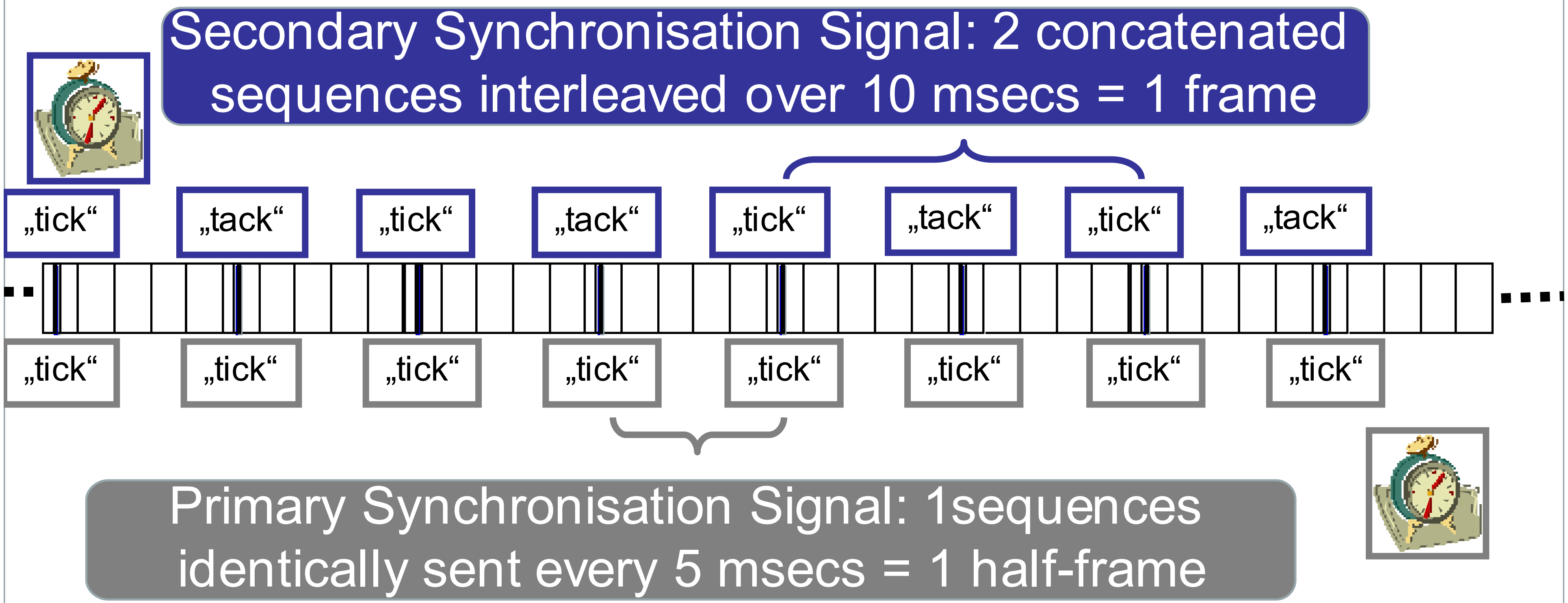
Primary Sync Channel P-SCH: 3 possible sequences to identify physical layer identity $N_{ID}^{(2)}$ = 0,1,2

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

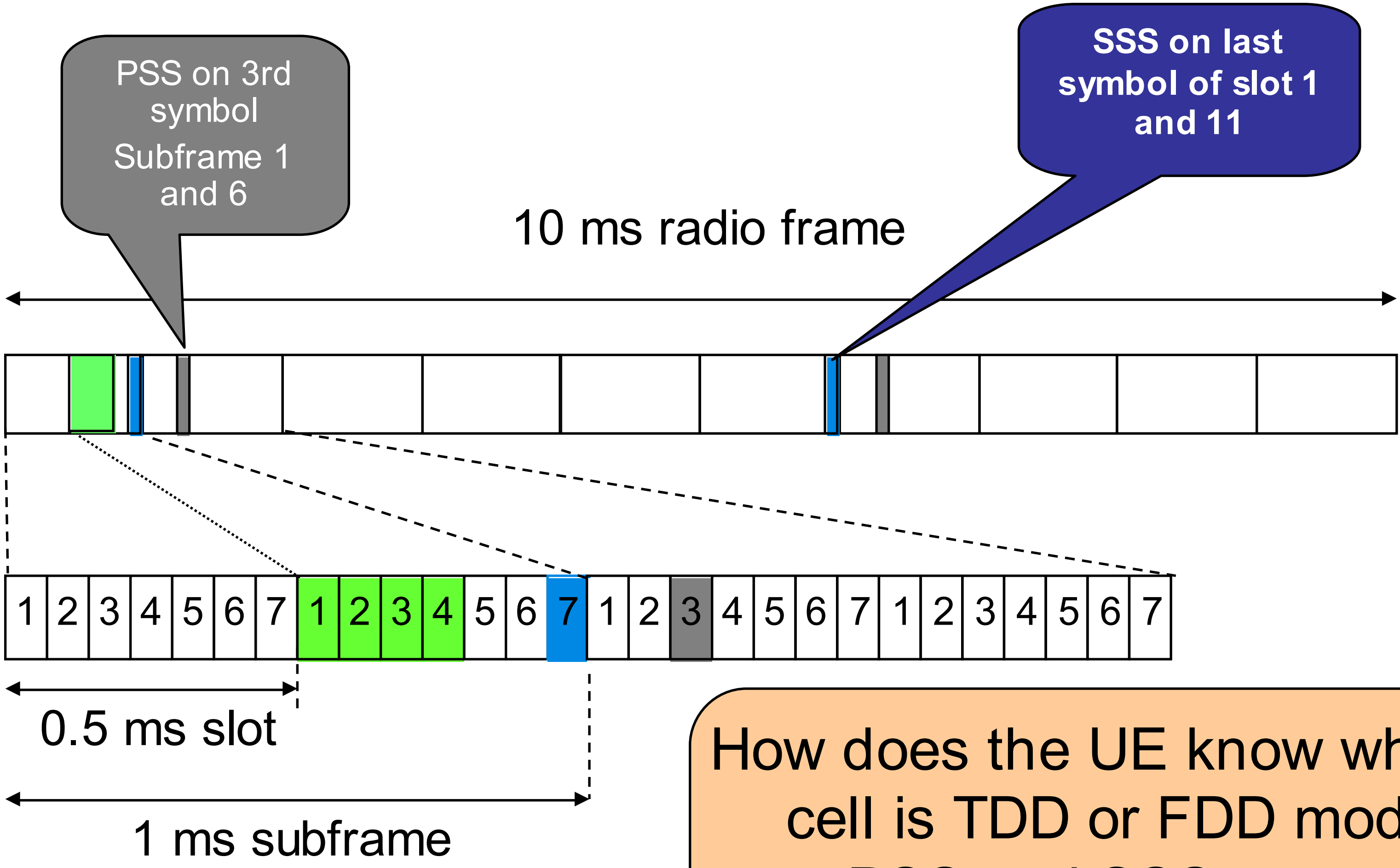
LTE Downlink: P-SCH and S-SCH



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**

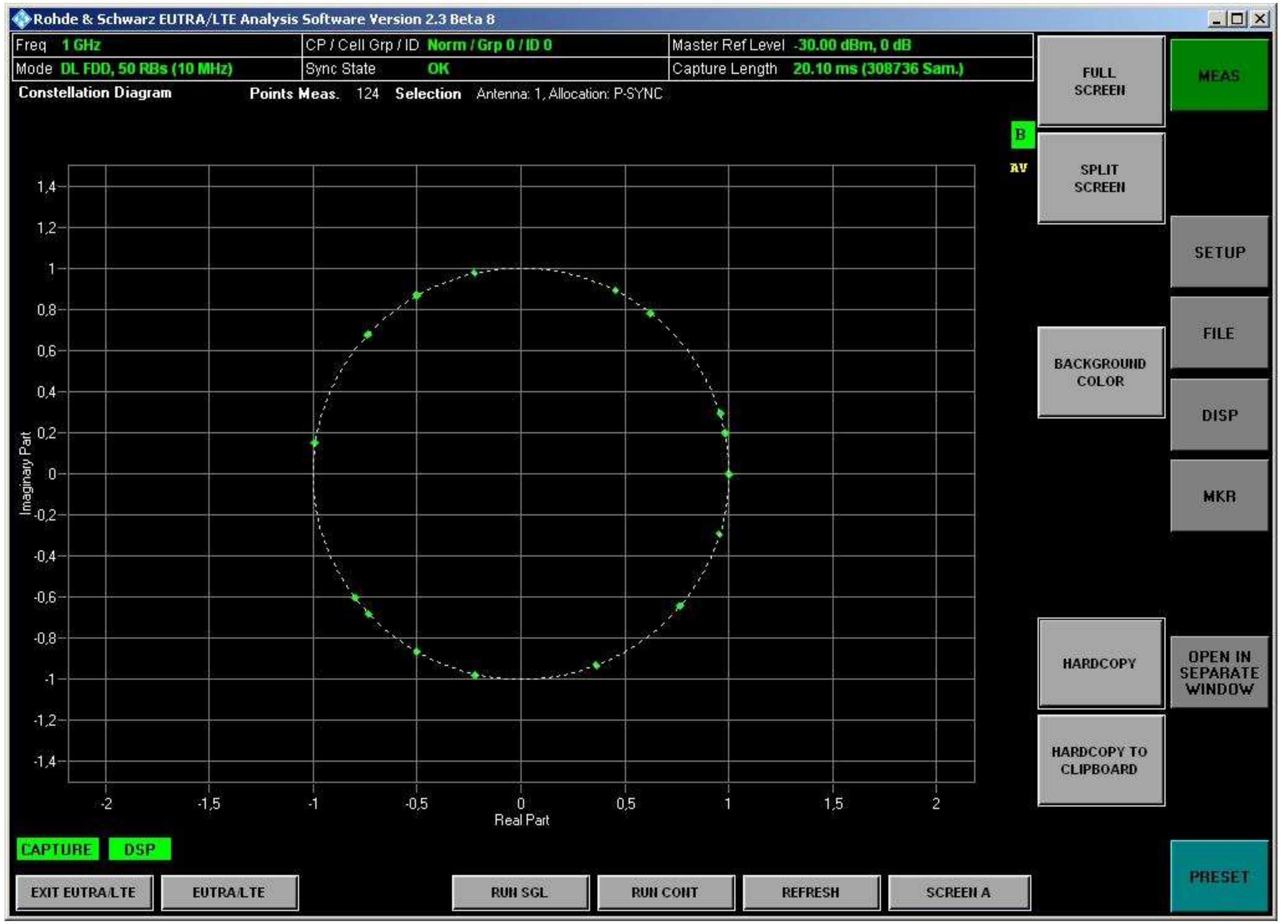
$$a_{k,l} = d(n), \qquad n = 0,\ldots,61$$

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

Alleviates search,
UE can use
size 64 FFT window

Primary Synchronisation Signal PSS

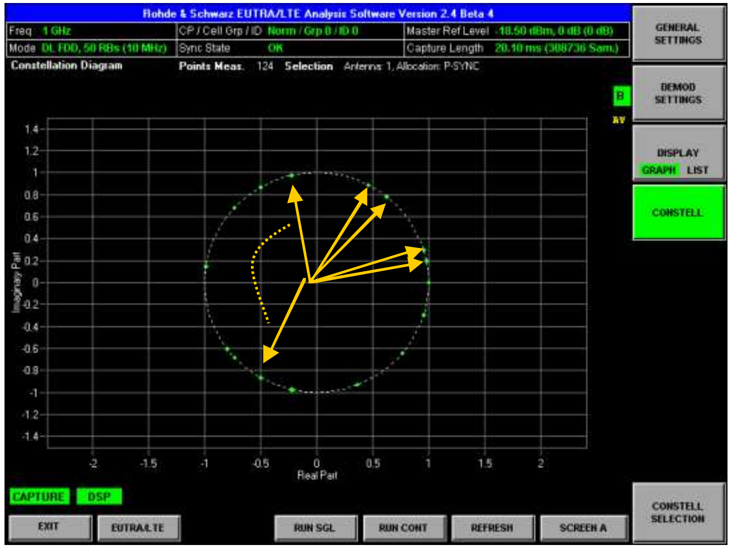
$$N_{\mathrm{ID}}^{(2)} = 0$$



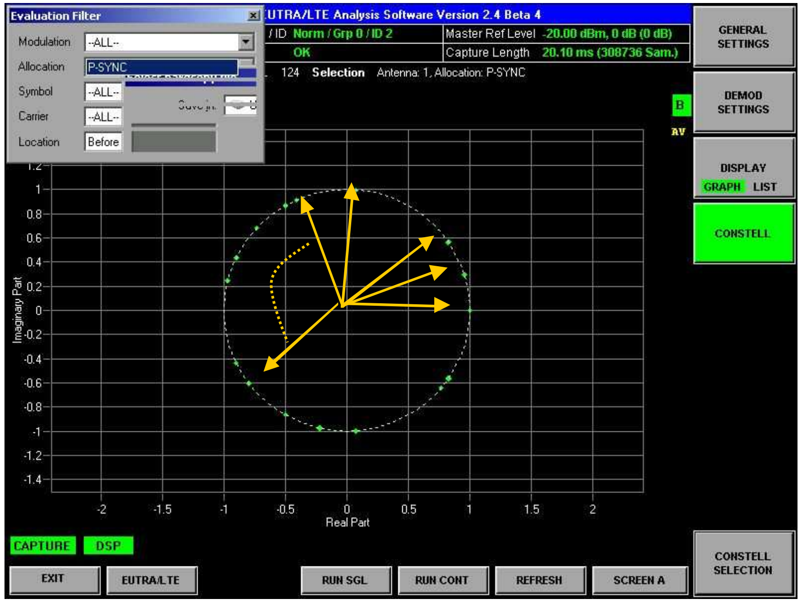
Primary Synchronisation Signal PSS

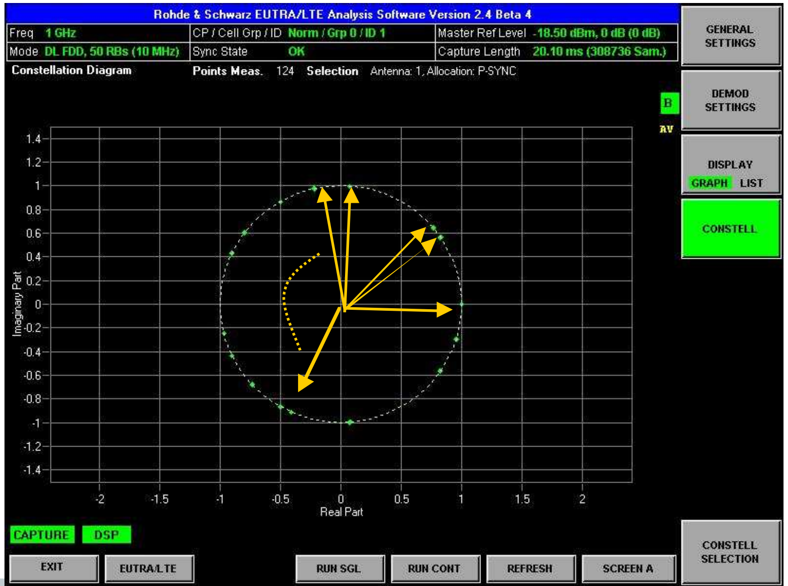
PSS is characterized by different phase shifts

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



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





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

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**

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

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

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

FDD mode

TDD mode

Secondary Synchronisation Signal

Indices m0 and m1 defines the physical layer cell identity group $N_{\mathrm{ID}}^{(1)}$

Even resource element

$$d(2n)=\begin{cases} s_0^{(m_0)}(n)c_0(n) & \text{in subframe 0} \\ s_1^{(m_1)}(n)c_0(n) & \text{in subframe 5} \end{cases}$$

$$d(2n+1)=\begin{cases} s_1^{(m_1)}(n)c_1(n)z_1^{(m_0)}(n) & \text{in subframe 0} \\ s_0^{(m_0)}(n)c_1(n)z_1^{(m_1)}(n) & \text{in subframe 5} \end{cases}$$

Odd resource element

identify physical layer cell identity group $N_{\mathrm{ID}}^{(1)}$

Sequence s() is a pseudo random sequence, given as:

$$s_0^{(m_0)}(n)=\tilde{s}((n+m_0)\bmod 31)$$
$$s_1^{(m_1)}(n)=\tilde{s}((n+m_1)\bmod 31)$$

$$\tilde{s}(i)=1-2x(i)$$

$$x(\bar{i}+5)=\left(x(\bar{i}+2)+x(\bar{i})\right)\bmod 2, \qquad 0\le \bar{i}\le 25$$

$$x(0)=0,\quad x(1)=0,\quad x(2)=0,\quad x(3)=0,\quad x(4)=1$$

Sequence c() is a pseudo random sequence used as scrambling sequence

identify cell, within eNodeB

$$c_0(n)=\tilde{c}((n+N_{\mathrm{ID}}^{(2)})\bmod 31)$$
$$c_1(n)=\tilde{c}((n+N_{\mathrm{ID}}^{(2)}+3)\bmod 31)$$

$$\tilde{c}(i)=1-2x(i)$$

$$x(\bar{i}+5)=\left(x(\bar{i}+3)+x(\bar{i})\right)\bmod 2, \qquad 0\le \bar{i}\le 25$$

Sequence z() is a pseudo random sequence used as scrambling sequence

identify cell at cell edge

$$z_1^{(m_0)}(n)=\tilde{z}((n+(m_0 \bmod 8))\bmod 31)$$

$$z_1^{(m_1)}(n)=\tilde{z}((n+(m_1 \bmod 8))\bmod 31)$$

$$\tilde{z}(i)=1-2x(i)$$

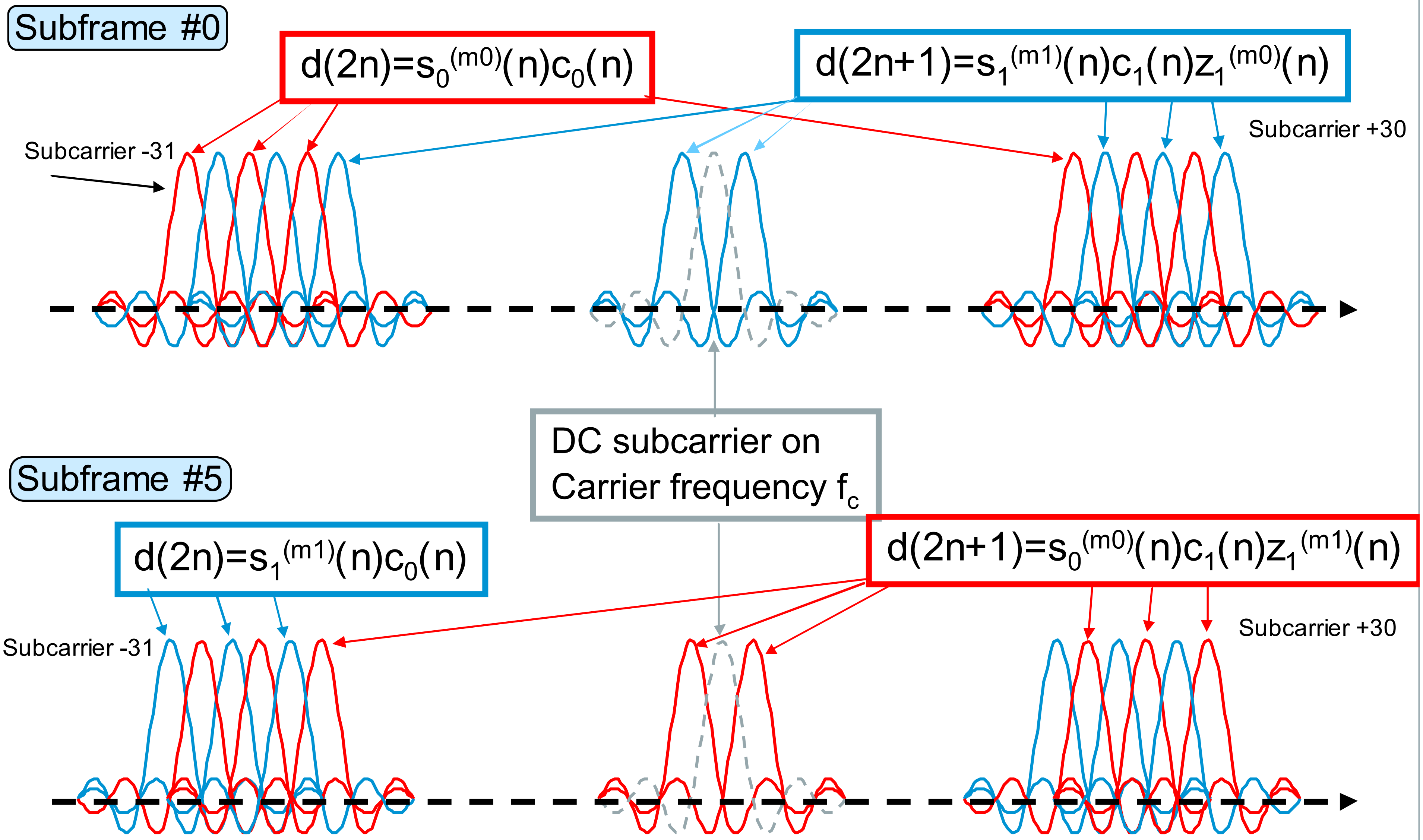
$$x(\bar{i}+5)=\left(x(\bar{i}+4)+x(\bar{i}+2)+x(\bar{i}+1)+x(\bar{i})\right)\bmod 2, \qquad 0\le \bar{i}\le 25$$

Secondary Synchronisation Signal

Indices m0 and m1 defines the physical layer cell identity group $N_{ID}^{(1)}$

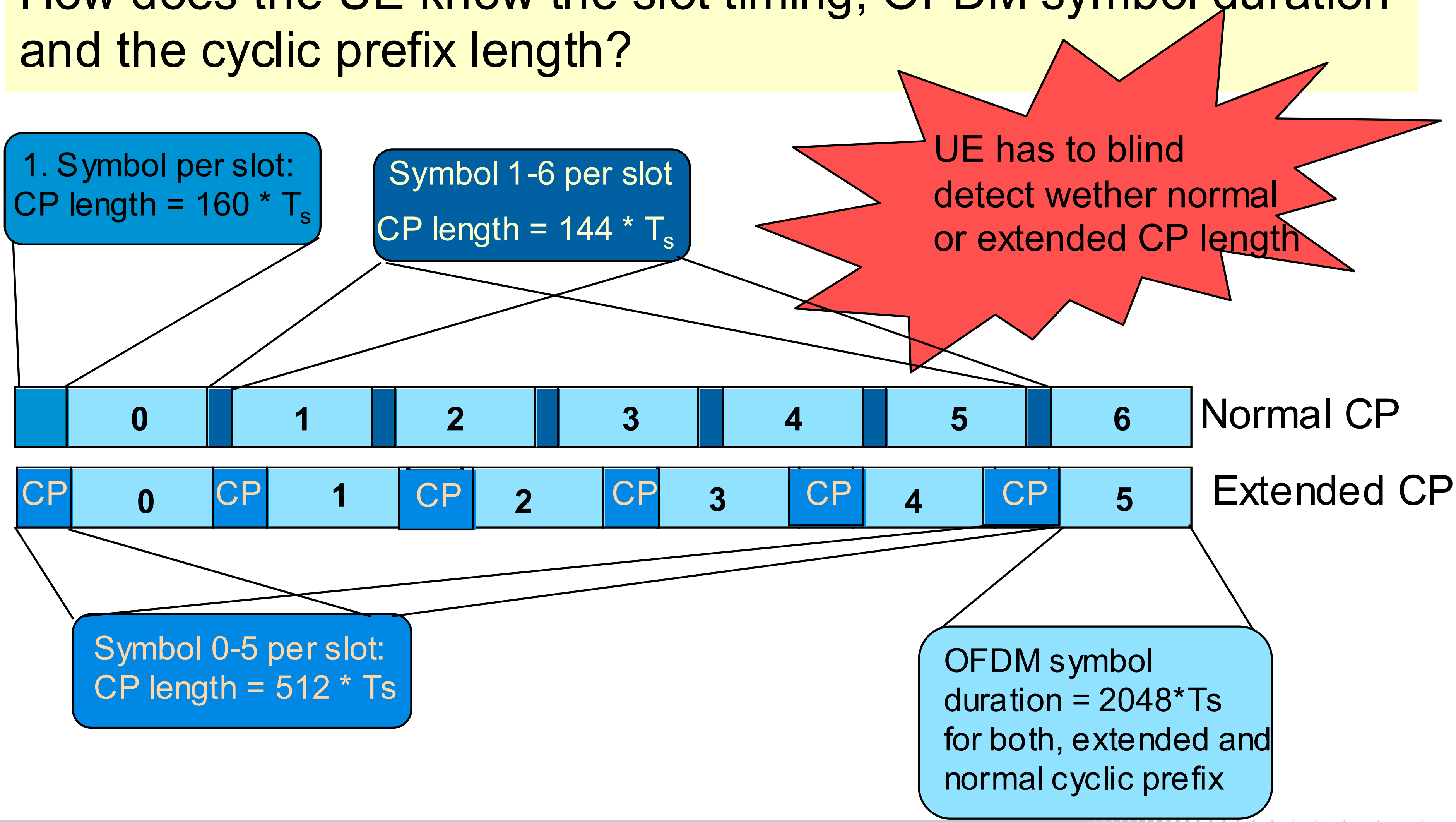
$N_{ID}^{(1)}$	m_0	m_1	$N_{ID}^{(1)}$	m_0	m_1	$N_{ID}^{(1)}$	m_0	m_1	$N_{ID}^{(1)}$	m_0	m_1	$N_{ID}^{(1)}$	m_0	m_1
0	0	1	34	4	6	68	9	12	102	15	19	136	22	27
1	1	2	35	5	7	69	10	13	103	16	20	137	23	28
2	2	3	36	6	8	70	11	14	104	17	21	138	24	29
3	3	4	37	7	9	71	12	15	105	18	22	139	25	30
4	4	5	38	8	10	72	13	16	106	19	23	140	0	6
5	5	6	39	9	11	73	14	17	107	20	24	141	1	7
6	6	7	40	10	12	74	15	18	108	21	25	142	2	8
7	7	8	41	11	13	75	16	19	109	22	26	143	3	9
8	8	9	42	12	14	76	17	20	110	23	27	144	4	10
9	9	10	43	13	15	77	18	21	111	24	28	145	5	11
10	10	11	44	14	16	78	19	22	112	25	29	146	6	12
11	11	12	45	15	17	79	20	23	113	26	30	147	7	13
12	12	13	46	16	18	80	21	24	114	0	5	148	8	14
13	13	14	47	17	19	81	22	25	115	1	6	149	9	15
14	14	15	48	18	20	82	23	26	116	2	7	150	10	16
15	15	16	49	19	21	83	24	27	117	3	8	151	11	17
16	16	17	50	20	22	84	25	28	118	4	9	152	12	18
17	17	18	51	21	23	85	26	29	119	5	10	153	13	19
18	18	19	52	22	24	86	27	30	120	6	11	154	14	20
19	19	20	53	23	25	87	0	4	121	7	12	155	15	21
20	20	21	54	24	26	88	1	5	122	8	13	156	16	22
21	21	22	55	25	27	89	2	6	123	9	14	157	17	23
22	22	23	56	26	28	90	3	7	124	10	15	158	18	24
23	23	24	57	27	29	91	4	8	125	11	16	159	19	25
24	24	25	58	28	30	92	5	9	126	12	17	160	20	26
25	25	26	59	0	3	93	6	10	127	13	18	161	21	27
26	26	27	60	1	4	94	7	11	128	14	19	162	22	28
27	27	28	61	2	5	95	8	12	129	15	20	163	23	29
28	28	29	62	3	6	96	9	13	130	16	21	164	24	30
29	29	30	63	4	7	97	10	14	131	17	22	165	0	7
30	0	2	64	5	8	98	11	15	132	18	23	166	1	8
31	1	3	65	6	9	99	12	16	133	19	24	167	2	9
32	2	4	66	7	10	100	13	17	134	20	25	-	-	-
33	3	5	67	8	11	101	14	18	135	21	26	-	-	-

Secondary Synchronisation Signal



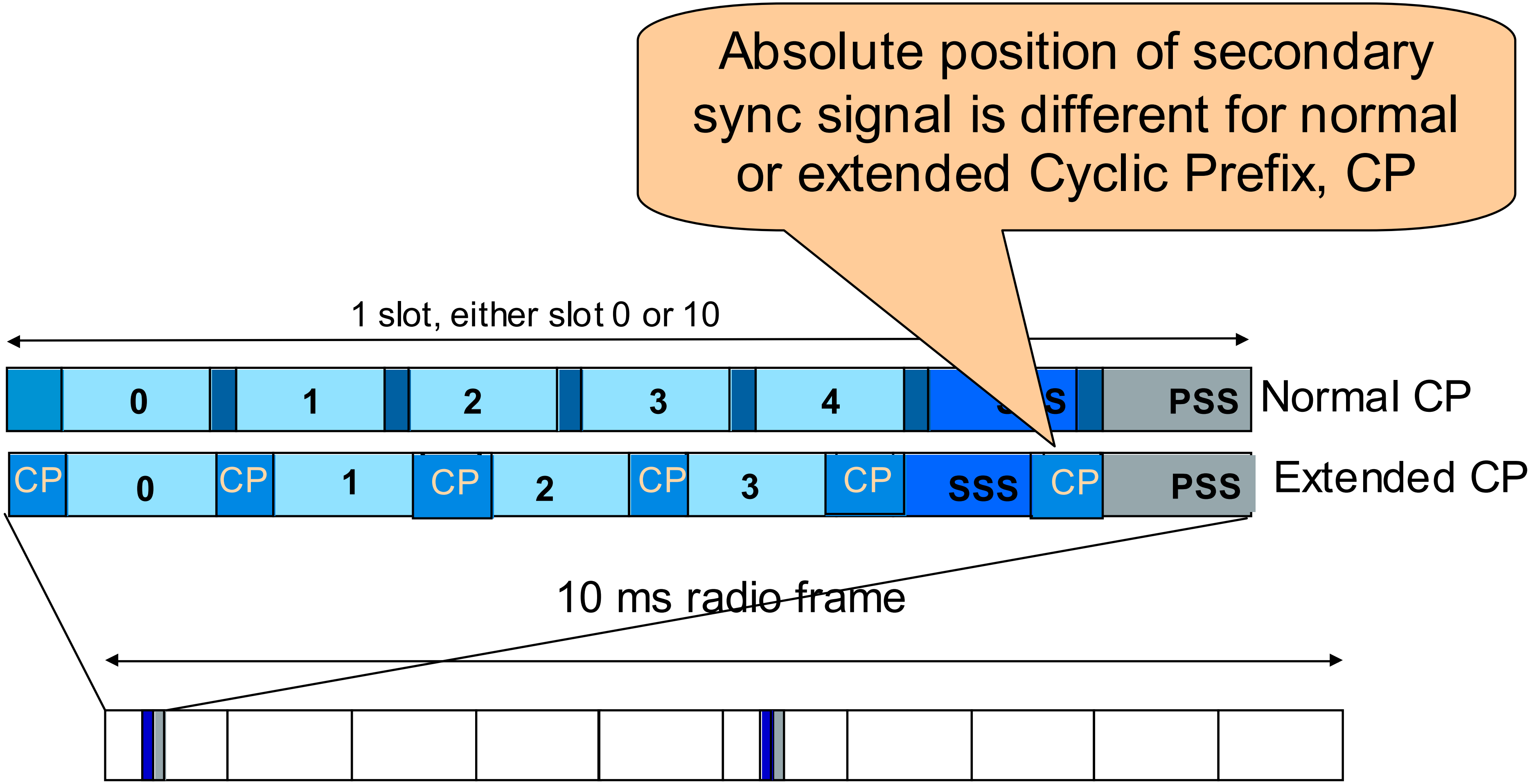
LTE timing + estimate slot and symbol duration

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?



Cell specific reference signal

- **Reference signal sequence given as:**

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

- **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

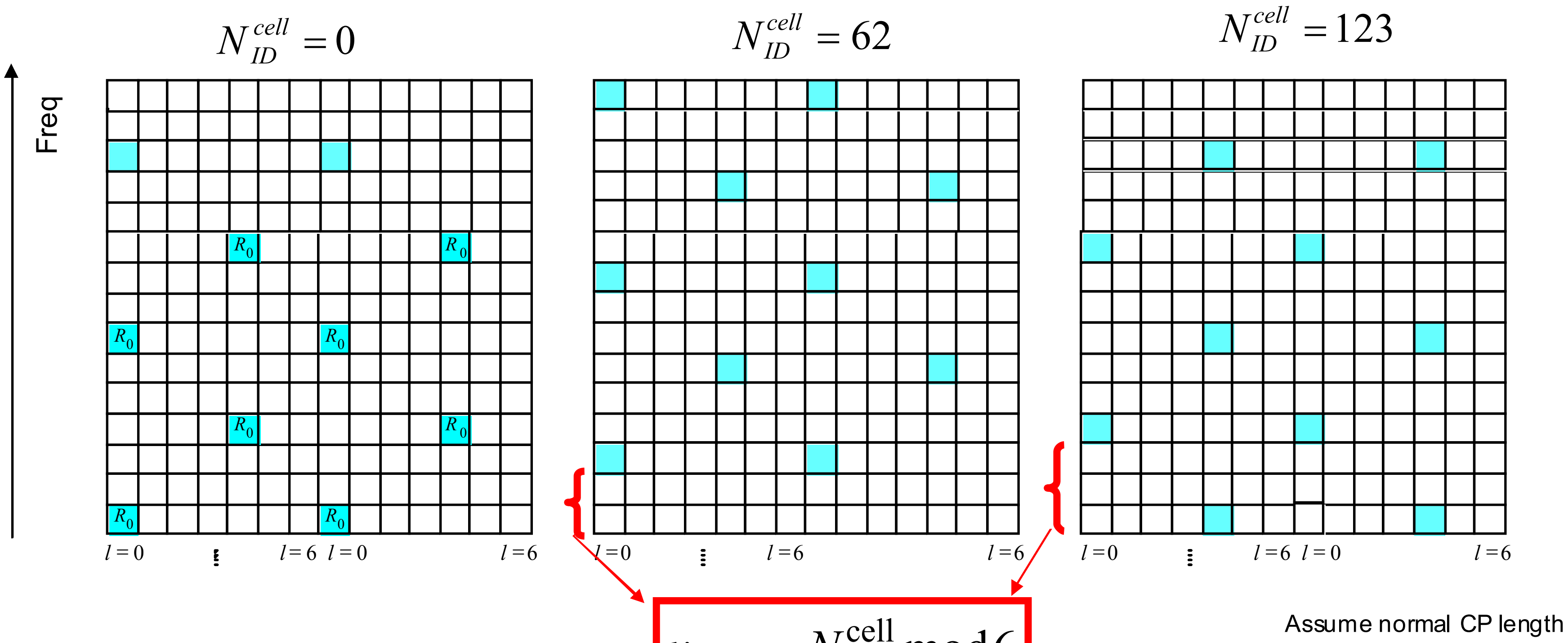
Physical layer cell identity

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**

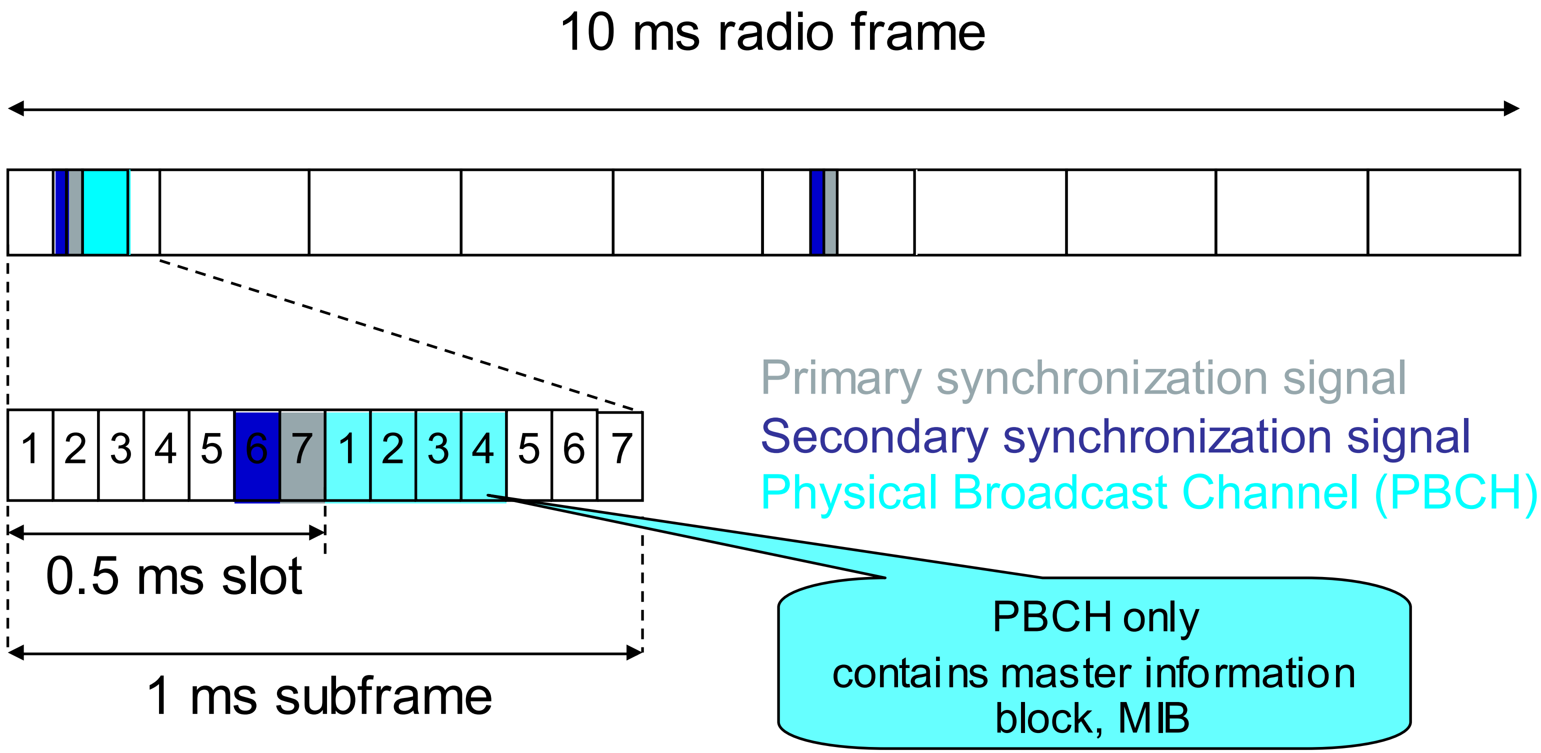
Cell specific reference signals



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

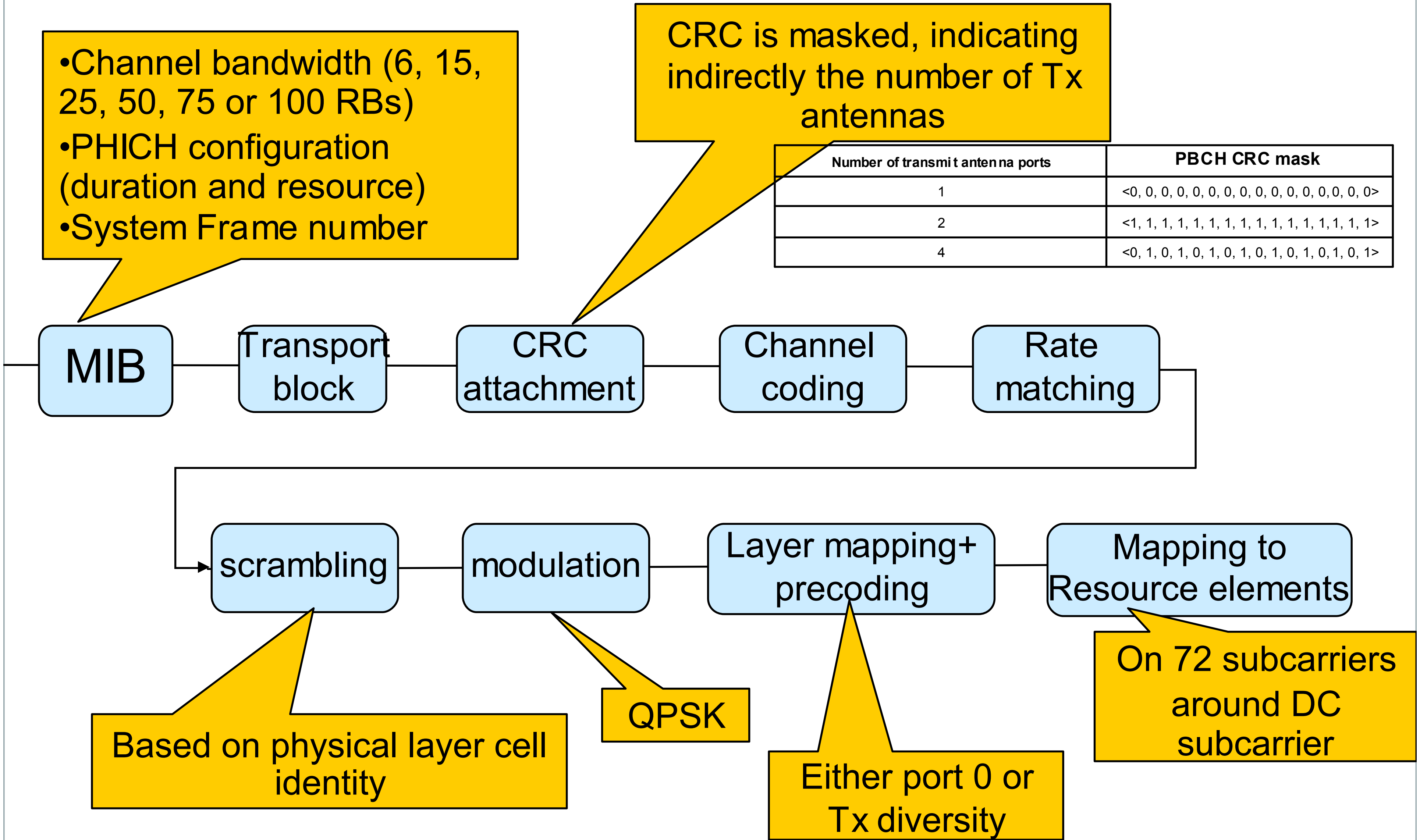
Cell specific reference symbols are frequency staggered with frequency shift depending on cell identity to ease detection. Example here 3 neighbour cells with different identities

LTE Downlink
Configuration of physical broadcast channel



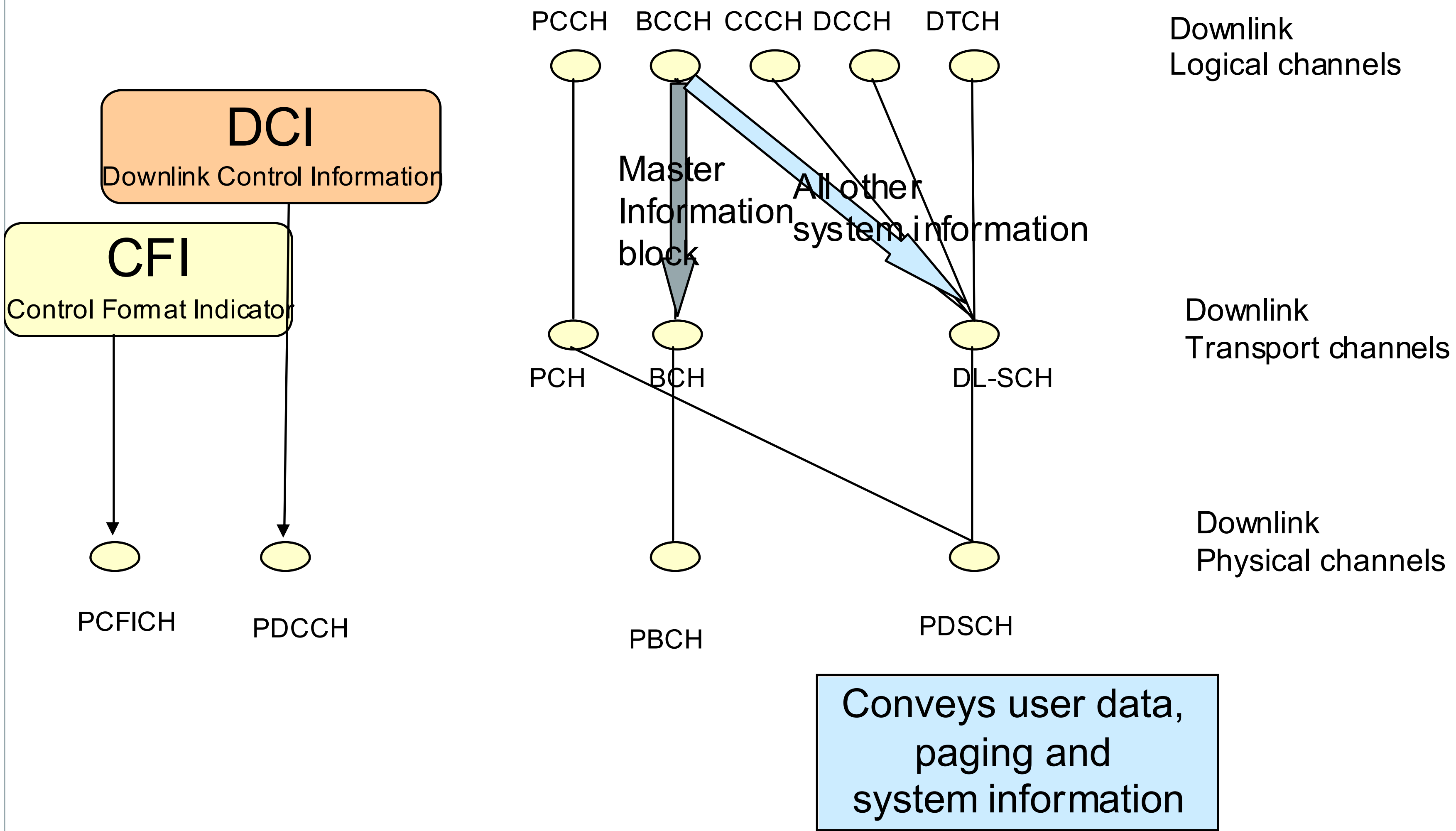
PBCH has 40 ms transmission time interval

Physical Broadcast Channel, PBCH

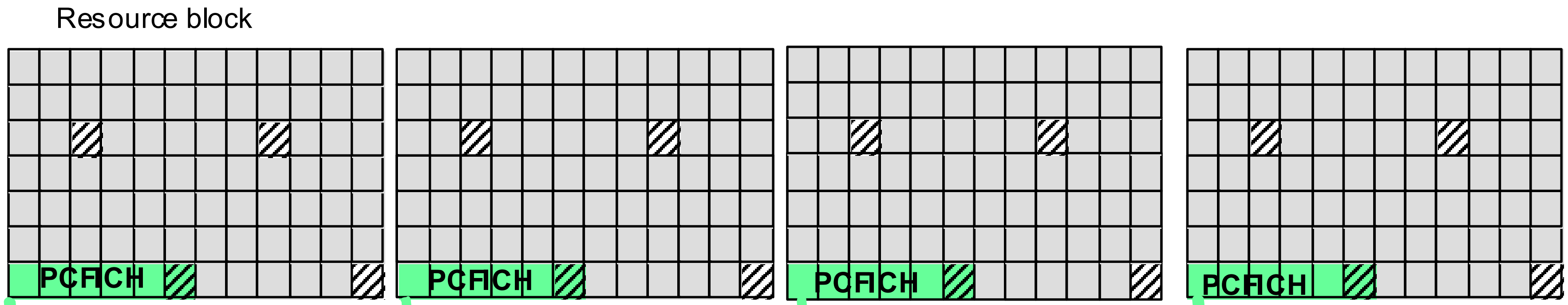


Number of transmit antenna ports	PBCH CRC mask
1	<0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0>
2	<1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1>
4	<0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1>

LTE – acquiring system information

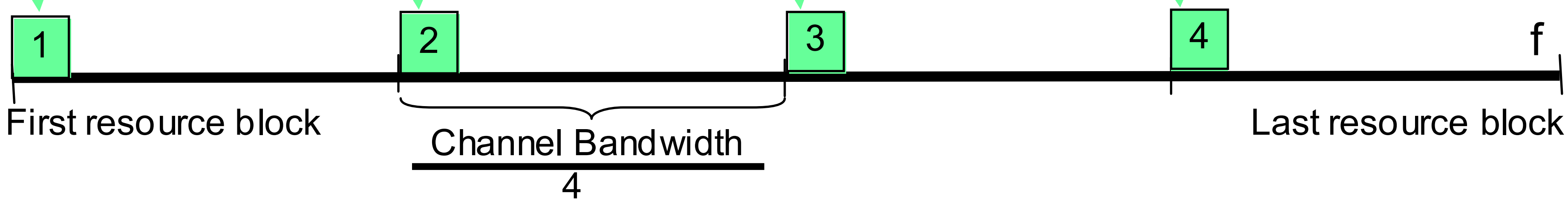


PCFICH mapping on physical resource



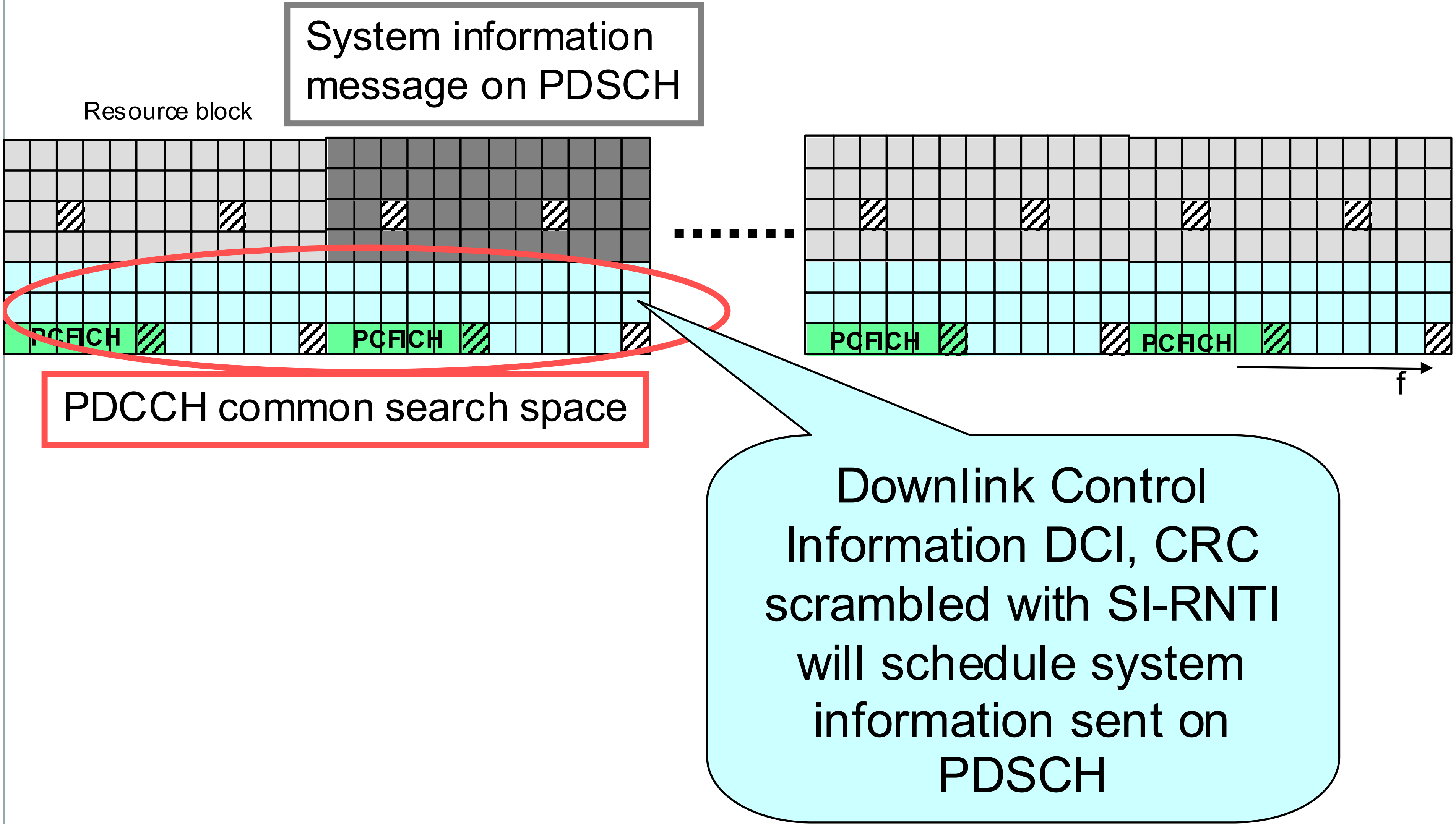
Mapping of PCFICH onto resource elements is based on Physical layer cell Identity!

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

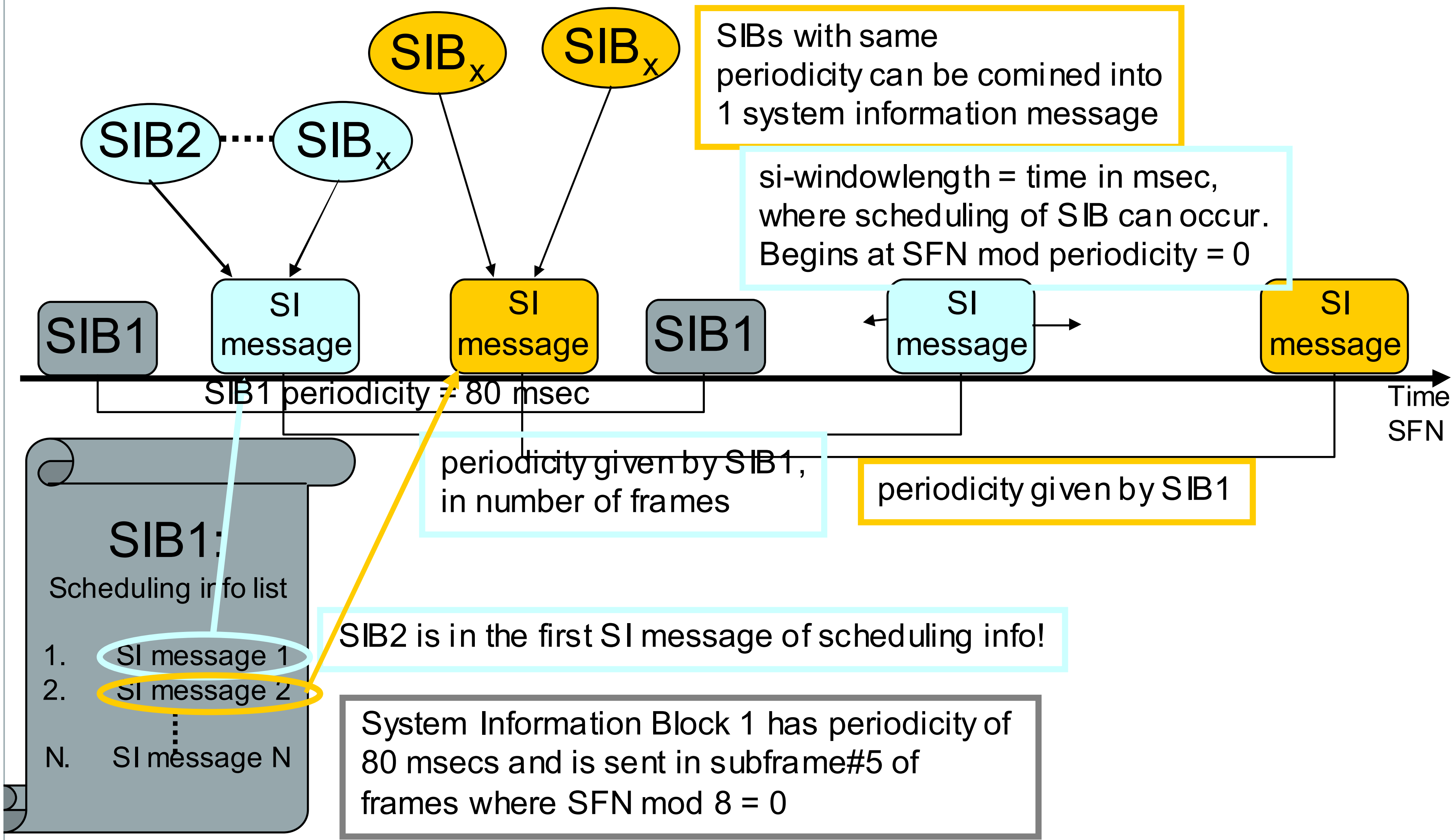


UE knows channel bandwidth and Physical layer cell identity from MIB and sync channels -> UE reads PCFICH to know where PDCCH is

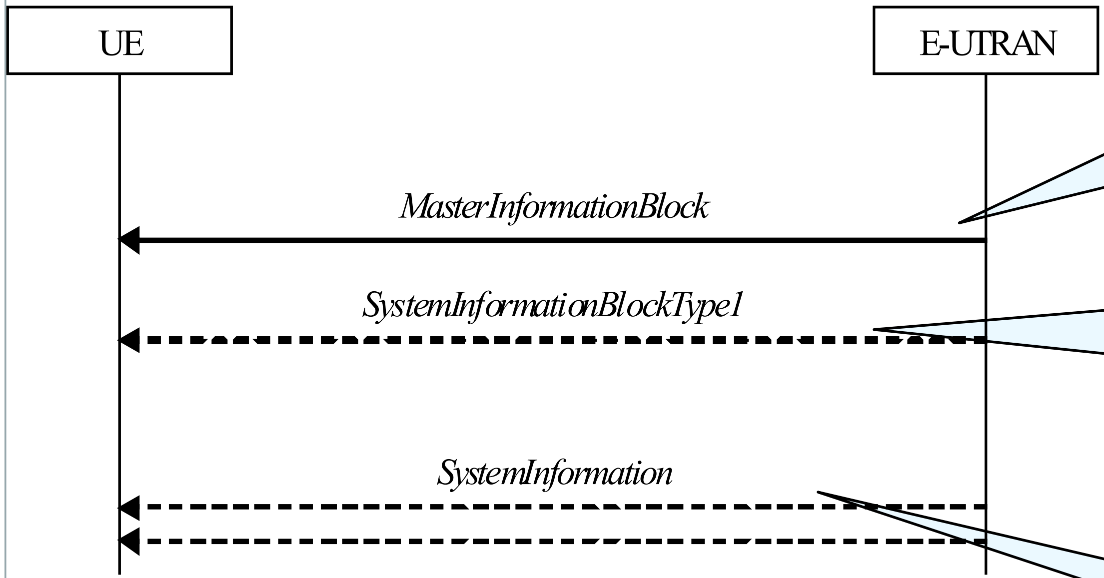
PDCCH scheduling SysInfo on PDSCH



System Information Scheduling



System information broadcast



Master Information Block (on BCH), periodicity 40 ms:
System bandwidth, number of transmit antennas, PHICH configuration, SFN

System Information Block Type 1 (on DL-SCH), periodicity 80 ms:
PLMN IDs, Tracking Area Code, Cell identity, Access restrictions, scheduling information,…

System information blocks with same scheduling requirements can be mapped to same SI message (DL-SCH)

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

System information

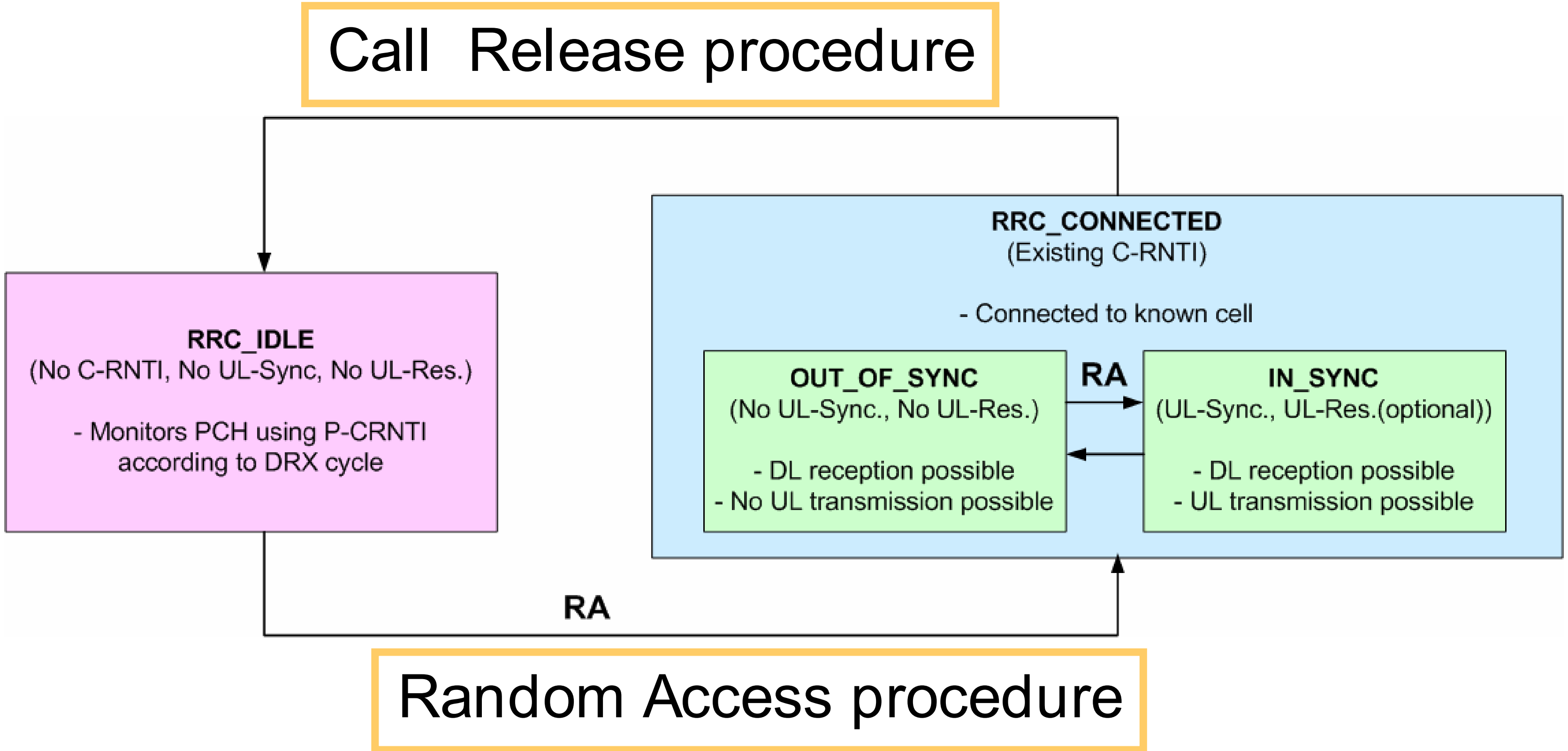
MIB: Physical layer info	SIB Type 1: Access restrictions, SIB scheduling info	SIB Type 2: Common and shared channel info
SIB Type 3: Cell reselection info	SIB Type 4: Cell reselection info, intra-fr. neighbour info	SIB Type 5: Cell reselection info, inter-fr. neighbour info
SIB Type 6: Cell reselection 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

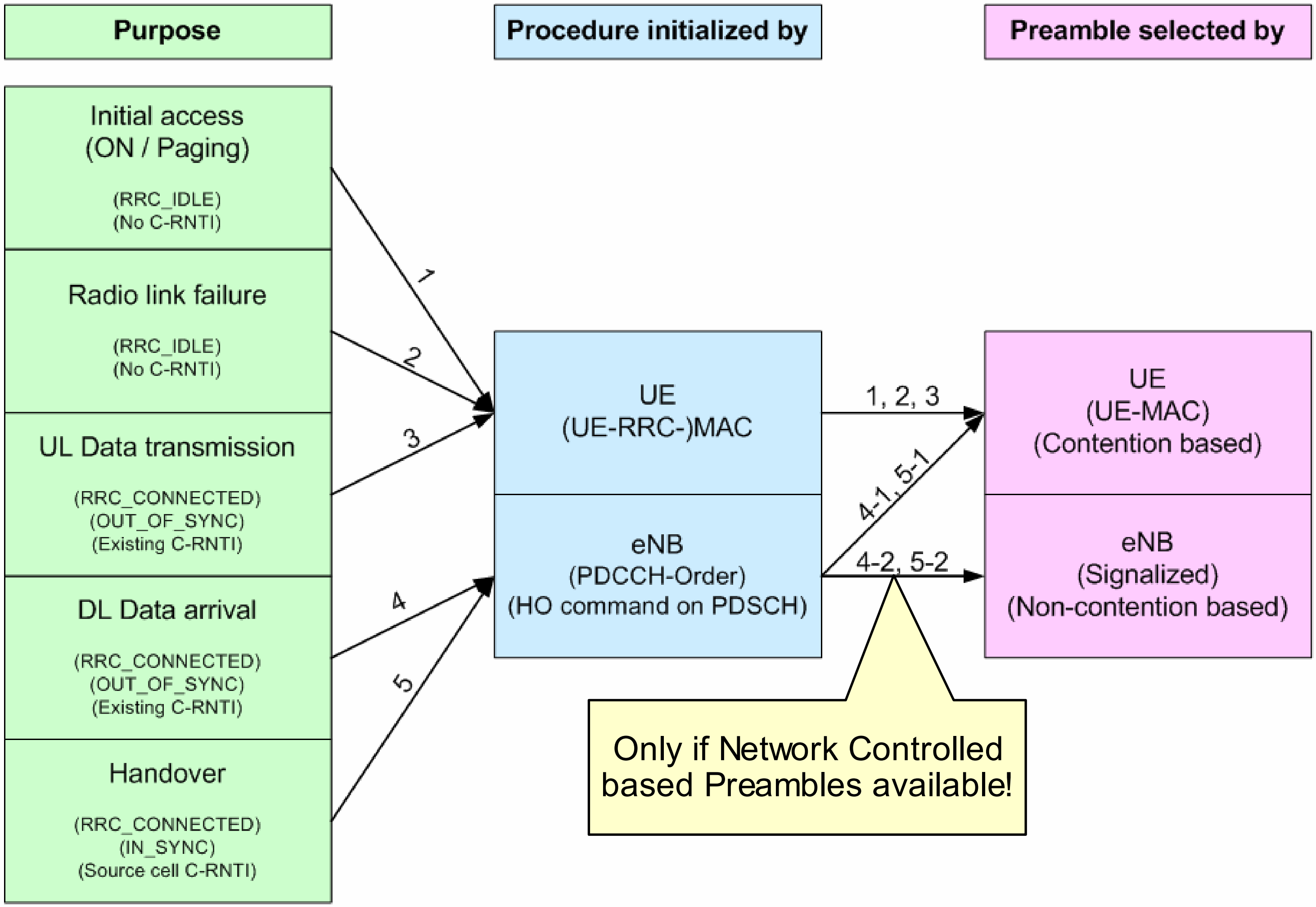
- ETWS = Earthquake and Tsunami Warning System

Random Access Procedure in LTE

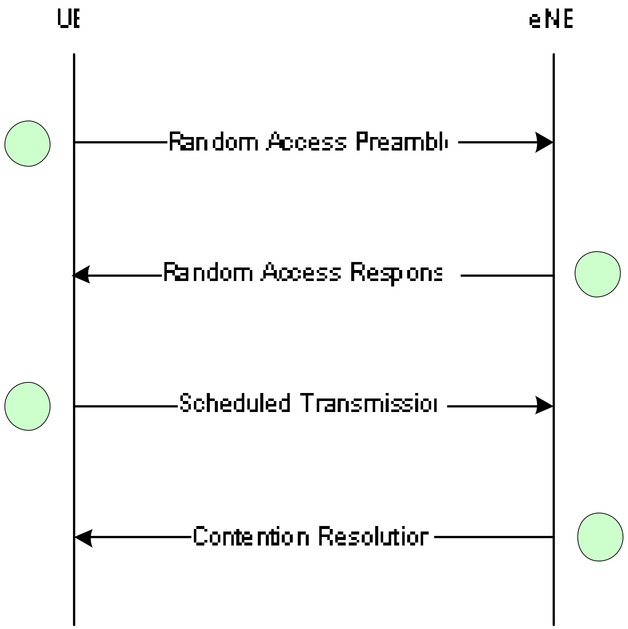
LTE terminal states



Some Random Access Scenarios (Cases)

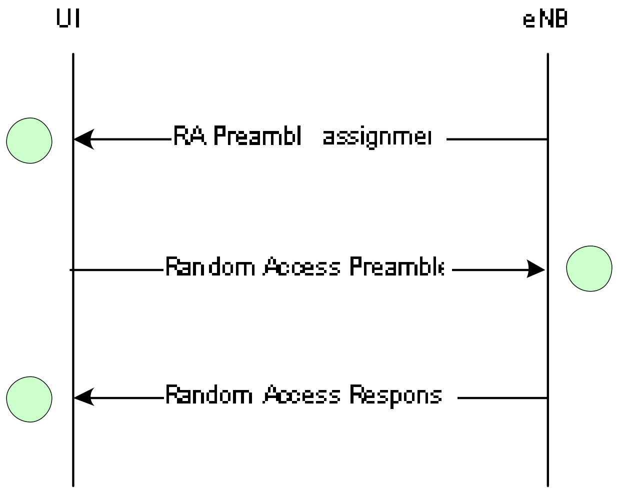


RACH Procedure



Contention based (C)

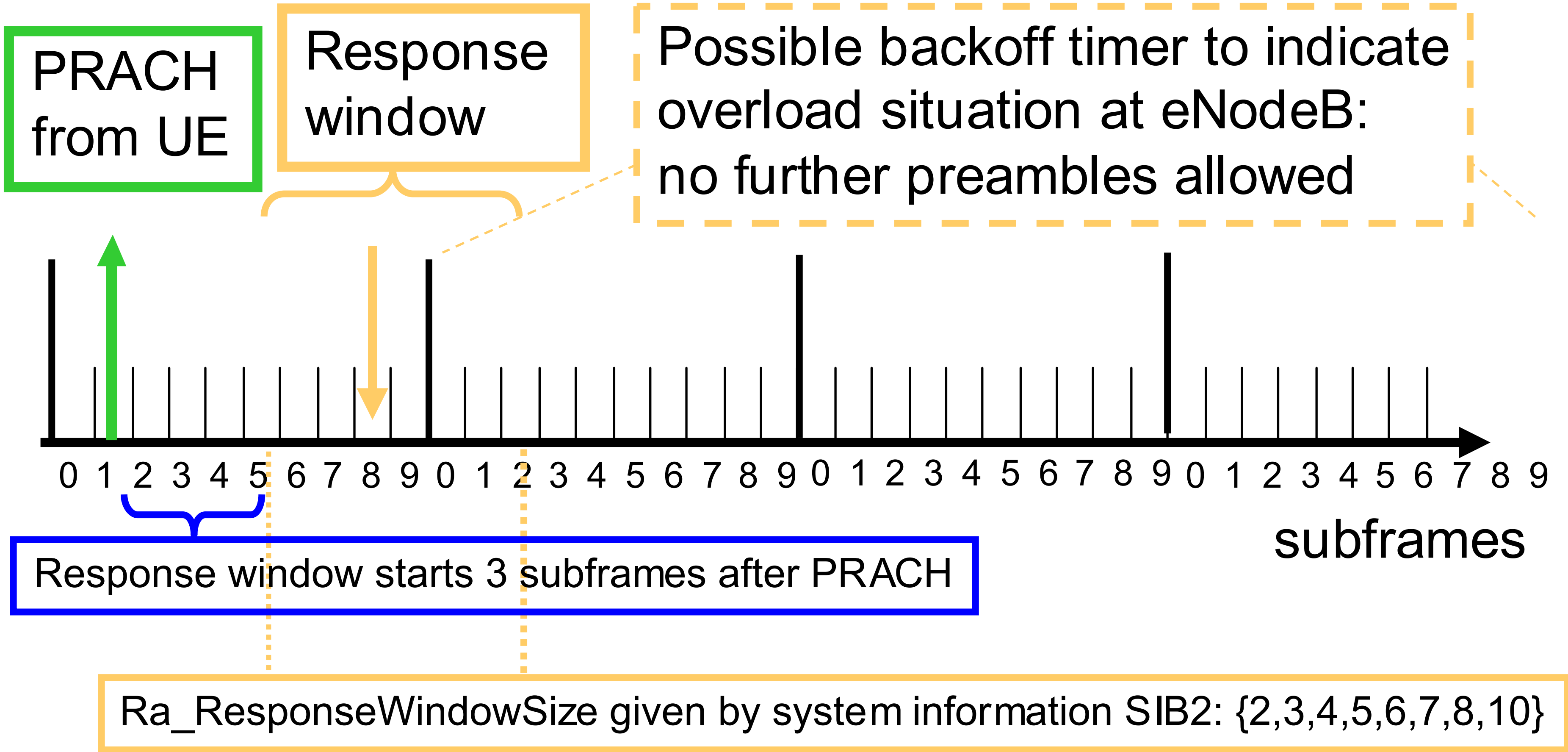
[36.300:10.1.5.1]



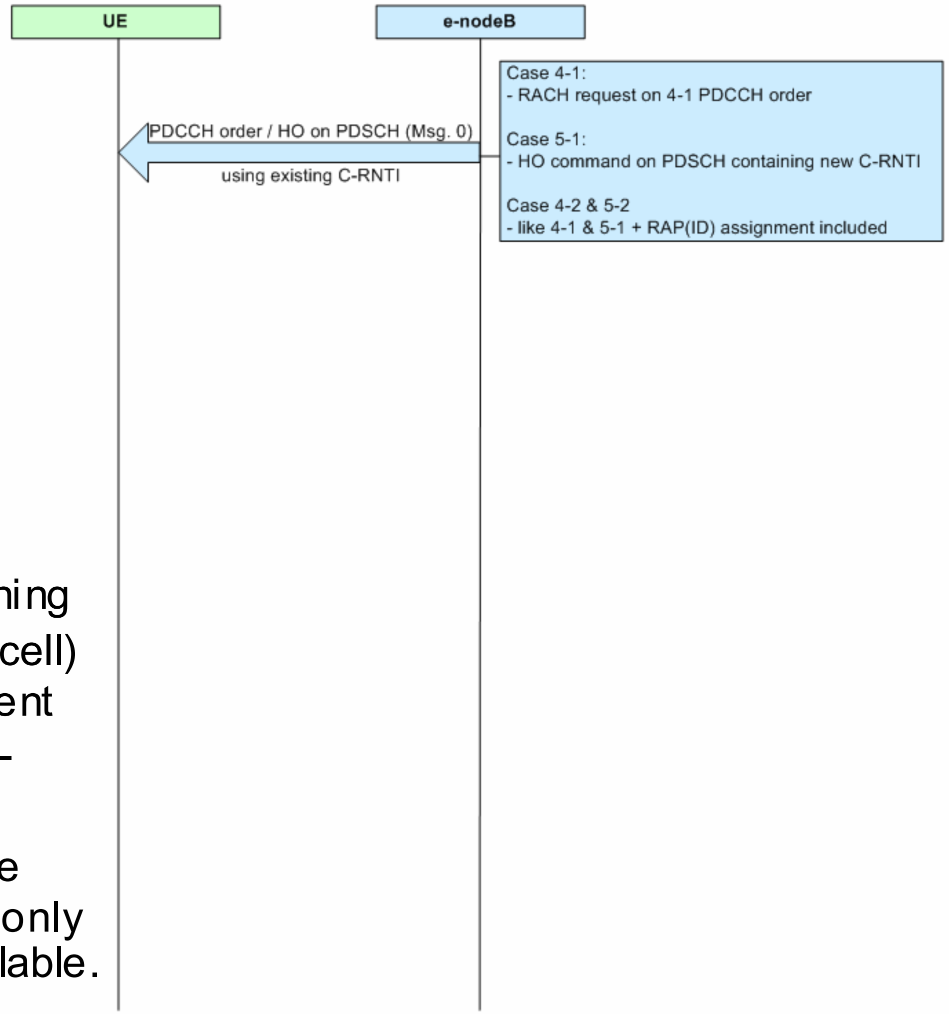
Non contention based (nC)

[36.300:10.1.5.2]

RACH Procedure

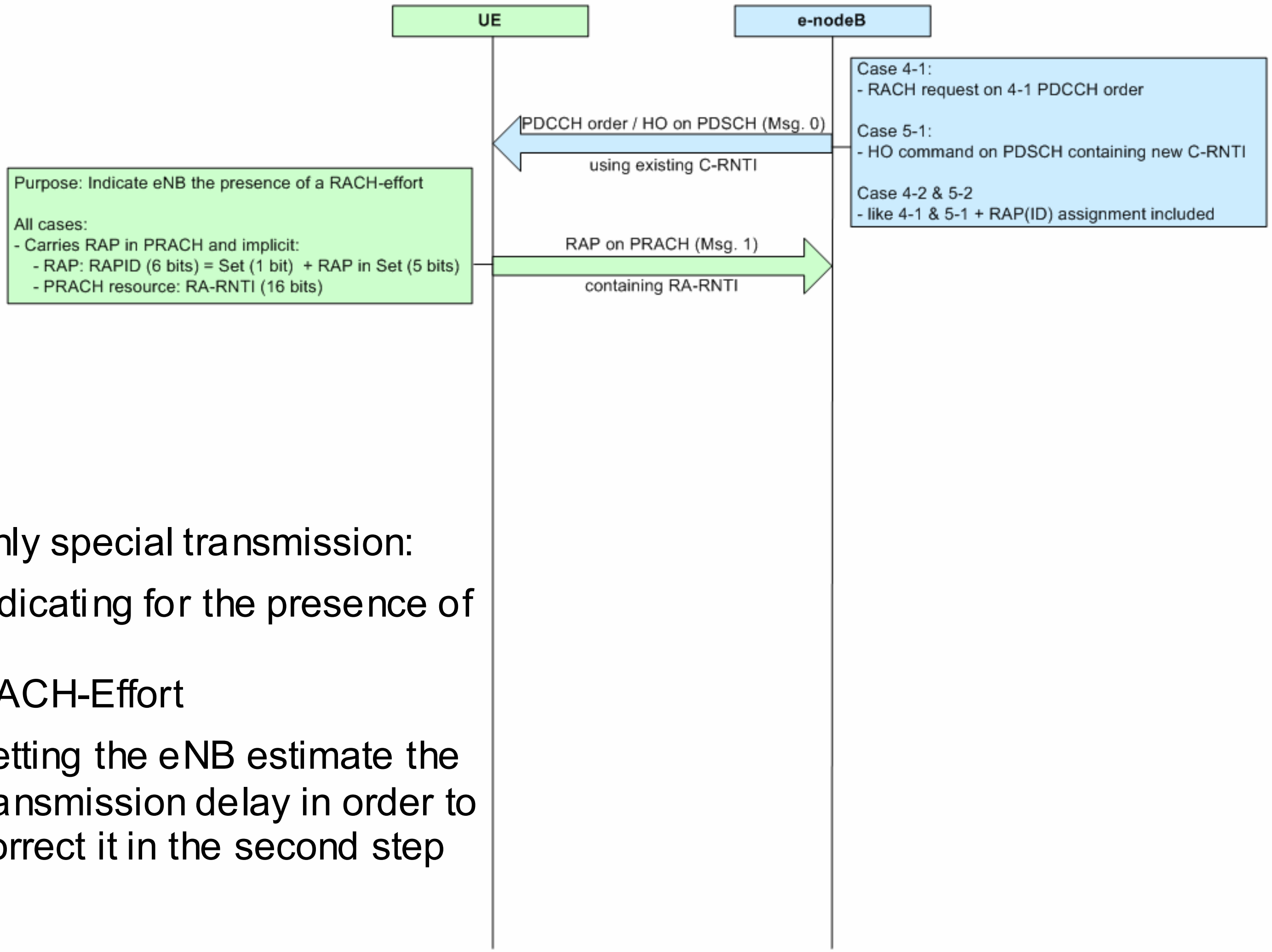


RA initialized by eNB + NC-based (Msg.0)



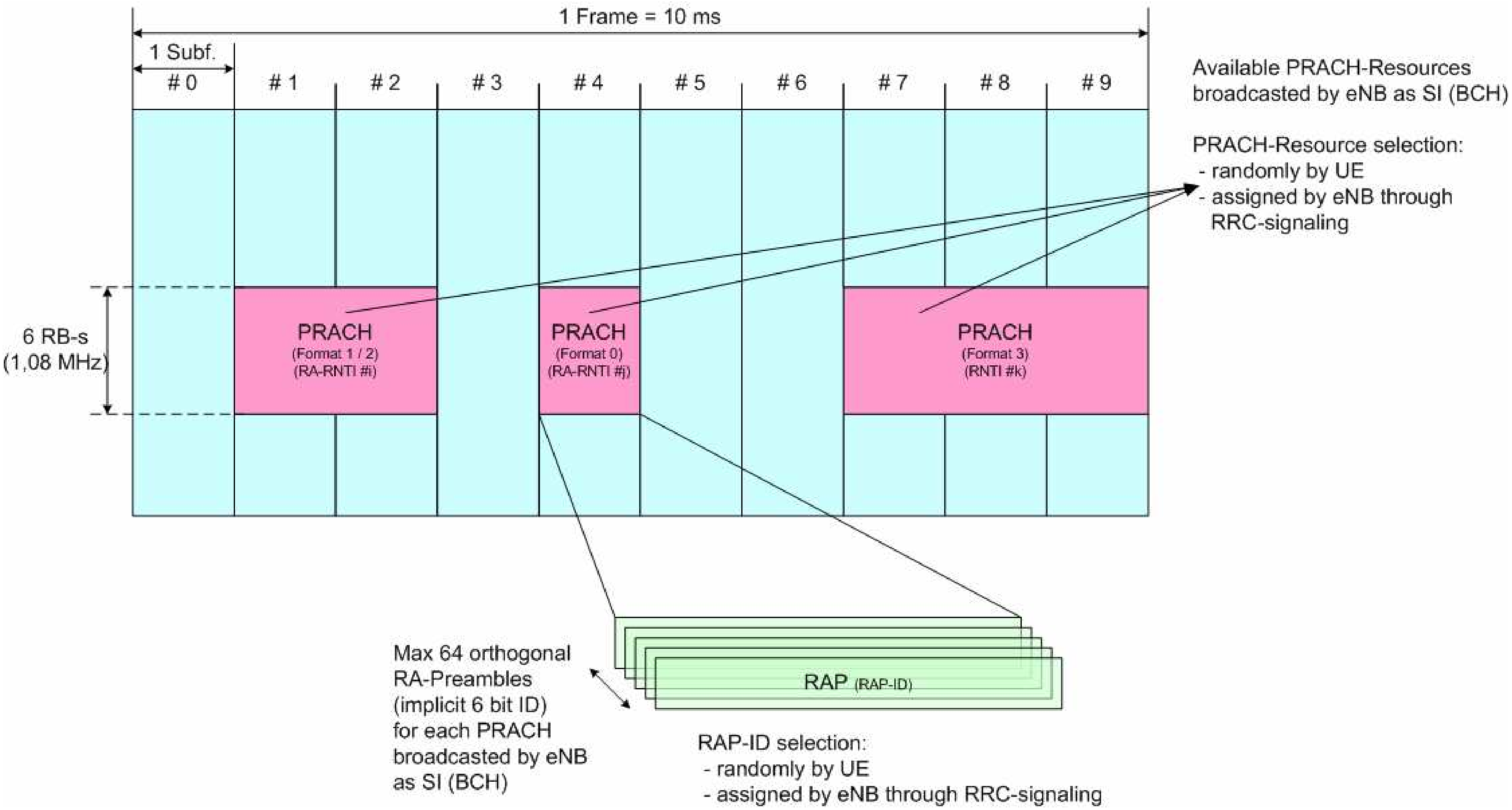
- HO-Command on DCCH (→ DL-SCH → PDSCH) containing the new C-RNTI (for the target cell) generated by target eNB and sent via source eNB using the old C-RNTI (of the source cell)
- By NC-cases the RAP-ID will be assigned as well, nevertheless only if there are NC-Preambles available.

1. RA Preamble transmission (Msg.1)

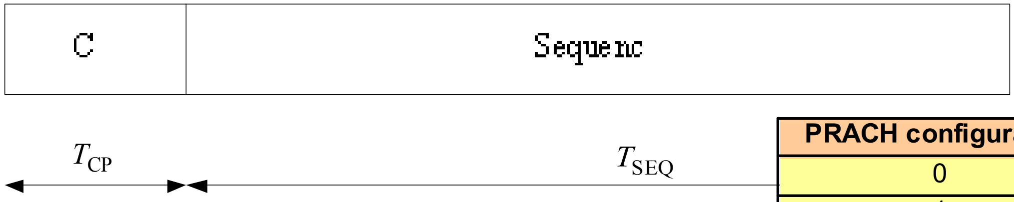


- The only special transmission:
  - Indicating for the presence of a RACH-Effort
  - Letting the eNB estimate the transmission delay in order to correct it in the second step

PRACH – Resources



LTE Uplink
Random access preamble

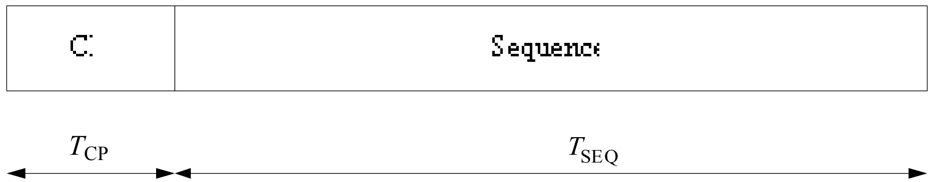


PRACH configuration	System frame number	Subframe number
0	Even	1
1	Even	4
2	Even	7
3	Any	1
4	Any	4
5	Any	7
6	Any	1, 6
7	Any	2 ,7
8	Any	3, 8
9	Any	1, 4, 7
10	Any	2, 5, 8
11	Any	3, 6, 9
12	Any	0, 2, 4, 6, 8
13	Any	1, 3, 5, 7, 9
14	Any	0, 1, 2, 3, 4, 5, 6, 7, 8, 9
15	Even	9

- **4 different preamble formats for FDD mode**
- **Preamble transmission restricted to certain time / frequency resources**
- **Preamble occupies 6 resource blocks in frequency domain configured by higher layers**

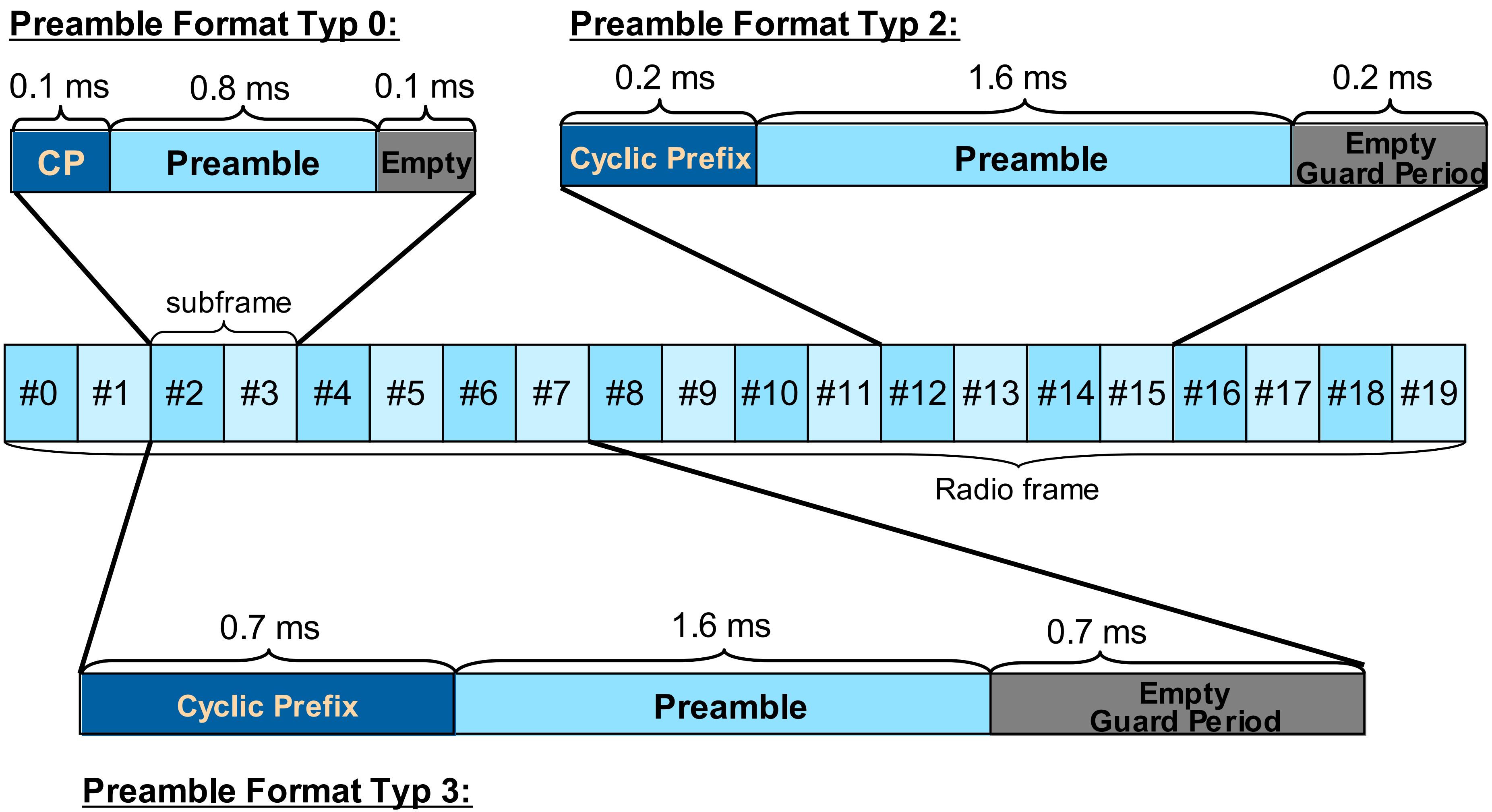
Random Access Preamble

- Consumes 6 Resource Blocks in frequency domain (1.08 MHz)
- No frequency hopping (RAN1#53b pre-preference: fixed position next to the bottom of maximum PUCCH bandwidth**)**
- **<u>FDD:</u>** Maximum of one PRACH resource per subframe
  <u>TDD:</u> Resources per subframe vary between 0.5 and 6
- Subcarrier spacing is 1250 Hz only (7500 Hz for preamble format 4)



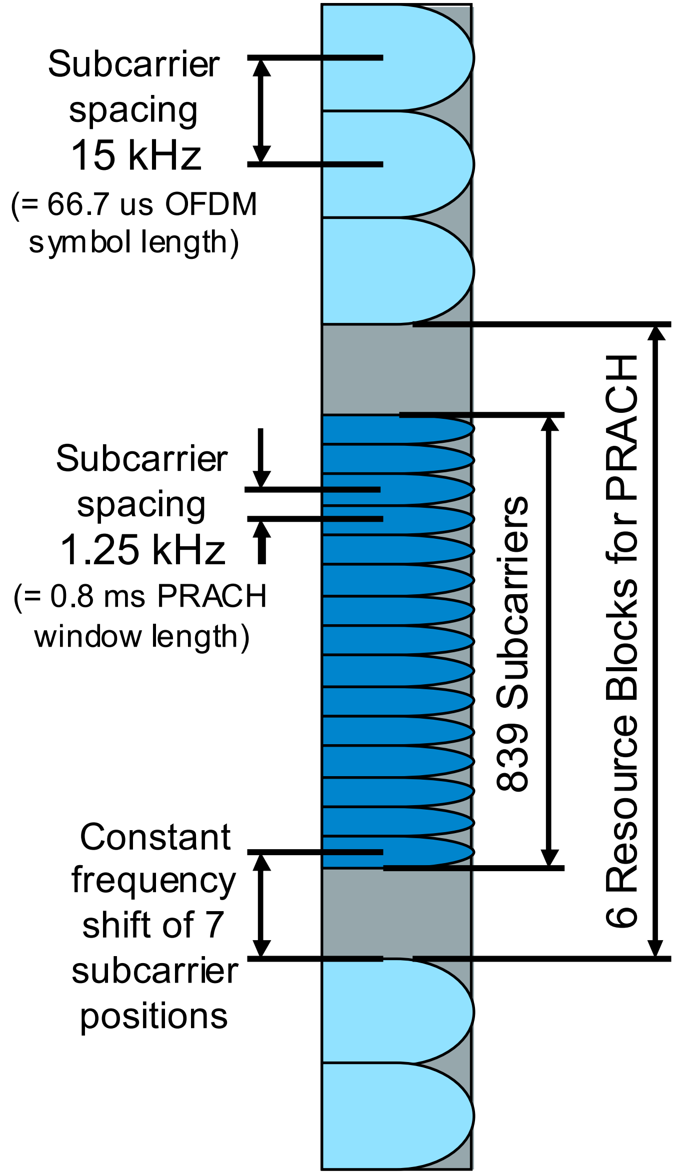
Preamble format	T_{CP}	T_{SEQ}	Applicable
0	$3168 \cdot T_s$	$24576 \cdot T_s$	FDD/TDD
1	$21024 \cdot T_s$	$24576 \cdot T_s$	FDD/TDD
2	$6240 \cdot T_s$	$2 \cdot 24576 \cdot T_s$	FDD/TDD
3	$21024 \cdot T_s$	$2 \cdot 24576 \cdot T_s$	FDD/TDD
4	$448 \cdot T_s$	$4096 \cdot T_s$	TDD

PRACH Formats



PRACH Signal

- CAZAC property requires prime-length sequences
- Subcarrier spacing of preamble differs by factor 12 enabling reuse of existing FFT-modules
- Each cell has an own set of 64 different preambles created by cyclic shifts of one or more assigned Zadoff-Chu root sequences
- Up to a maximum of 64 UEs in a cell can perform a simultaneous random access without collision
- Match detector in the eNodeB detects the cyclic shift of the preamble and the transmission delay
- For placement of PRACH in TDD UpPTS: 139 carriers, 7.5 kHz subcarrier spacing, 2 carriers frequency shift



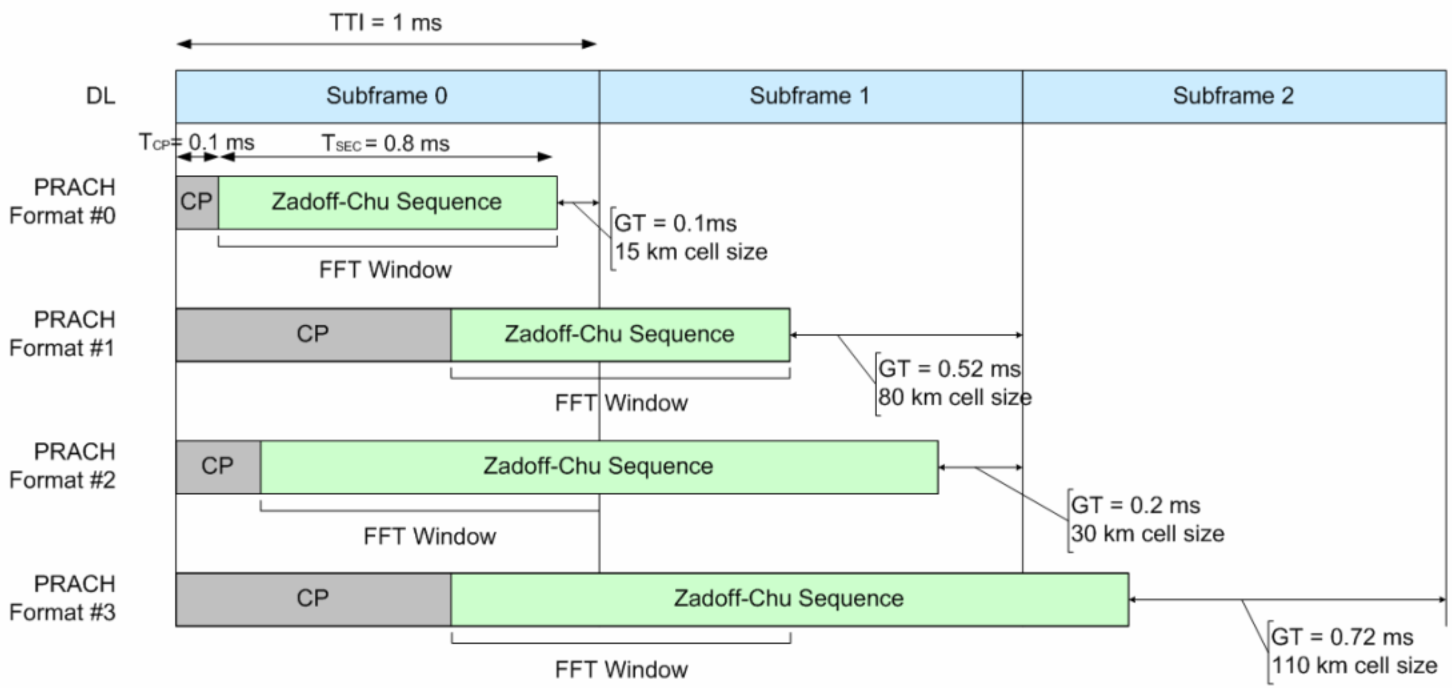
RACH Preamble (RAP)

- RA Preamble = not standard modulated data but CAZAC (Zadoff / Chu Sequence) in TDD/FDD

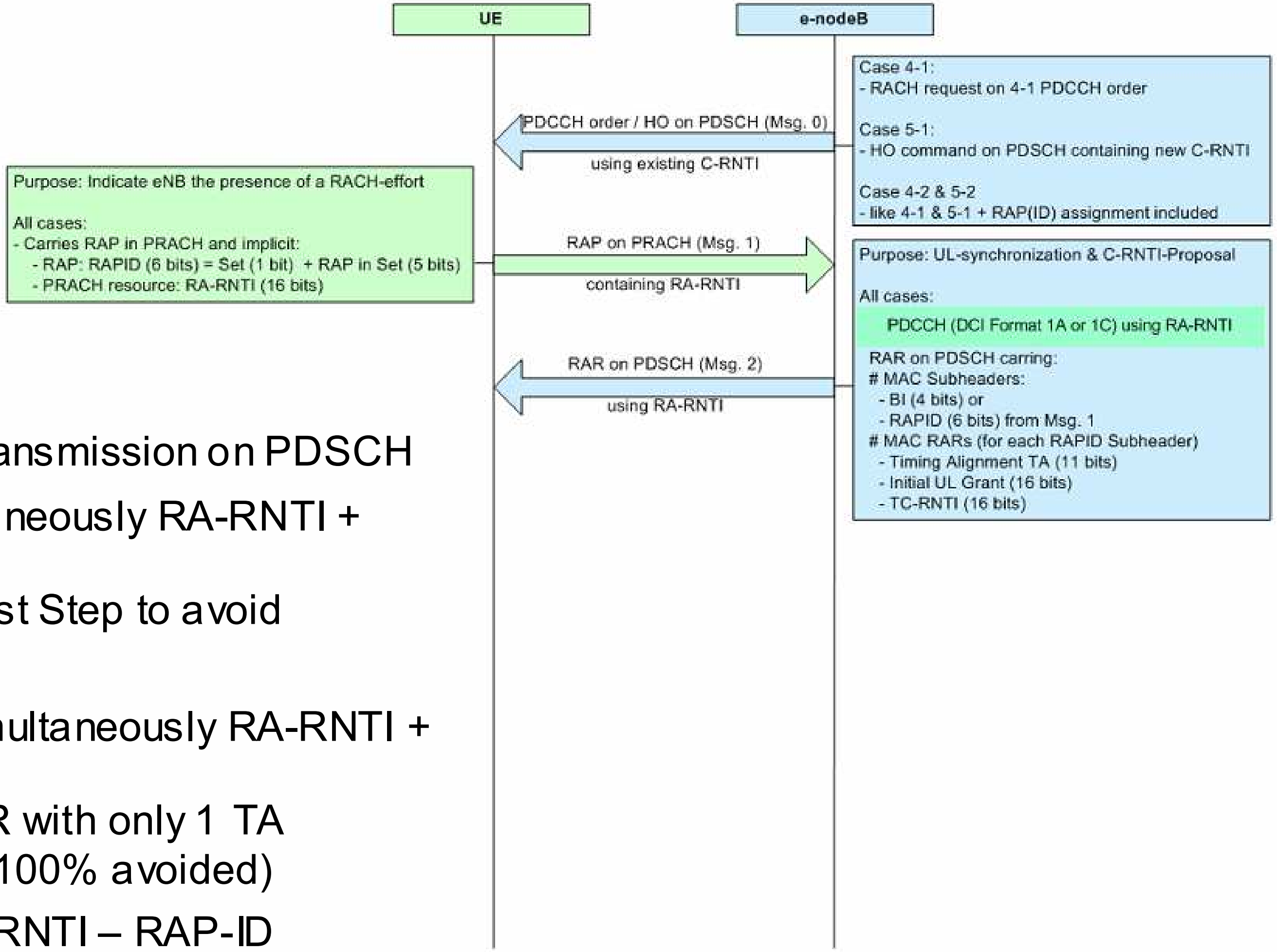
  Zadoff / Chu Sequence = Root seq. + Time Shift / Phaserotation
- In TDD: Preamble = 1 long (not F4) OFDM Symbol of Zadoff / Chu Sequence → Orthogonality

  + CP → Easy processing in frequency domain

  + GT→ Avoids Subf.-Interference by no UL-Synchronization
- Different formats for different cell sizes: 0-3 (FDD: 1,2,3 Subframes), 4 (TDD: 1 Symbol)

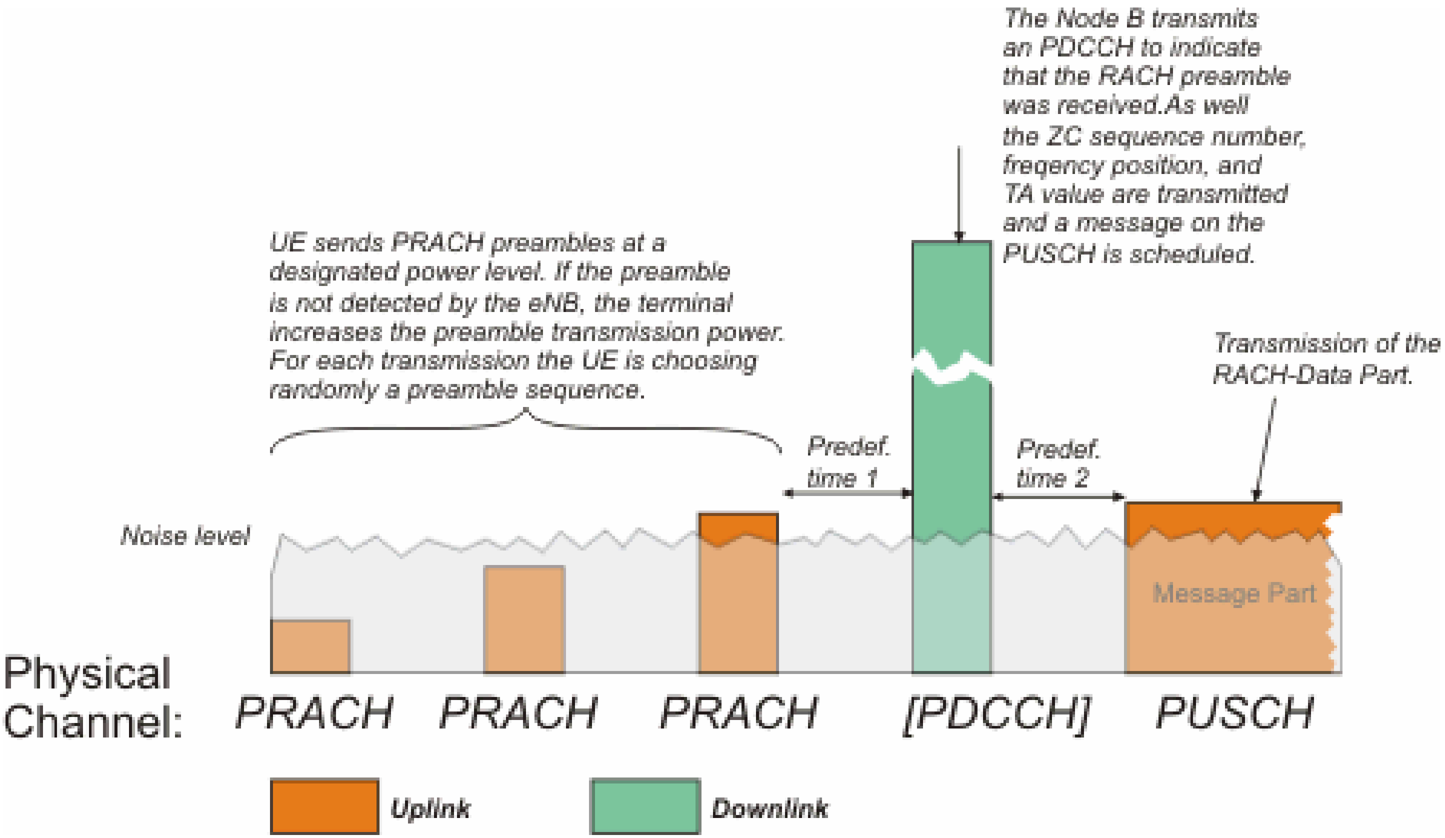


2. RA Response (Msg.2) → UL-Sync, TC-RNTI



- Normal DL-transmission on PDSCH
- Same simultaneously RA-RNTI + RAP-ID
  → no RAR (1st Step to avoid collision)
- Same not simultaneously RA-RNTI + RAP-ID
  → only 1 RAR with only 1 TA (collision not 100% avoided)
- Different RA-RNTI – RAP-ID
  → different RAR-s

RAP – Power Ramping

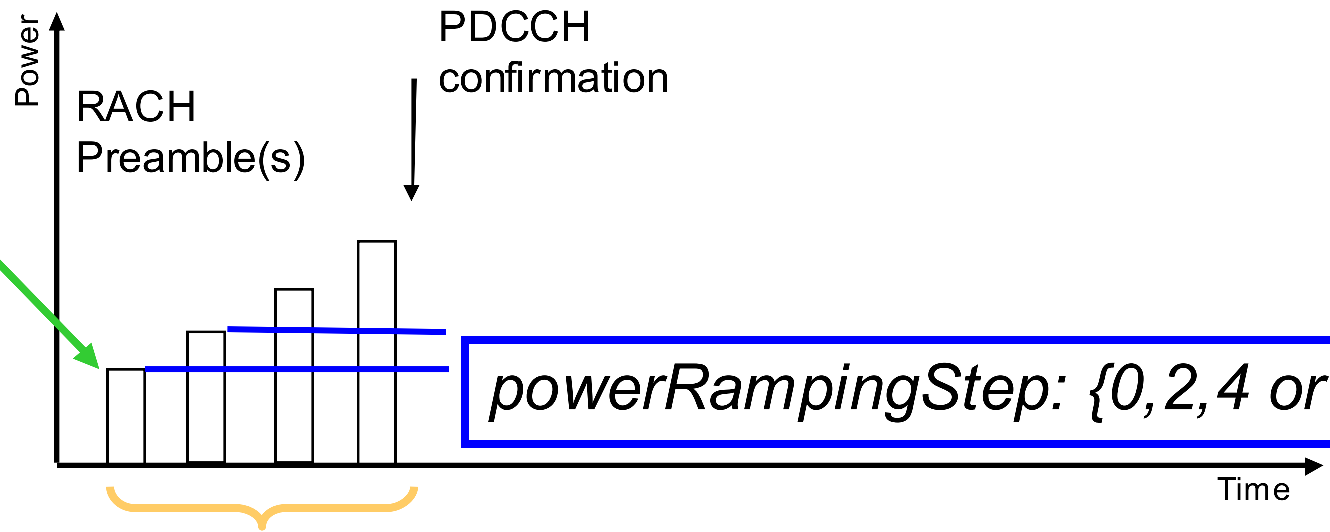


$$P_{PRACH} = \min\{P_{\max}, P_{TX} + PL_{DL}\}$$

$$P_{TX} = P_{Init} + Counter * P_{Step}$$

PRACH procedure

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



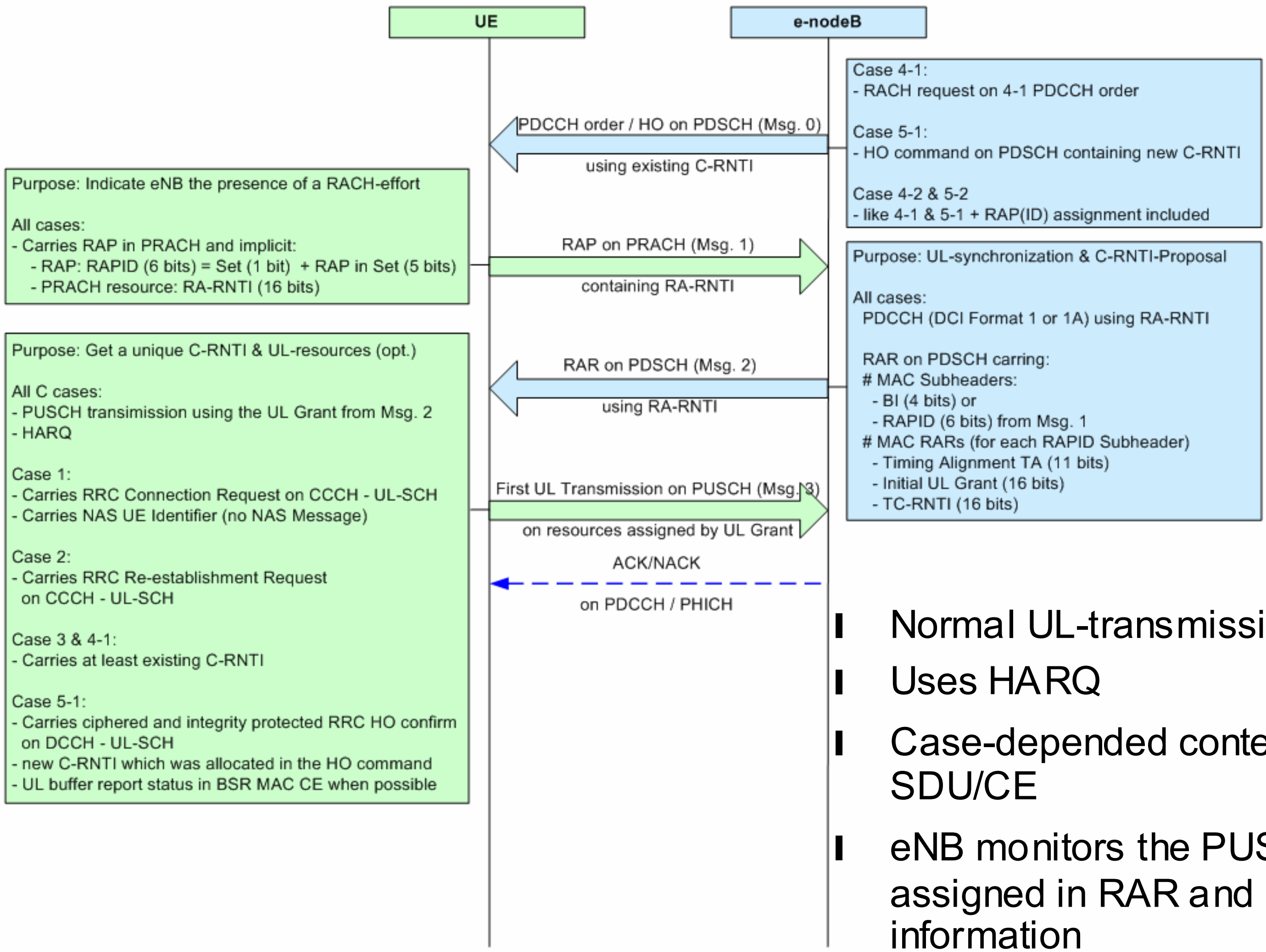
Preamble contains RA-RNTI

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

preambleTransMax in SIB2 indicates maximum number of PRACH preambles

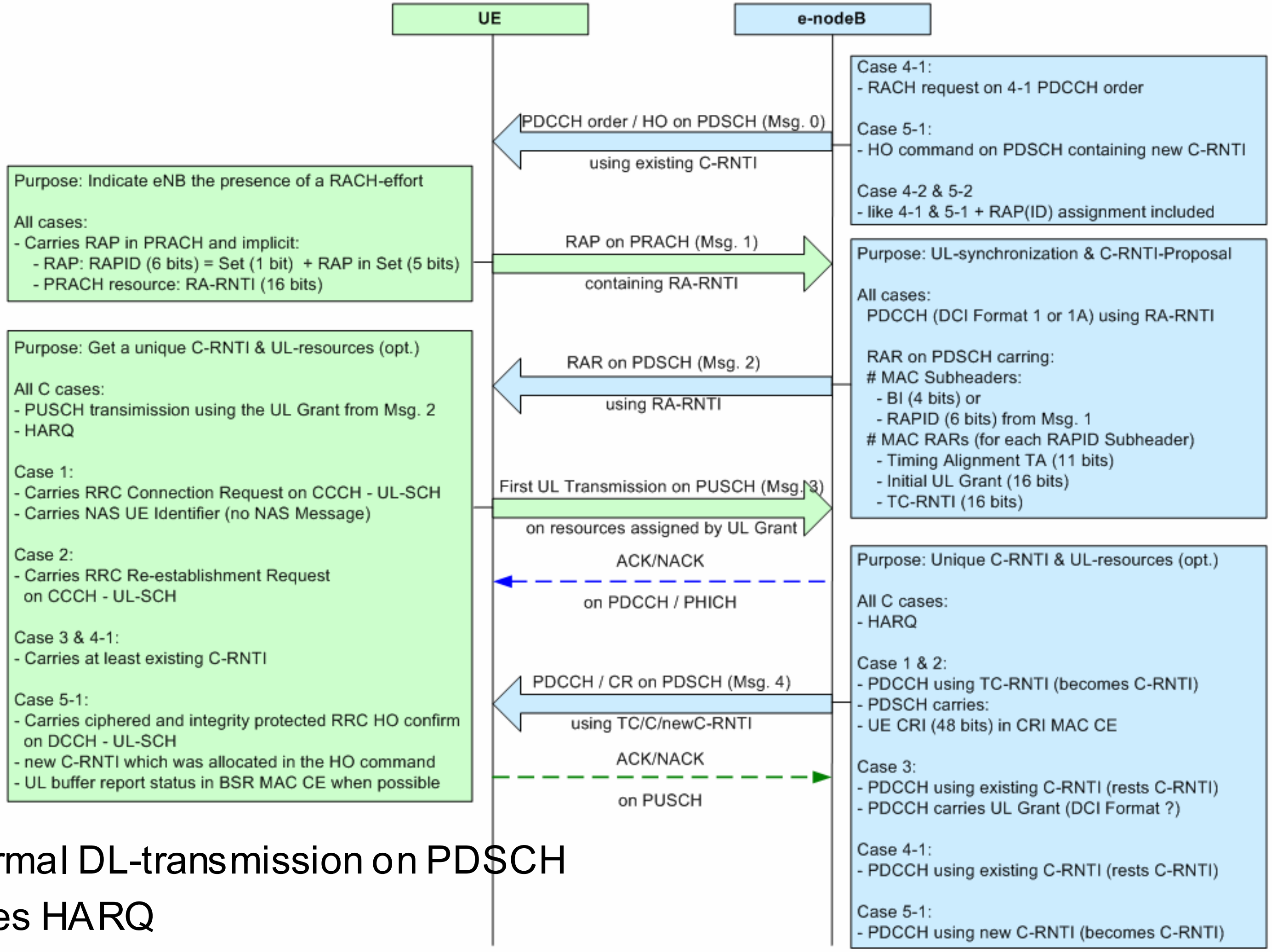
RA-RNTI = Random Acces Radio Network Transaction Identifier

3. Scheduled transmission (C) (Msg.3)



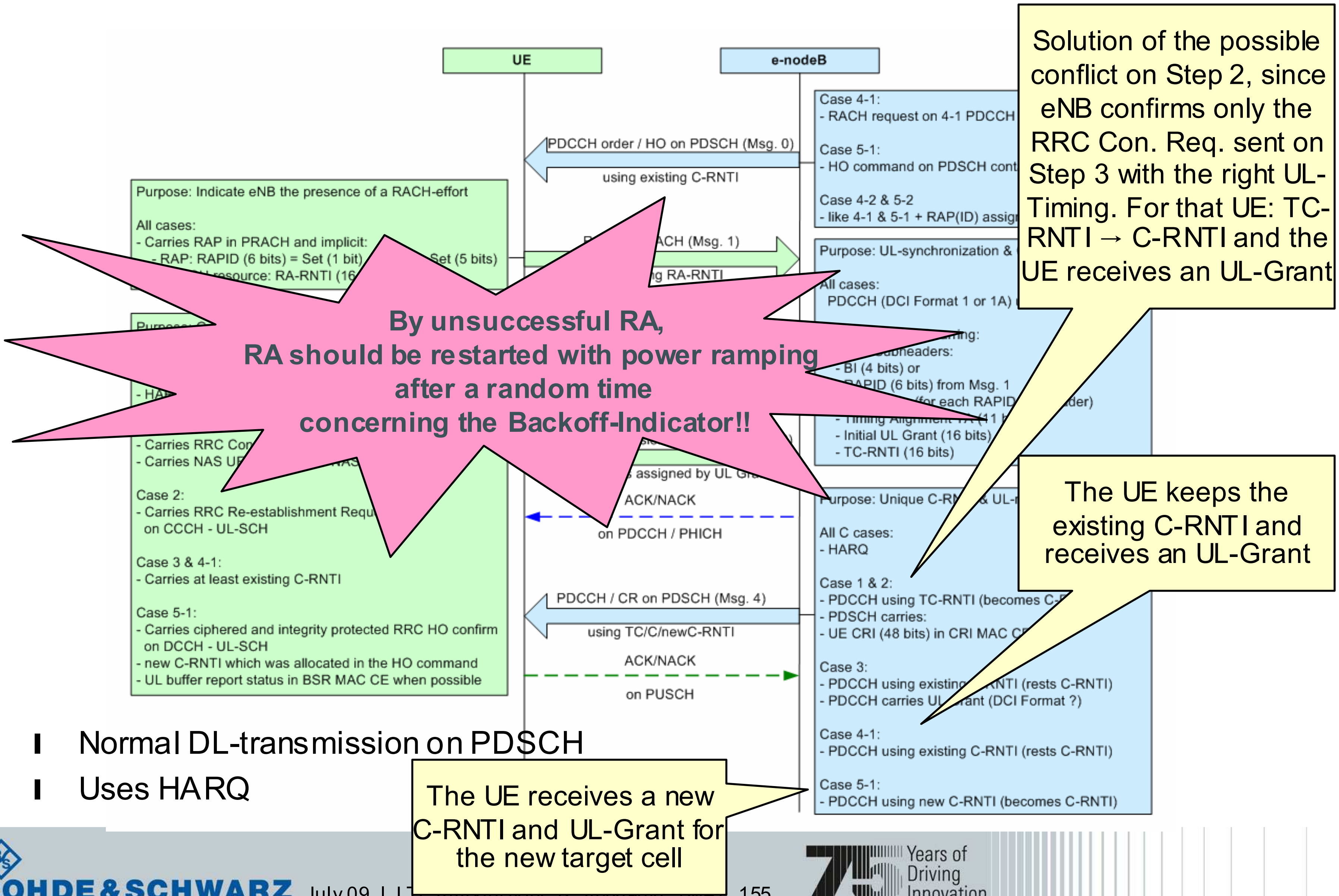
- Normal UL-transmission on PUSCH
- Uses HARQ
- Case-depended contents as MAC SDU/CE
- eNB monitors the PUSCH resources assigned in RAR and processes the information

4. Cont. Res. (C) (Msg.4) → C-RNTI, UL-Grant



- Normal DL-transmission on PDSCH
- Uses HARQ

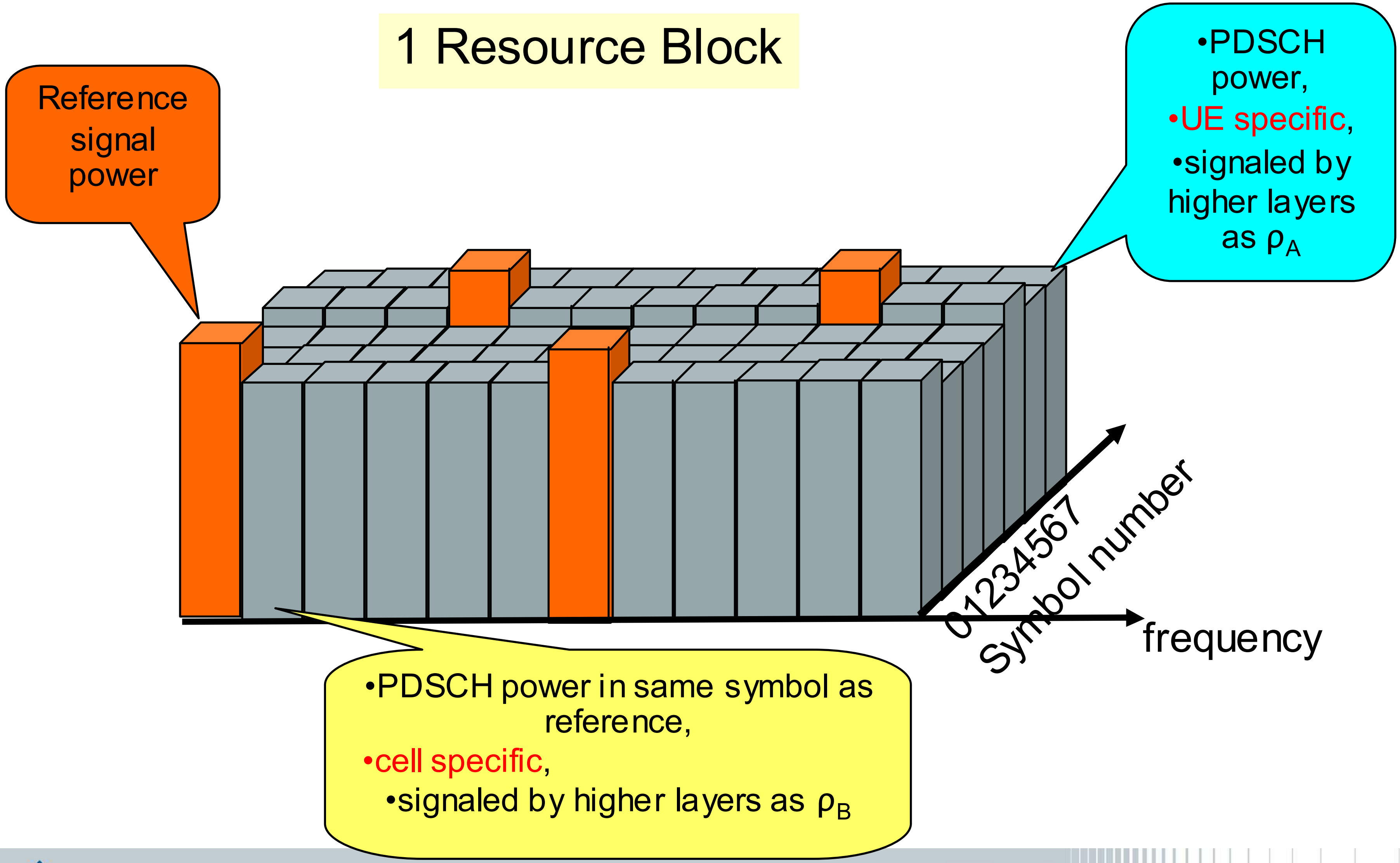
4. Cont. Res. (C) (Msg.4) → C-RNTI, UL-Grant



- Normal DL-transmission on PDSCH
- Uses HARQ

Power Control Aspects

Downlink power



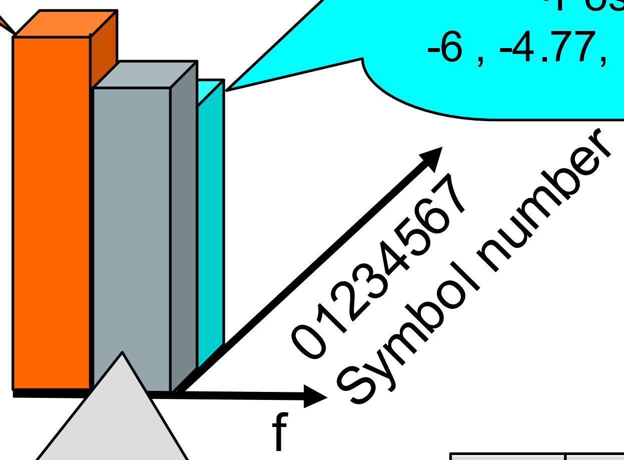
Downlink power

1 Resource Block extract

Reference signal power given by system information SIB2
Range: -60 .. + 50dBm

RS EPRE = Reference Signal Energy per Resource Element

Reference signal power = linear average of all Ref. Symbols over whole channel bandwidth



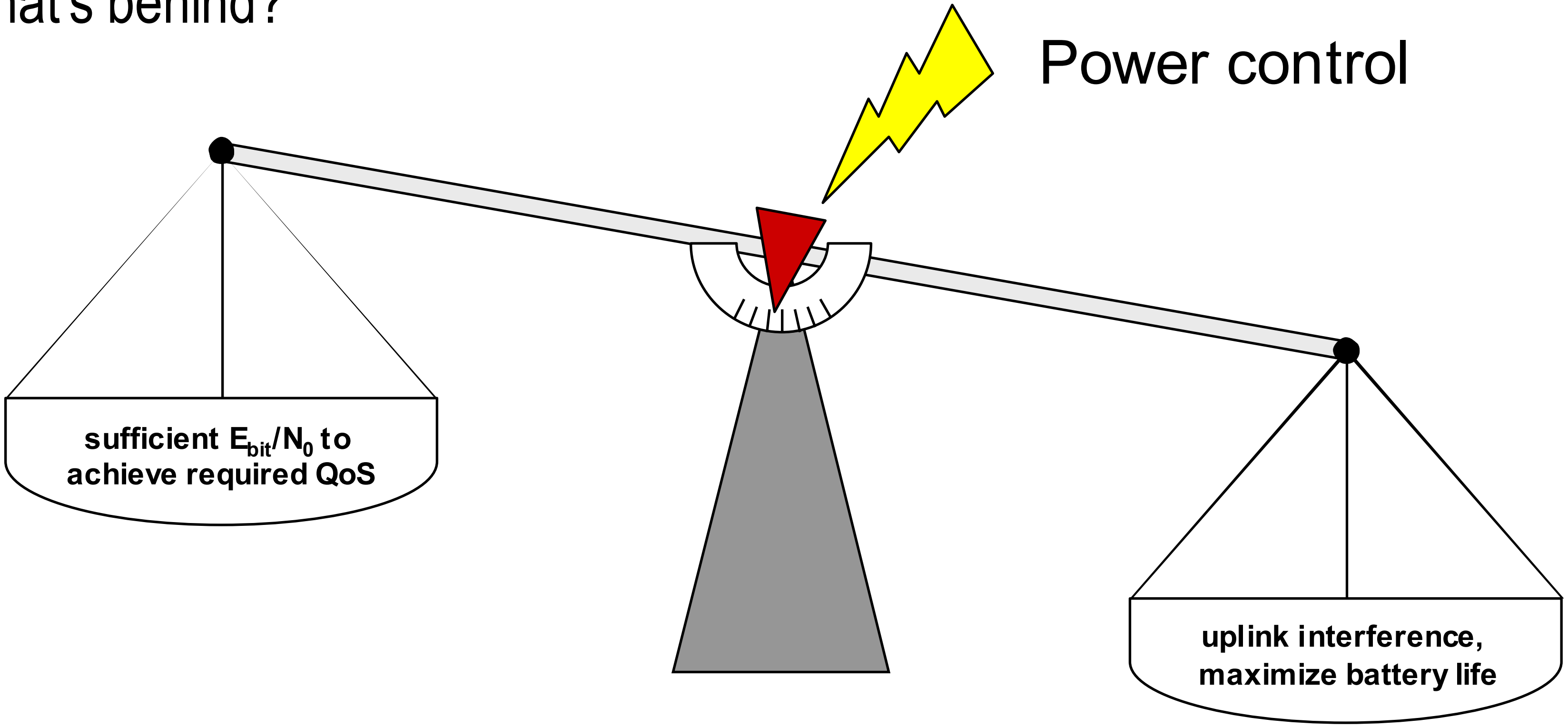
- PDSCH power in OFDM symbols with no reference symbol,
- UE specific value,
- signaled by higher layers as ρ_A
- Possible values for P_A:
-6 , -4.77, -3 , -1.77, 0 , 1 , 2, 3dB

PDSCH power in same symbol as reference,
cell specific, relative to ρ_A
signaled by higher layers as ρ_B

P_B	ρ_B / ρ_A	
	One Antenna Port	**Two and Four Antenna Ports**
0	1	5/4
1	4/5	1
2	3/5	3/4
3	2/5	1/2

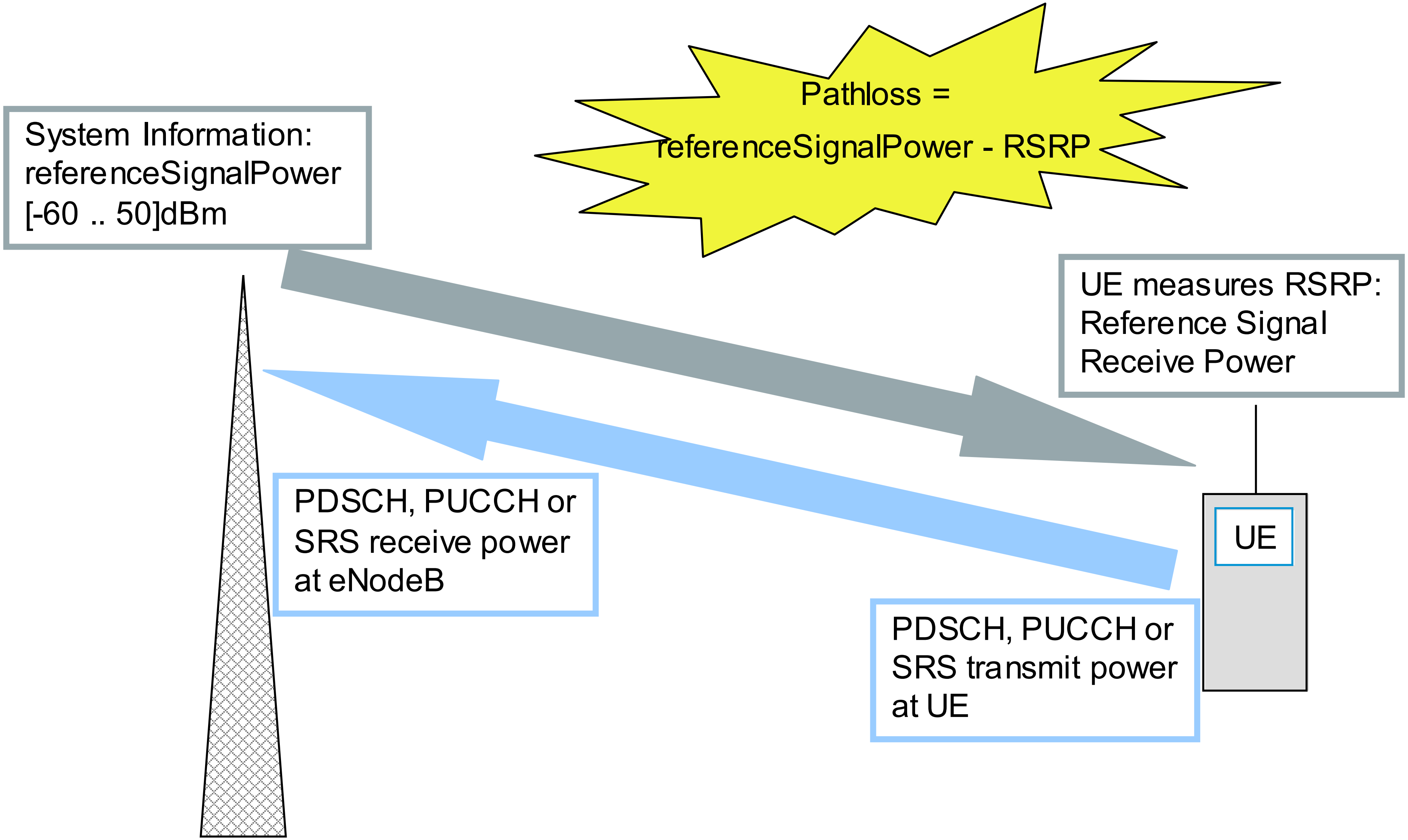
Uplink power control

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



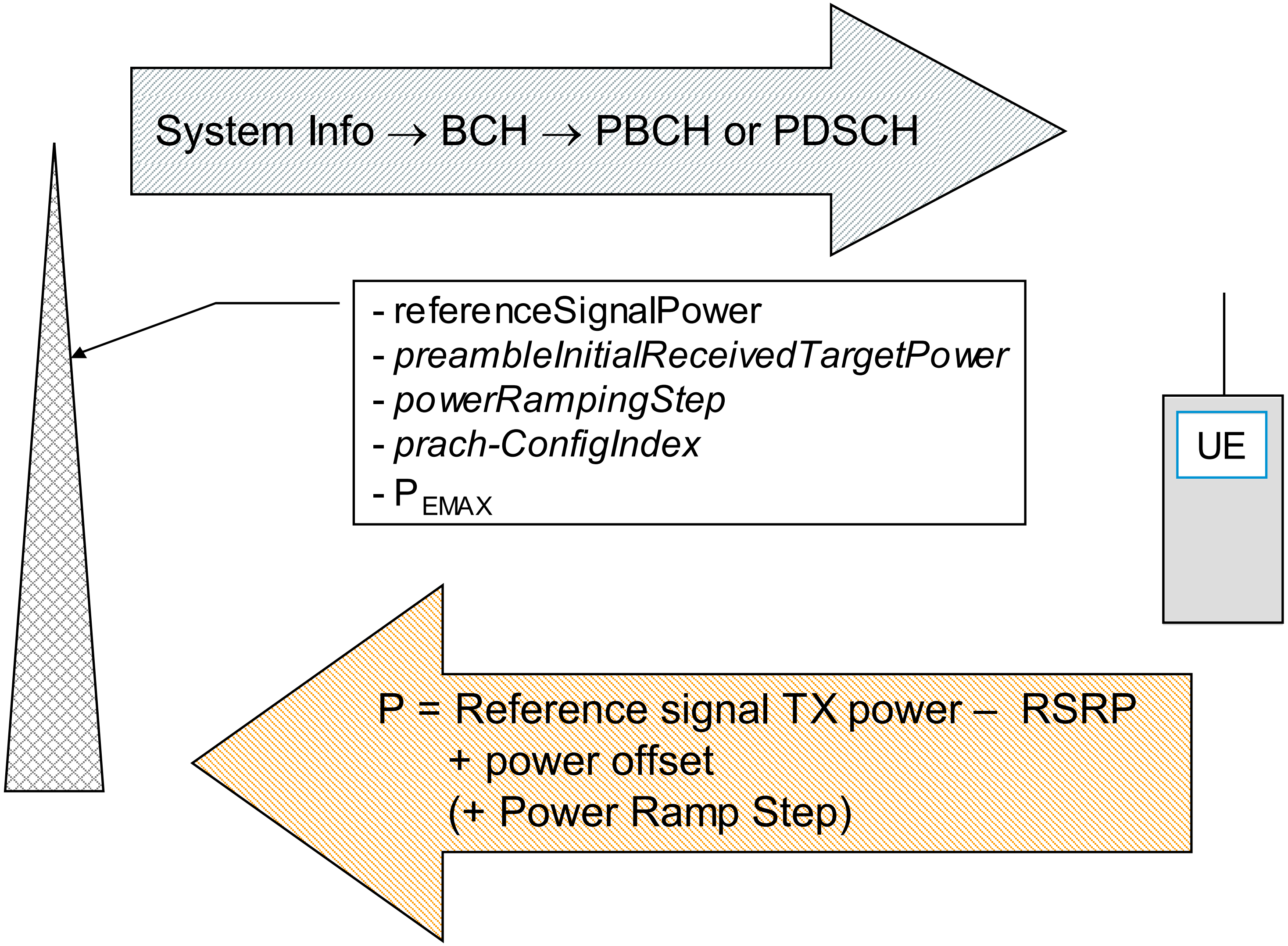
Types of transmit power control

TPC

(Transmit Power Control)

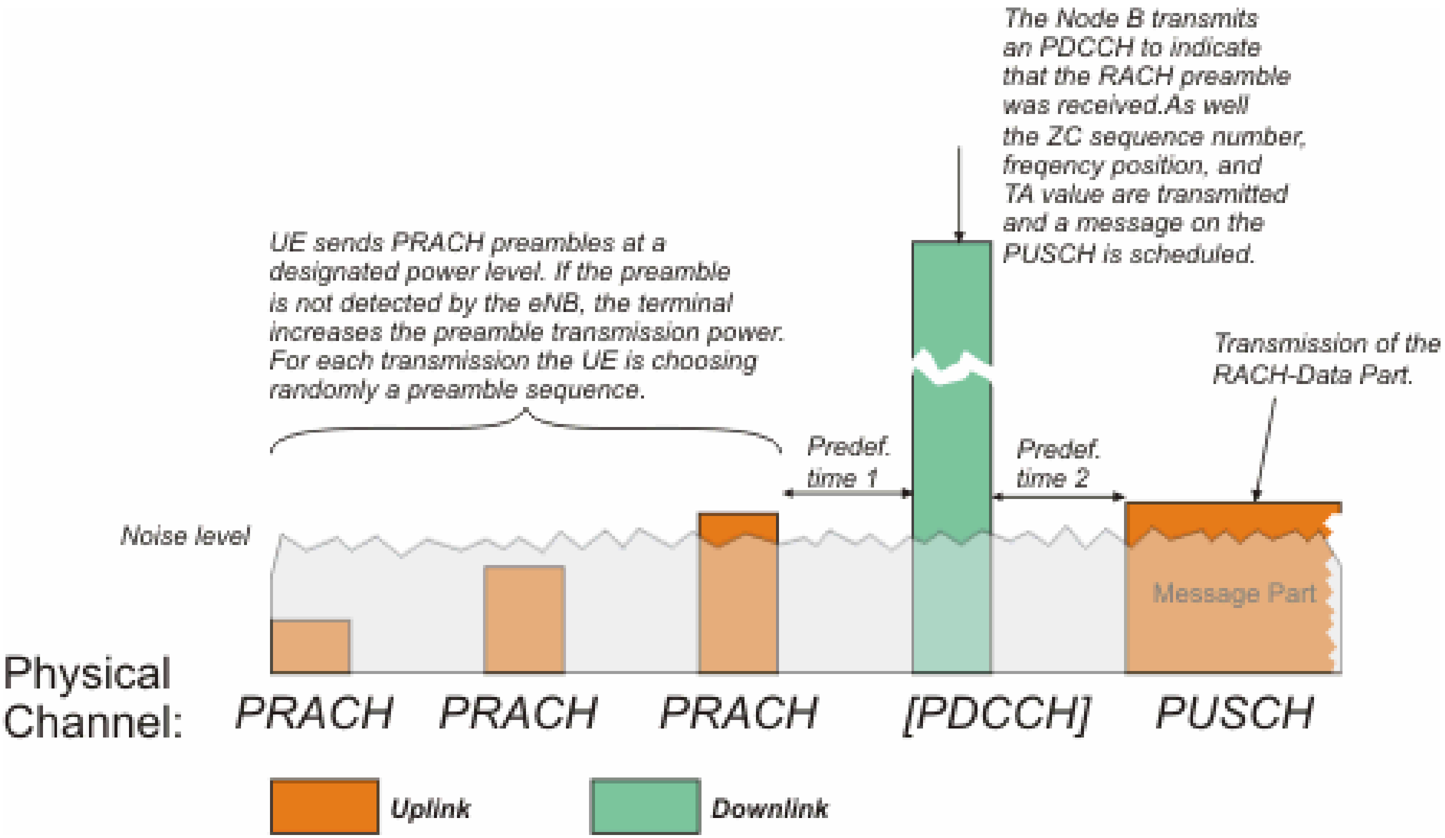
open loop Power Control	*closed loop Power Control*
For random access procedure	In connected mode: Power control to compensate fading

LTE Open loop power control



75 Years of Driving Innovation

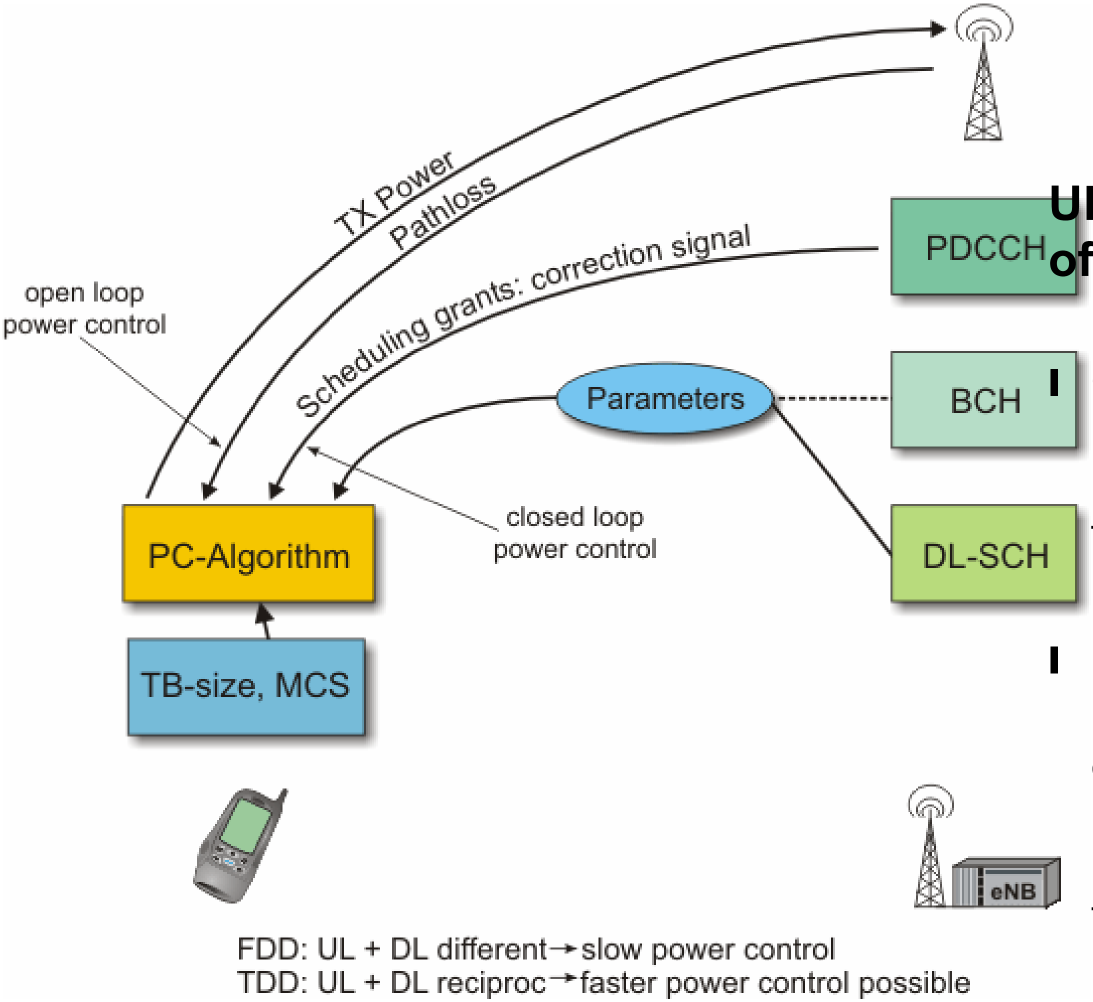
RAP – Power Ramping



$$P_{PRACH} = \min\{P_{\max}, P_{TX} + PL_{DL}\}$$

$$P_{TX} = P_{Init} + Counter * P_{Step}$$

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

PUSCH power control

- Power level [dBm] of PUSCH is calculated every subframe i based on the following formula out of TS 36.213

MPR

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

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

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)

Transmit power for PUSCH in subframe i in dBm

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}

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

- **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),
```

Description based on 3GPP baseline June '09!
Calculation of P_{CMAX} changes with September '09 version!

  - 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)

Pcmax definition

„lower“ tolerance

„corrected“ UE power

„upper“ tolerance

$$P_{CMAX\_L} - T(P_{CMAX\_L}) \leq P_{CMAX} \leq P_{CMAX\_H} + T(P_{CMAX\_H})$$

$$P_{CMAX\_L} = \min\{P_{EMAX\_L}, P_{UMAX}\}$$

Max. power permitted in cell, considering bandwidth confinement

Max. power for UE, considering maximum power reduction

$$P_{CMAX\_H} = \min\{P_{EMAX\_H}, P_{PowerClass}\}$$

Max. power permitted in cell

Max. power for UE

Maximum UE power - analogies

$$P_{CMAX\_L} - T(P_{CMAX\_L}) \leq P_{CMAX} \leq P_{CMAX\_H} + T(P_{CMAX\_H})$$

$$P_{CMAX\_L} = \min\{P_{EMAX\_L}, P_{UMAX}\} \qquad P_{CMAX\_H} = \min\{P_{EMAX\_H}, P_{PowerClass}\}$$

Maximum speed = 280 km/h

$=P_{PowerClass}$

$=P_{EMAX\_H}$

$=P_{EMAX\_L}$

$=P_{UMAX}$

Under those conditions,
I shall drive more carefully!
Not going to the max seed!
-> speed reduction

Pcmax definition

- $P_{CMAX\_L} - T(P_{CMAX\_L}) \leq P_{CMAX} \leq P_{CMAX\_H} + T(P_{CMAX\_H})$,

- $P_{CMAX\_L} = \min\{P_{EMAX\_L}, P_{UMAX}\}$,
  - P_{EMAX_L} 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 Type1,

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,
                                                                                Cond TDD

                                                                                Need OP
```

P-Max information element

```
-- ASN1START

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

-- ASN1STOP
```

  - P_{EMAX_L} is reduced by 1.5 dB when the transmission BW is confined within F_{UL_low} and F_{UL_low} +4 MHz or F_{UL_high} – 4 MHz and F_{UL_high},
  - P_{UMAX} corresponds to maximum power (depending on power class, see next slide) taking into account MPR and A-MPR,

Pcmax definition

- $P_{CMAX\_L} - T(P_{CMAX\_L}) \le P_{CMAX} \le P_{CMAX\_H} + T(P_{CMAX\_H})$

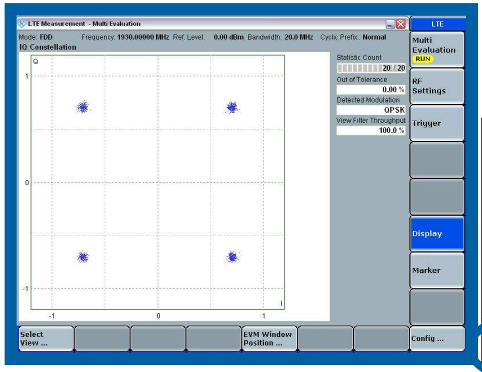
- $T(P_{CMAX})$ **corresponds to power tolerance,**

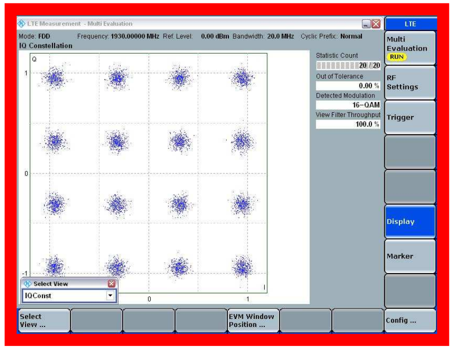
P_{CMAx} (dBm)	Tolerance $T(P_{CMAX})$ (dB)
$21 \le P_{CMAX} \le 23$	2.0
$20 \le P_{CMAX} < 21$	2.5
$19 \le P_{CMAX} < 20$	3.5
$18 \le P_{CMAX} < 19$	4.0
$13 \le P_{CMAX} < 18$	5.0
$8 \le P_{CMAX} < 13$	6.0
$-40 \le P_{CMAX} < 8$	7.0

- $P_{CMAX\_H} = \min\{P_{EMAX\_H}, P_{PowerClass}\}$,
  - P_{EMAX_H} 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,
  - $P_{PowerClass}$. There is just one power class specified for LTE, corresponding to power class 3bis in WCDMA with +23 dBm ± 2dB, MPR and A-MPR are not taken into account,

UE Maximum Power Reduction

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





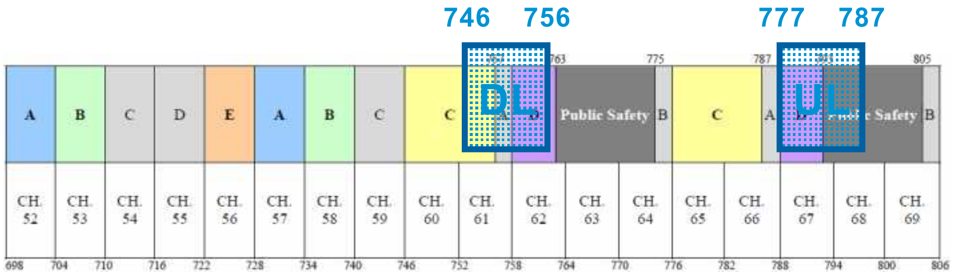
Modulation	Channel bandwidth / Transmission bandwidth configuration [RB]						MPR (dB)
	1.4 MHz	3.0 MHz	5 MHz	10 MHz	15 MHz	20 MHz	
QPSK	> 5	> 4	> 8	> 12	> 16	> 18	≤ 1
16 QAM	≤ 5	≤ 4	≤ 8	≤ 12	≤ 16	≤ 18	≤ 1
16 QAM Full	> 5	> 4	> 8	> 12	> 16	> 18	≤ 2

Higher order modulation schemes require more dynamic -> UE will slightly repeal its confinement for maximum power

PUSCH power control

Transmit output power (→ P_{UMAX}), cont'd.

3GPP Band 13



Network Signalling Value	Requirements (sub-clause)	E-UTRA Band	Channel bandwidth (MHz)	Resources Blocks	A-MPR (dB)
…	…	…	…	…	…
NS_07	6.6.2.2.3 6.6.3.3.2	13	10	Table 6.2.4-2	Table 6.2.4-2
…					

Indicates the lowest RB index of transmitted resource blocks

Defines the length of a contiguous RB allocation

	Region A		Region B		Region C
RB_{Start}	0 – 12		13 – 18	19 – 42	43 – 49
L_{CRB} [RBs]	6 – 8	1 – 5 to 9 – 50	≥8	≥18	≤2
A-MPR [dB]	8	12	12	6	3

- In case of EUTRA Band 13 depending on RB allocation as well as number of contiguously allocated RB different A-MPR needs to be considered.

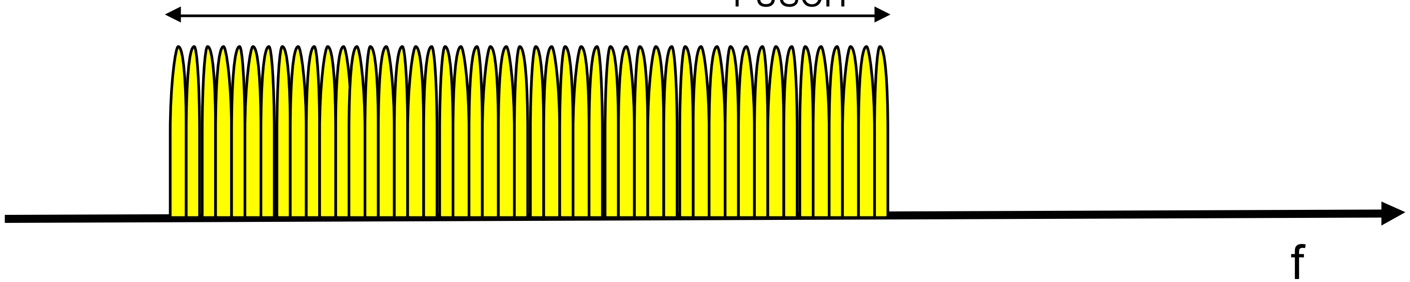
PUSCH power control

M_{PUSCH}

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

- **Power calculation depends also on allocated resource blocks for uplink data transmission,**

Number of resource blocks M_{PUSCH} varies from 1 to 100



$10*\log_{10}(M_{PUSCH}(i))$

M=1: 10*log(1) = 0

M=10: 10*log(10) = 10

M=100: 10*log(100) = 20

PUSCH power control : P_{O_PUSCH}

$P_{0\_PUSCH}(j)$

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

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

3 different values

Full path loss compensation is considered…

…no path loss compensation is used.

  - 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_{O_PUSCH}

$P_{0\_PUSCH}(j)$

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

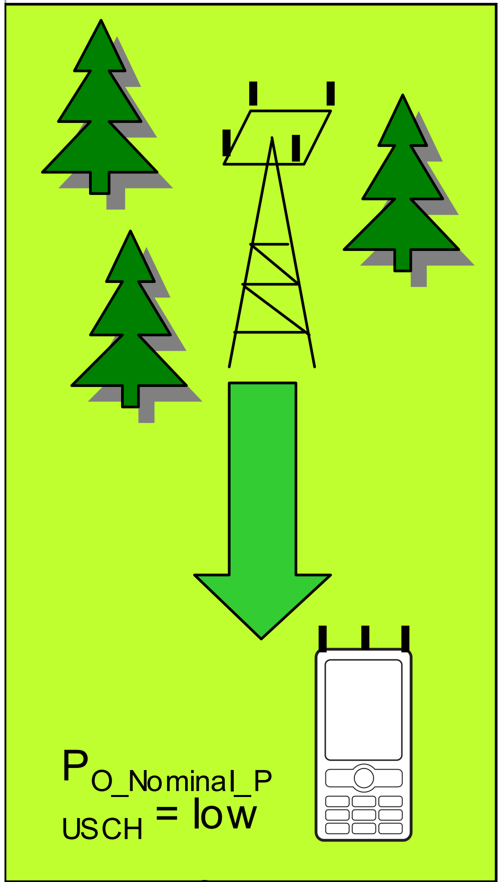
- *UplinkPowerControl* IE contains the required information about $P_{0\_Nominal\_PUSCH}$, $\Delta_{PREAMBLE\_Msg3}$ are part of *RadioResourceConfigCommon,*
- Via *RadioResourceConfigCommon* the terminal gets also access to *RACH-ConfigCommon* to extract from there information like *Preamble Initial Received Target Power* (P_{0_PRE}),
- *RadioResourceConfigCommon* IE is part of *System Information Block Type 2* (SIB Type 2)

SIB Type 2

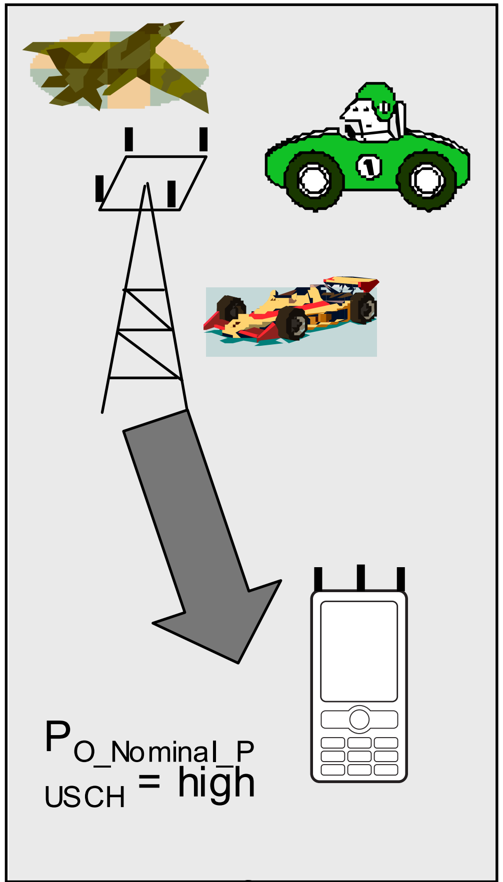
RadioResource
ConfigCommon

$P_{O\_Nominal\_PUSCH}$
Delta_preamble_msg3
PreambleInitialReceivedTargetPower

PUSCH power control: P_{O_PUSCH}

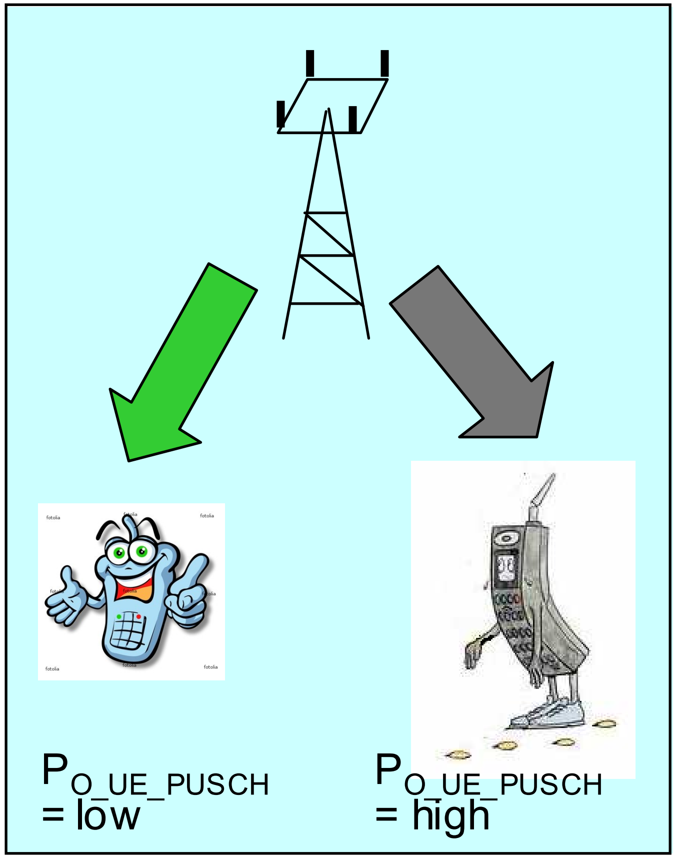


Low interference environment



High interference environment

$P_{O\_Nominal\_PUSCH}$ is cell dependent -> SIB2



$P_{O\_UE\_PUSCH}$ is UE dependent -> dedicated RRC signaling

PUSCH power control

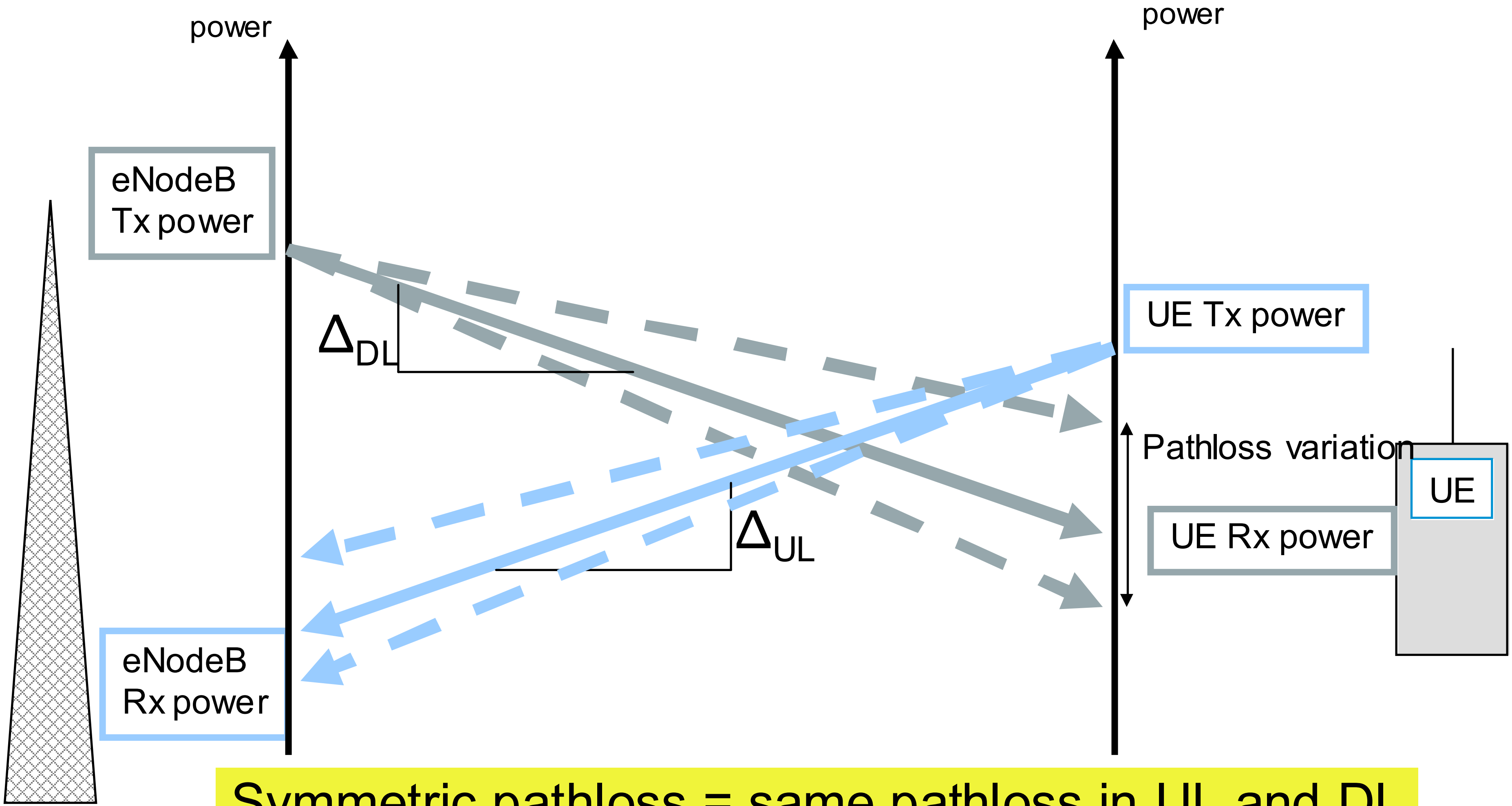
α(j) and PL

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

- 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



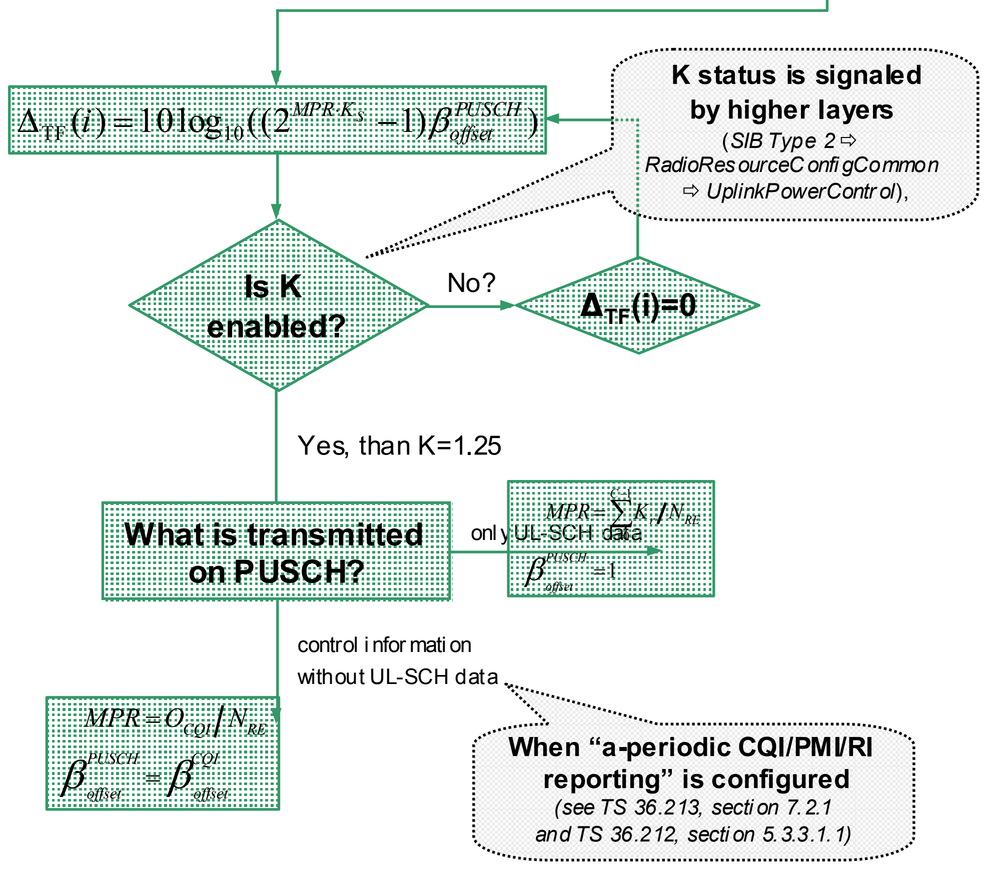
Symmetric pathloss = same pathloss in UL and DL

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

$\Delta_{TF}(i)$

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

deltaMCS = disabled

$\Delta_{TF}(i) = 0$

Default settings!

deltaMCS = enabled

$$\Delta_{TF}(i) = 10\log_{10}((2^{MPR\cdot K_S} - 1)\beta_{offset}^{PUSCH})$$

Sent in RRC messages to the UE, i.e. RRC_Connection_Setup

$$MPR = O_{CQI} / N_{RE}$$

$$\beta_{offset}^{PUSCH} = \beta_{offset}^{CQI}$$

$$MPR = \sum_{r=0}^{C-1} K_r / N_{RE}$$

$$\beta_{offset}^{PUSCH} = 1$$

O_{CQI} = number of CQI bits (max = 64 bits + CRC)
K_r = size of code block (max. 6144 bits)
N_{RE} = allocated bandwidth in subcarriers*number of symbols for initial PUSCH (12 or 10 symbols – symbols used for Sounding, SRS)
C = number of code blocks – after segmentation

PUSCH power control

f(i)

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

- 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}={$\pm$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,
  - $f(i)=f(i-1)+\delta_{PUSCH}(i-K_{PUSCH})$, 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 $P_{O\_PUSCH}(j)+\alpha(j)\cdot PL$; see previous slides),
  - $f(i)=\delta_{\mathrm{PUSCH}}(i-K_{\mathrm{PUSCH}})$, 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

f(i)

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

- Initial value f(0) for both cases (accumulative/absolute)
  - When $P_{O\_UE\_PUSCH}$ is signaled by higher layers, than f(0) = 0 else $f(0) = \boxed{\Delta P_{rampup}} + \delta_{msg2}$ where both parameters are configured by higher layers,

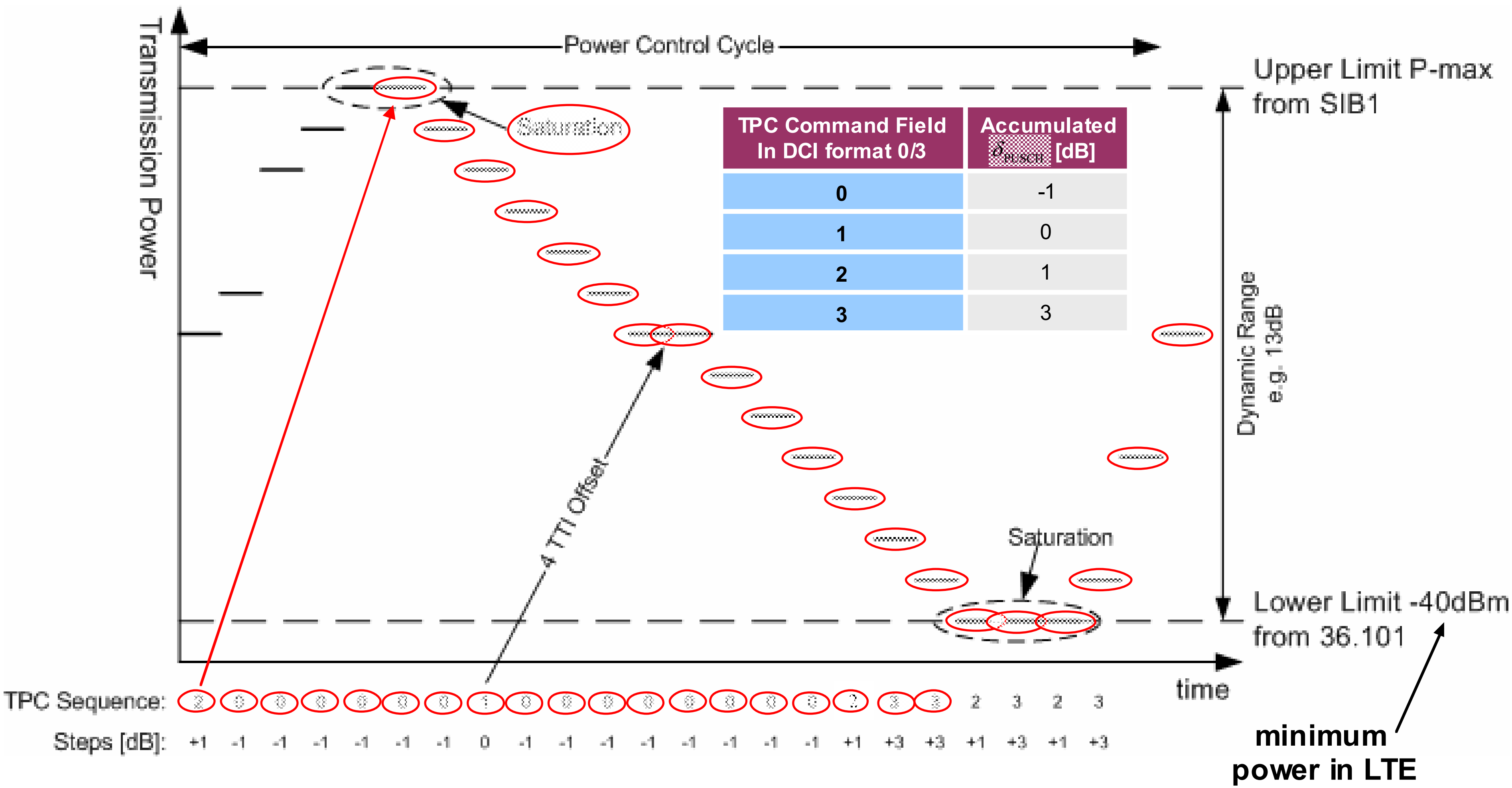
TPC command	Value (in dB)
0	-6
1	-4
2	-2
3	0
4	2
5	4
6	6
7	8

TS 36.213, table 6.2-1

Delta_ramp = Power between first and last PRACH preamble

PDCCH confirmation, containing Power control info, delta_msg2

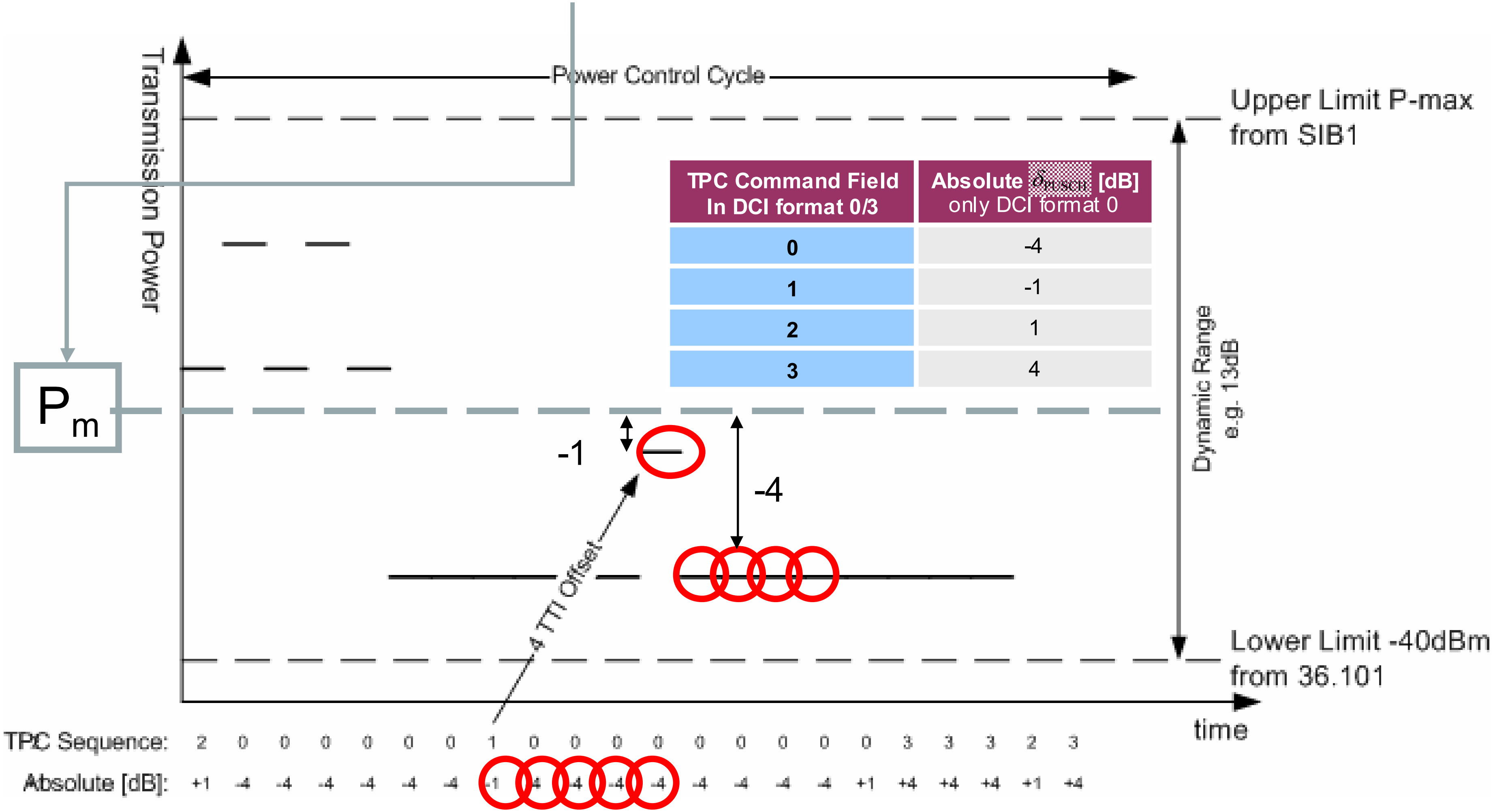
Accumulative TPC commands



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

Absolute TPC commands

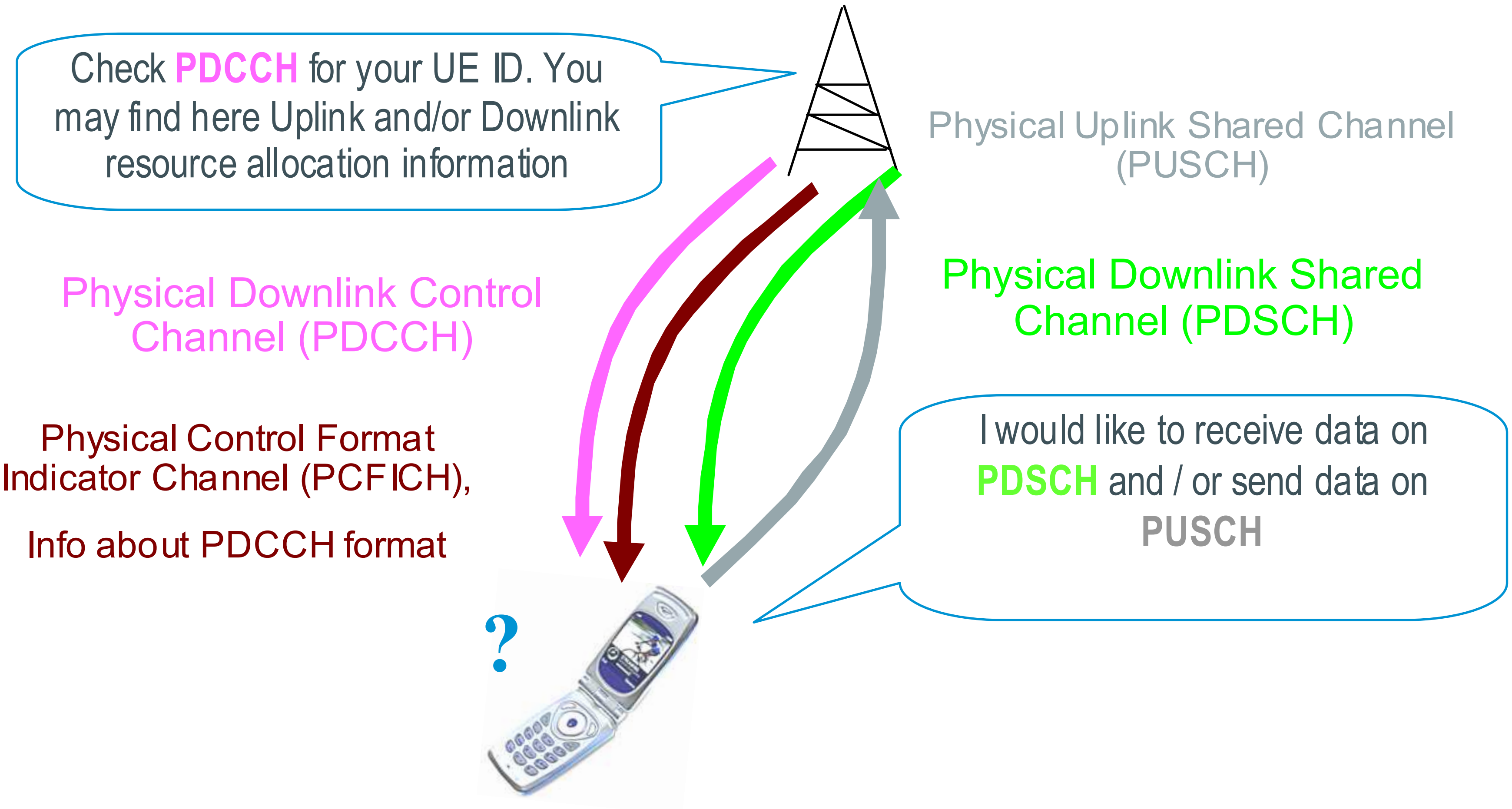
$$P_{PUSCH}(i) = \min\{P_{MAX}, \boxed{10\log_{10}(M_{PUSCH}(i)) + P_{O\_PUSCH}(j) + \alpha \cdot PL + \Delta_{TF}(TF(i))} + f(i)\}$$



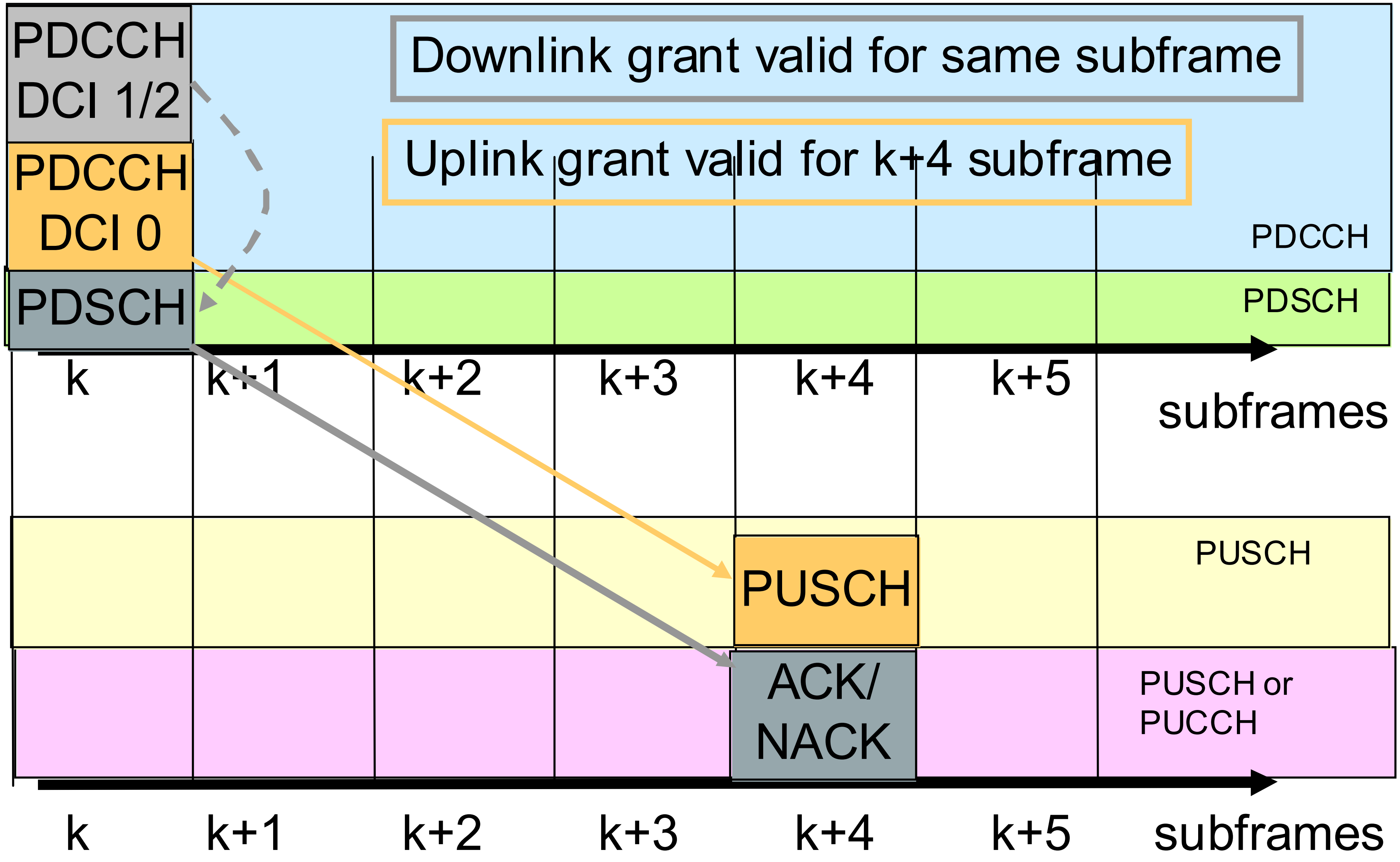
TPC Command Field In DCI format 0/3	Absolute δ_{PUSCH} [dB] only DCI format 0
0	-4
1	-1
2	1
3	4

LTE resource allocation principles

LTE resource allocation
Scheduling of downlink and uplink data



Resource allocation – timing aspects

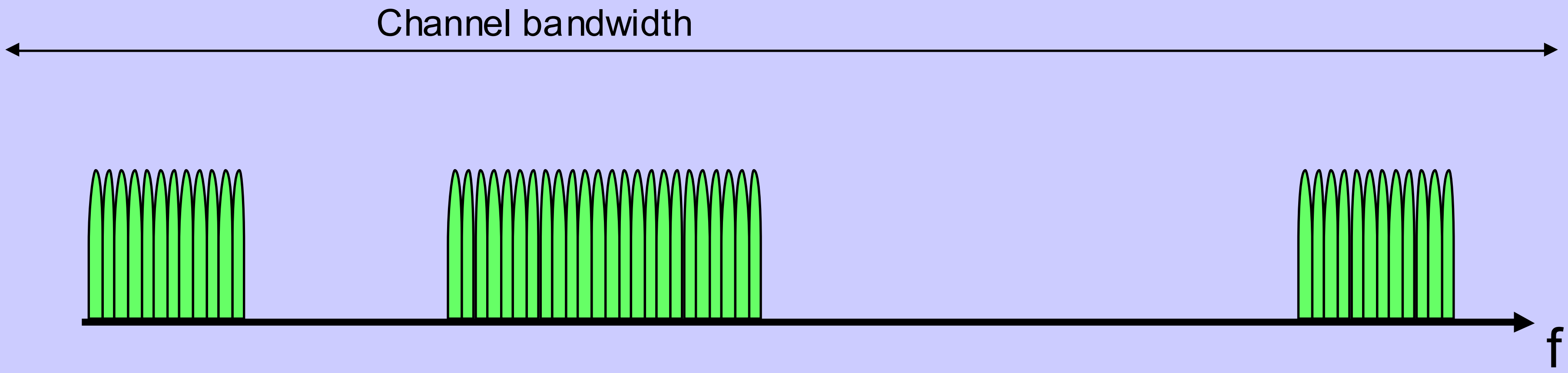


Resource allocation types in LTE

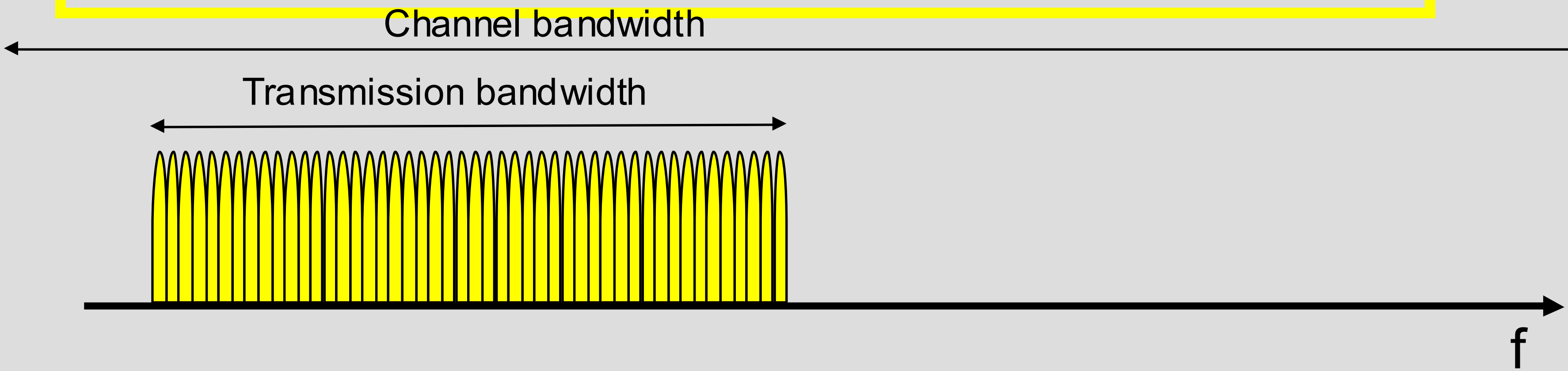
Allocation type	DCI Format	Scheduling Type	Antenna configuration
Type 0 / 1	DCI 1	PDSCH, one codeword	SISO, TxDiversity
	DCI 2A	PDSCH, two codewords	MIMO, open loop
	DCI 2	PDSCH, two codewords	MIMO, closed loop
Type 2	DCI 0	PUSCH	SISO
	DCI 1A	PDSCH, one codeword	SISO, TxDiversity
	DCI 1C	PDSCH, very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

Resource allocation types in LTE

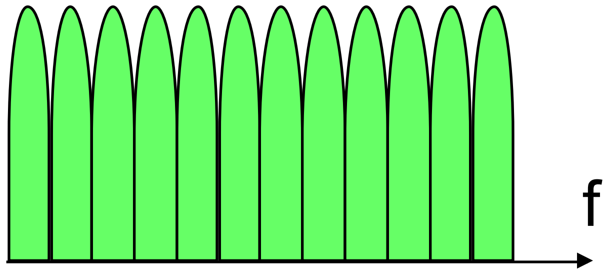
Type 0 and 1 for distributed allocation in frequency domain



Type 2 for contiguous allocation in frequency domain

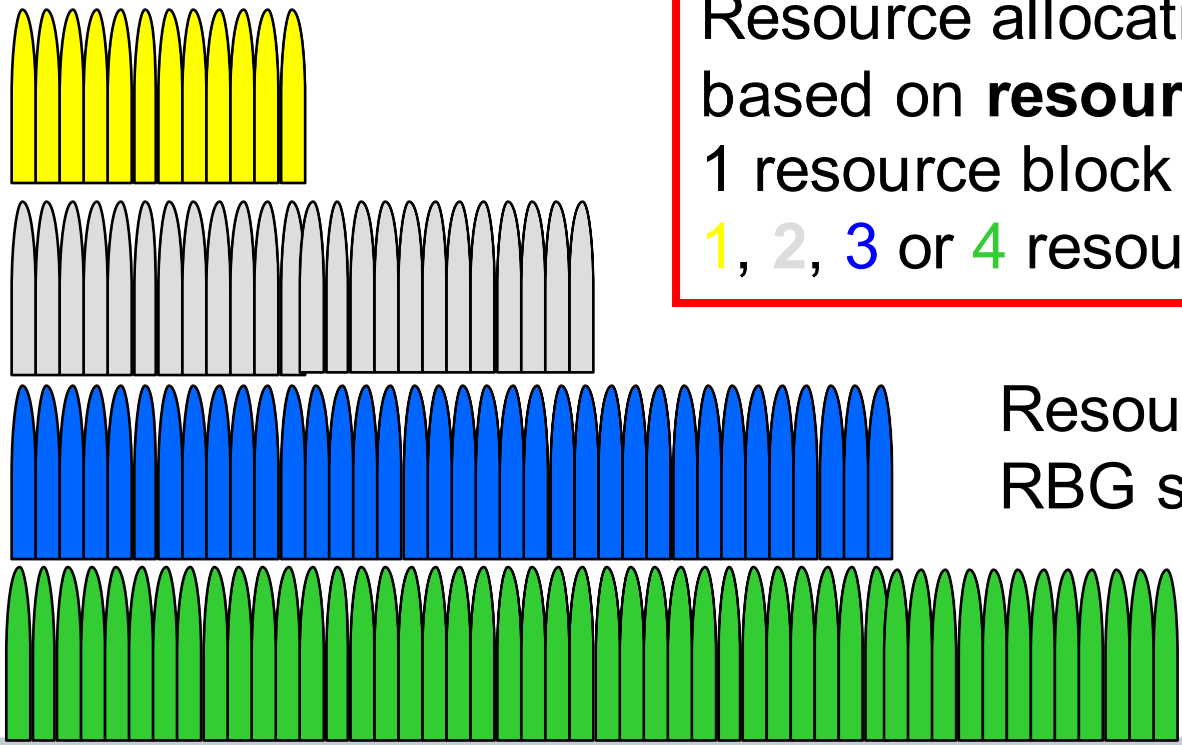


Resource Block Group



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 $N_{\mathrm{RB}}^{\mathrm{DL}} - P \cdot \lfloor N_{\mathrm{RB}}^{\mathrm{DL}} / P \rfloor$

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!

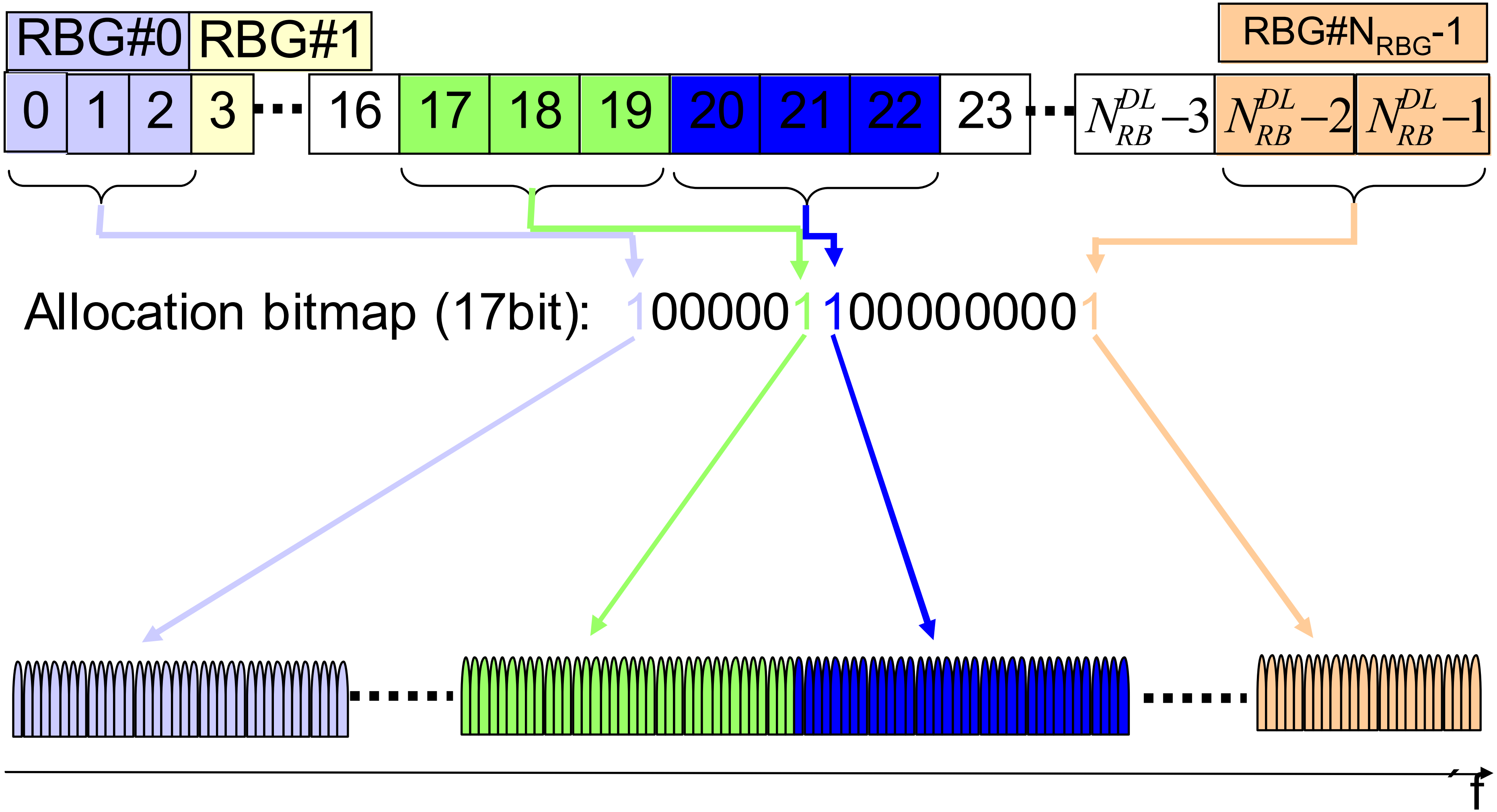
reminder

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

$\lfloor N_{\mathrm{RB}}^{\mathrm{DL}} / P \rfloor$ = 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



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

RBG#0			RBG#1											RBG#N_{RBG}-1	
0	1	2	3	…	16	17	18	19	20	21	22	23	…	$N_{RB}^{DL}-3$	$N_{RB}^{DL}-2$	$N_{RB}^{DL}-1$

RBG#0	RBG#3	RBG#6	RBG#9	RBG#12	RBG#15	RBG subset #0
RBG#1	RBG#4	RBG#7	RBG#10	RBG#13	RBG#16	RBG subset #1
RBG#2	RBG#5	RBG#8	RBG#11	RBG#14		RBG subset #2

P= Number of RBG subsets with length:

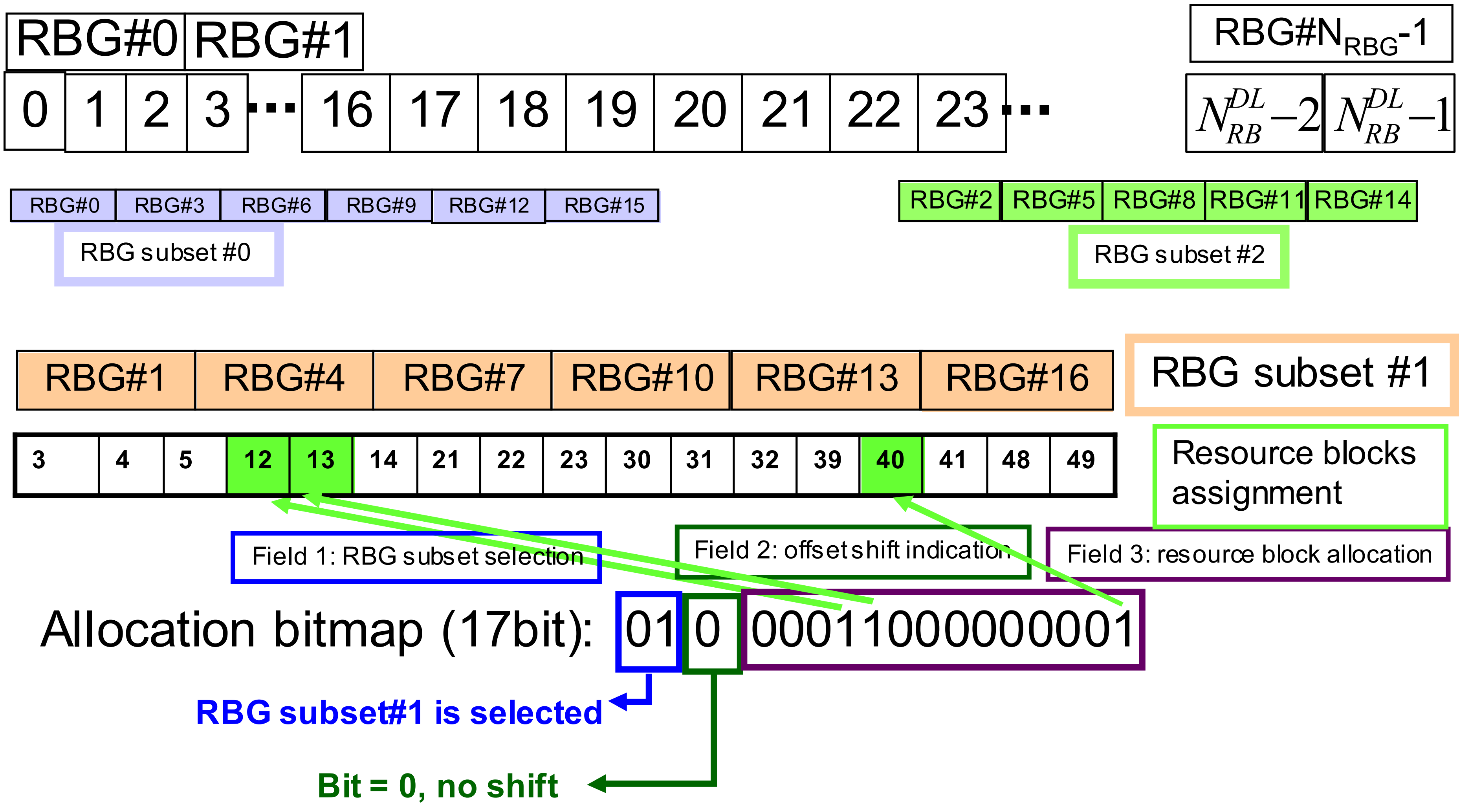
$$\lceil \log_2(P) \rceil$$

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

Number of bits to indicate subset

Resource allocation type 1

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

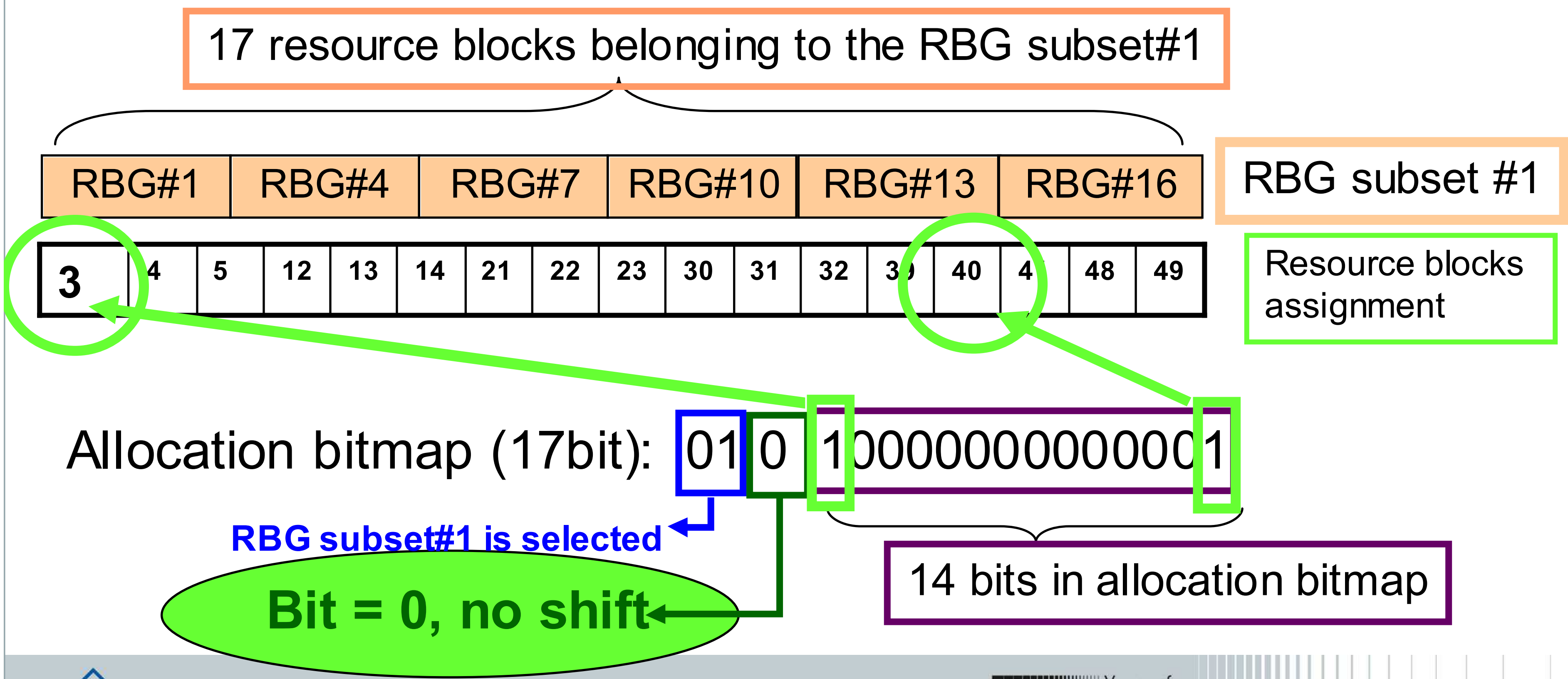


Resource allocation type 1

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

The meaning of the shift offset bit:

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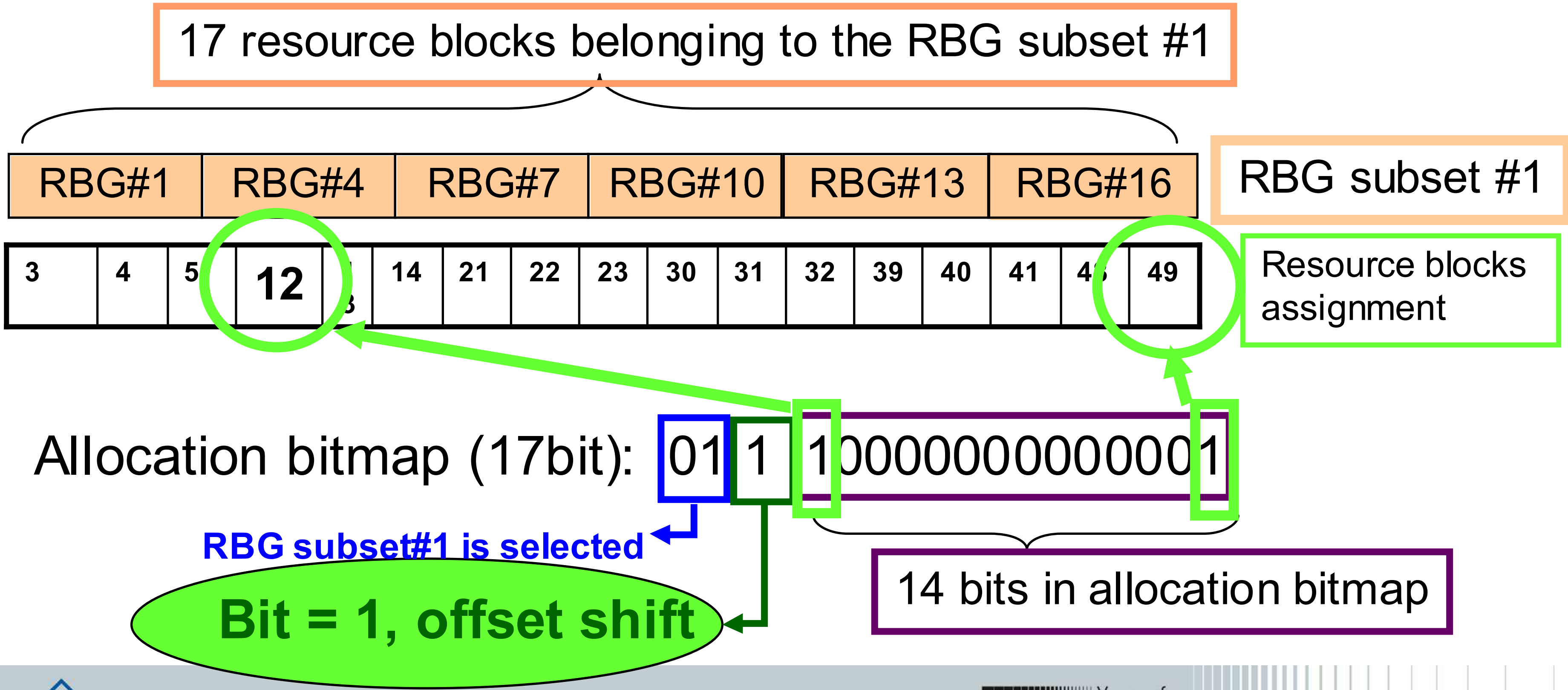
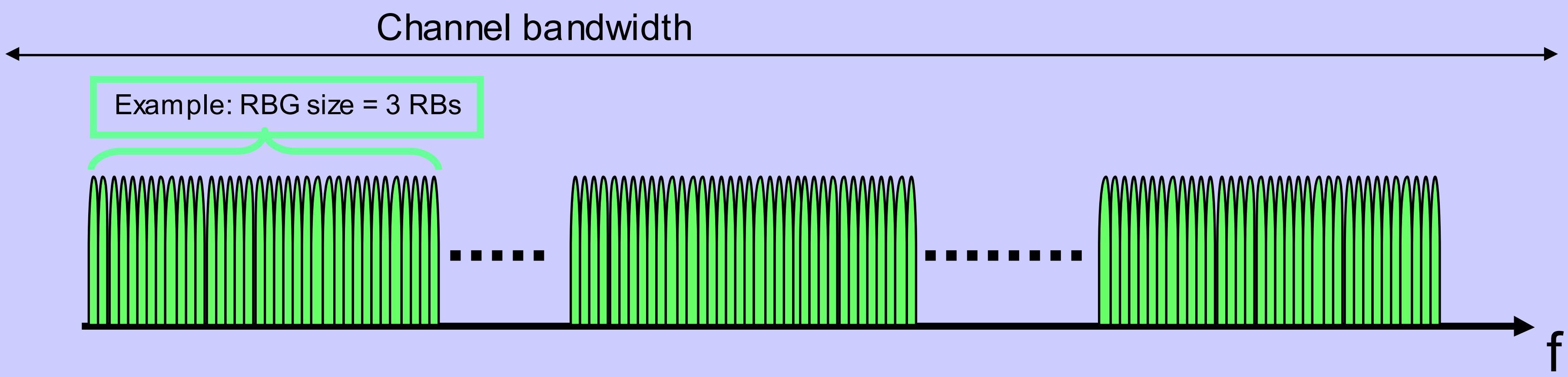
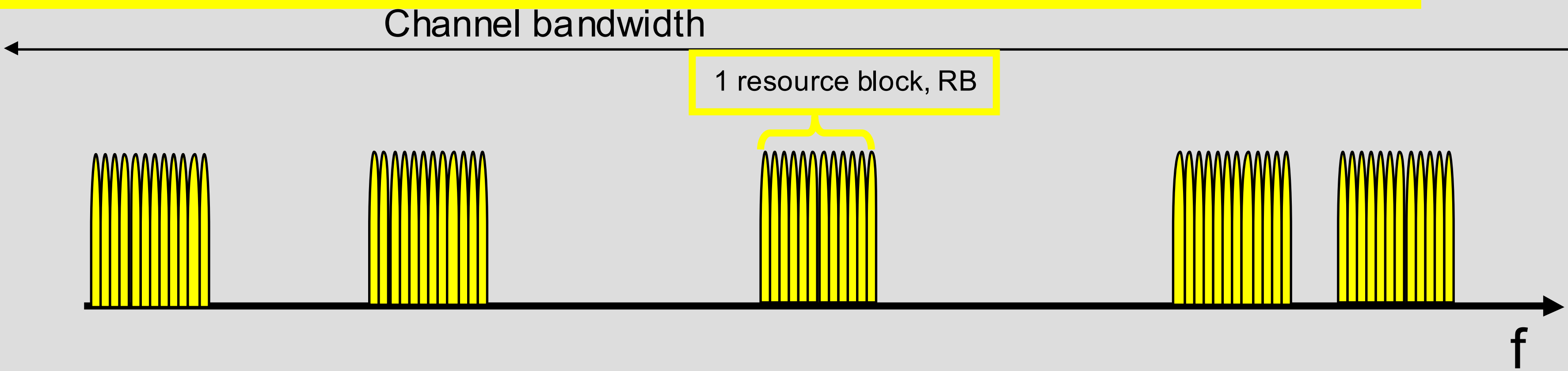


Resource allocation types in LTE

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:**

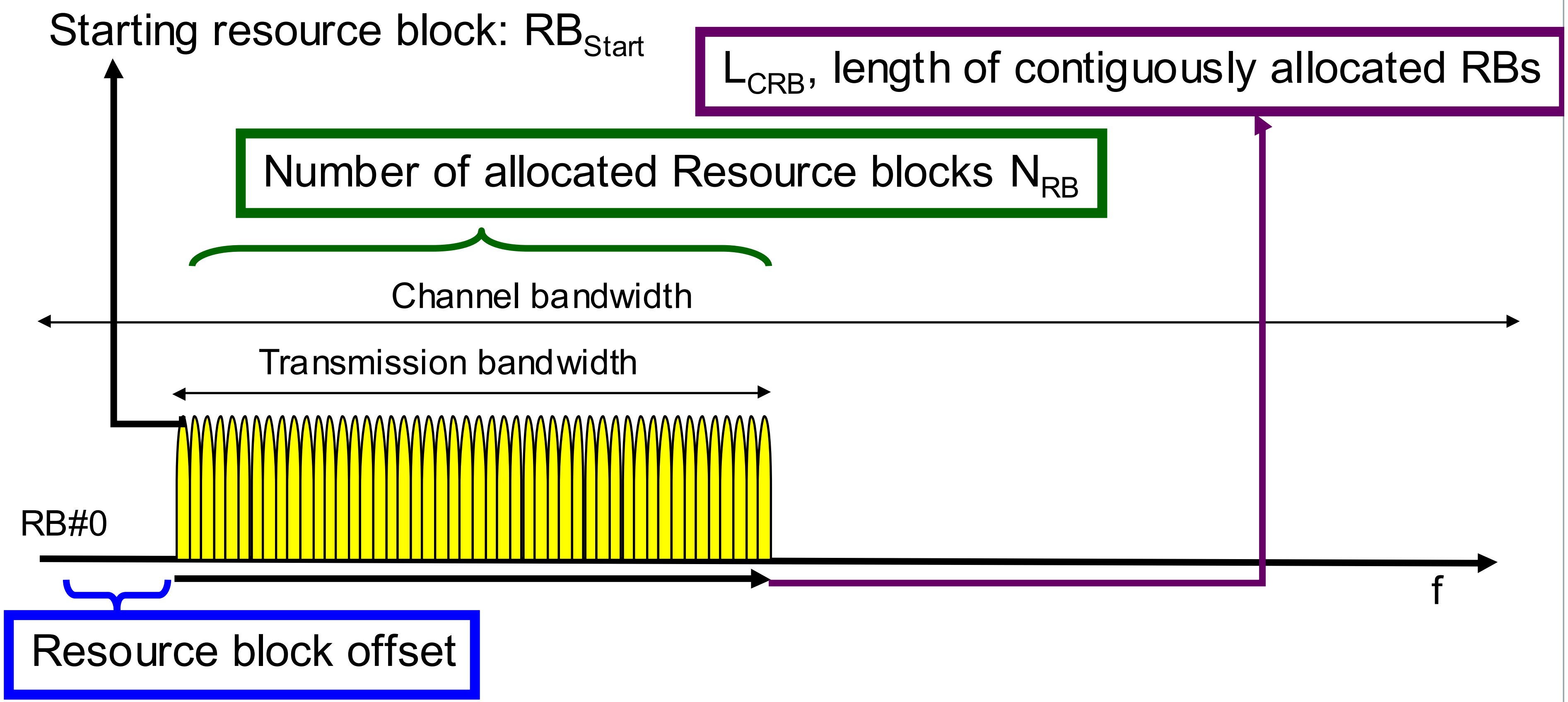
Localized mode

Distributed mode

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

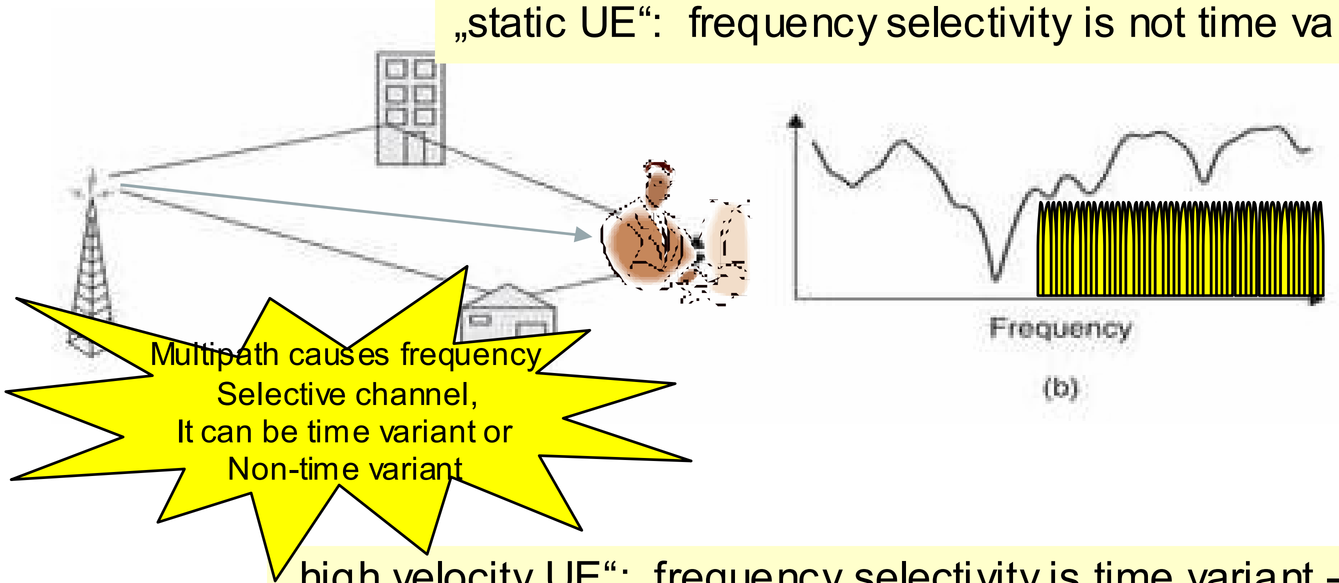
Resource allocation type 2

Localized mode

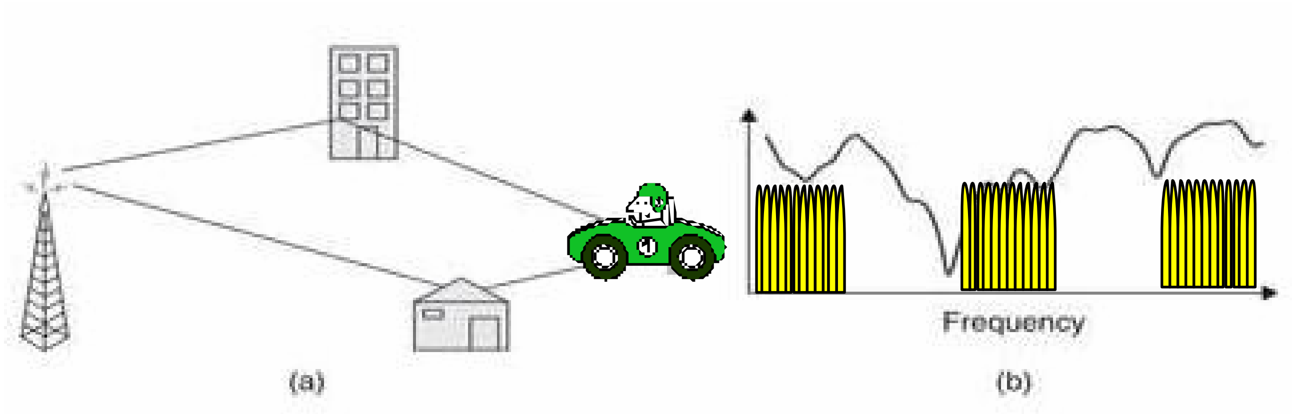


Benefit of localized or distributed mode

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



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



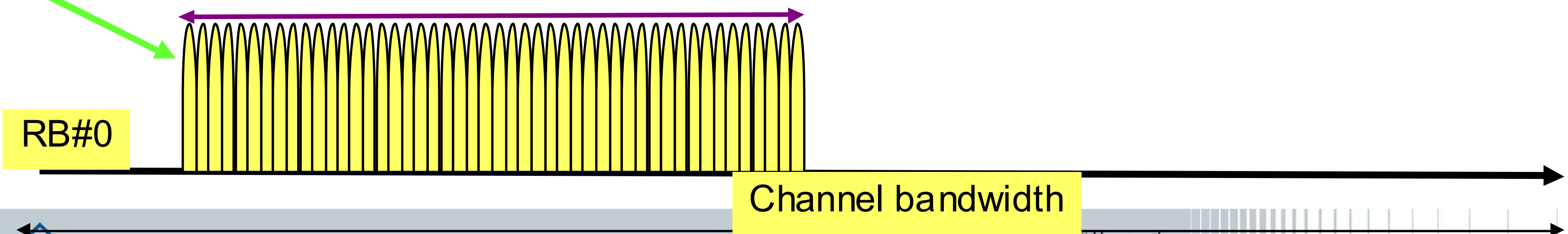
Resource allocation Uplink

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 uses Type 2 allocation

Starting resource block: RB_{Start}

L_{CRB}, length of contiguously allocated RBs



LTE Uplink: allocation of UL ressource

Scheduled UL bandwidth

UL bandwidth configuration

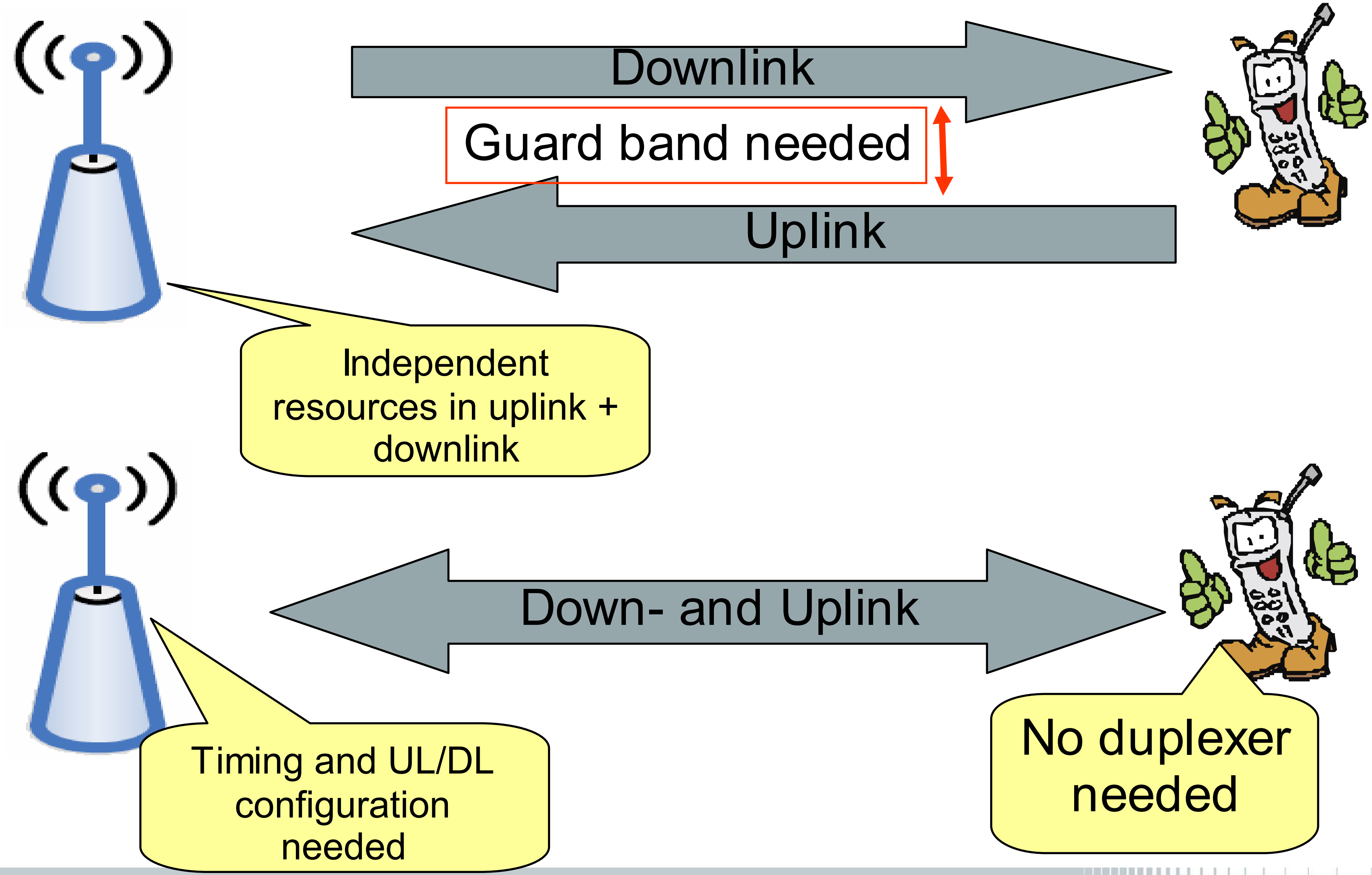
$$M_{\mathrm{RB}}^{\mathrm{PUSCH}} = 2^{\alpha_2} \cdot 3^{\alpha_3} \cdot 5^{\alpha_5} \leq N_{\mathrm{RB}}^{\mathrm{UL}}$$

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 TDD and FDD mode of operation

TDD versus FDD



General comments

What is called “Advantages of TDD vs. FDD mode”

- **Data traffic,**
  - Asymmetric setting between downlink and uplink possible, depending on the situation,

See interference aspects:
UL – DL and inter-cell

- **Channel estimation,**
  - Channel characteristic for downlink and uplink same,

In principle yes:
•But hardware influence!
•And: Timing delay UL and DL

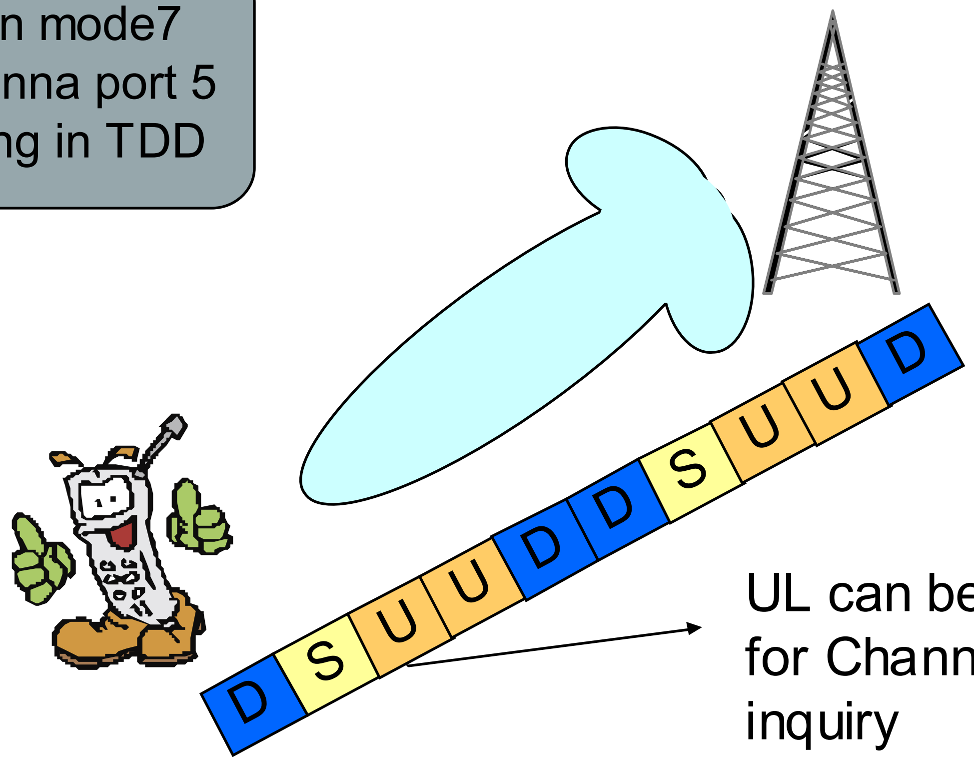
- **Design,**
  - No duplexer required, simplifies RF design and reduce costs.

But most UEs will be dual-mode: FDD and TDD!

Beamforming in LTE TDD

- **Adaptive Beamforming**
  - Beamforming in TDD mode is used via Specific antenna port 5
  - Channel estimation performed at eNodeB based on uplink timeslots

Transmission mode7
SISO, via antenna port 5
= beamforming in TDD



UL can be used by eNodeB for Channel Status information inquiry

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 TDD mode - overview

7 different UL/DL configurations are defined

Characteristics + differences of UL/DL configurations:

- Number of subframes dedicated to Tx and Rx
- Number of Hybrid Automatic Repeat Request, HARQ processes
- HARQ process timing: time between first transmission and retransmission
- Scheduling timing: What is the time between PDCCH and PUSCH?

9 different configurations for the „special subframe“ are defined

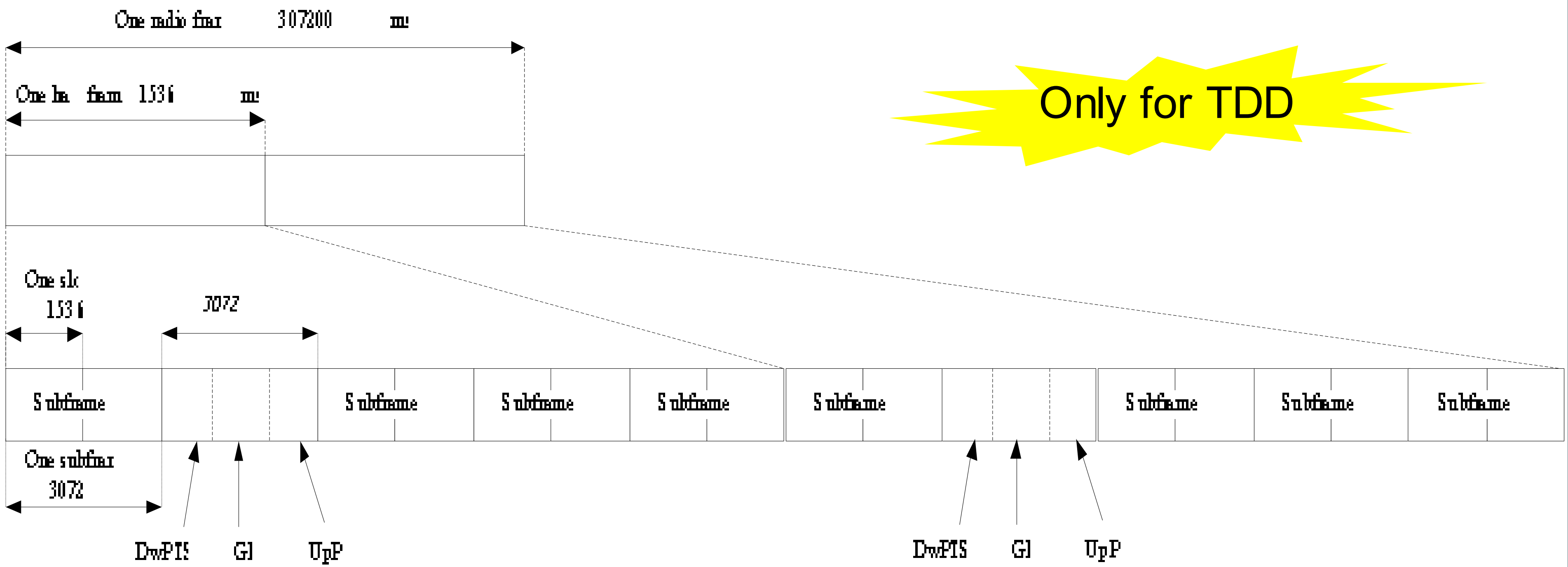
Definition of how long are the DL and UL pilot signals and how much control information can be sent on it. -> also has an impact on cell size

Differences between Uplink and Downlink in TD-LTE

- Characteristic of HARQ: Synchronuous or asynchronuous
- Number of Hybrid Automatic Repeat Request, HARQ processes
- HARQ process timing: time between first transmission and retransmission

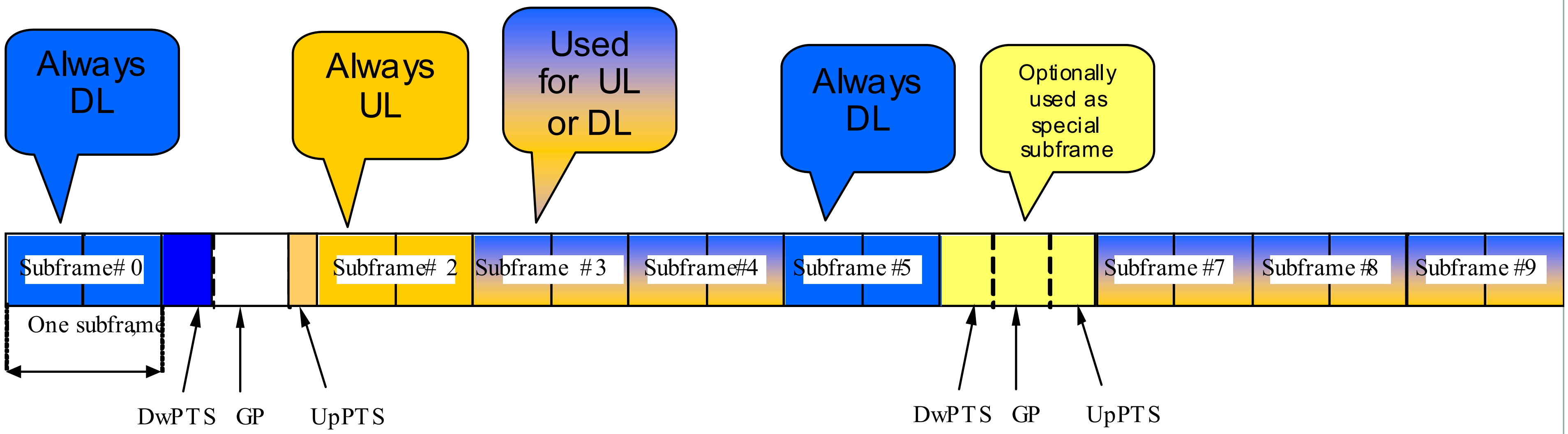
LTE Downlink:
Downlink slot and frame structure: type 2

Only for TDD



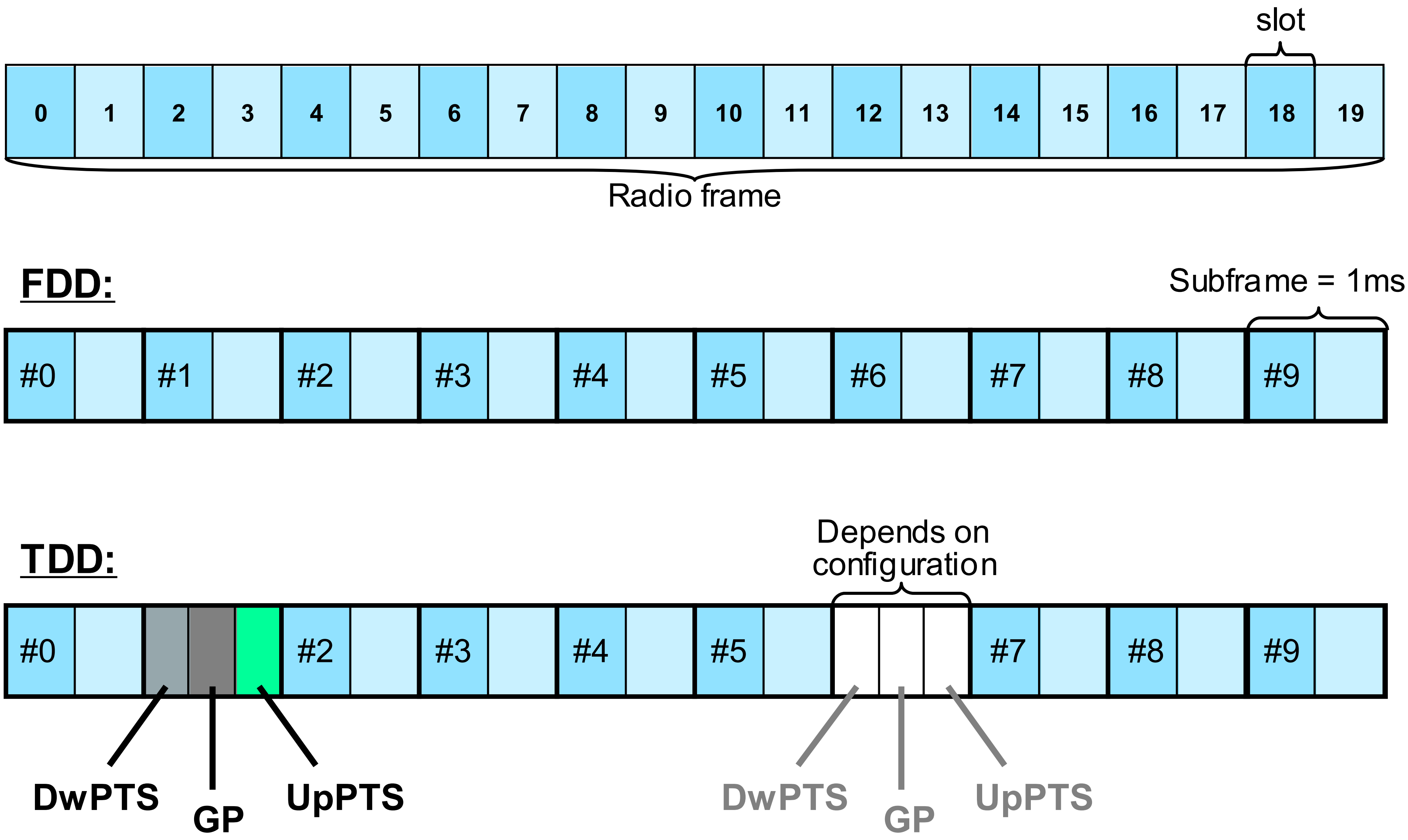
DwPTS = Downlink Pilot Time Slot
UpPTS = Uplink Pilot Time Slot

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

TDD versus FDD Frame



TD-LTE uplink-downlink configurations

First requirements, that need to be supported…

UL-DL configuration	DL-to-UL switch point periodicity	DL:UL Ratio	Peak data rate		Subframe number									
			DL	UL	0	1	2	3	4	5	6	7	8	9
0	5 ms	1:3	51.5	29.4	D	S	U	U	U	D	S	U	U	U
1	5 ms	2:2	81.4	19.6	D	S	U	U	D	D	S	U	U	D
2	5 ms	3:1	111.6	9.8	D	S	U	D	D	D	S	U	D	D
3	10 ms	6:3	101.0	14.7	D	S	U	U	U	D	D	D	D	D
4	10 ms	7:2	116.1	9.8	D	S	U	U	D	D	D	D	D	D
5	10ms	8:1	131.6	4.9	D	S	U	D	D	D	D	D	D	D
6	5 ms	3:5	66.3	24.5	D	S	U	U	U	D	S	U	U	D

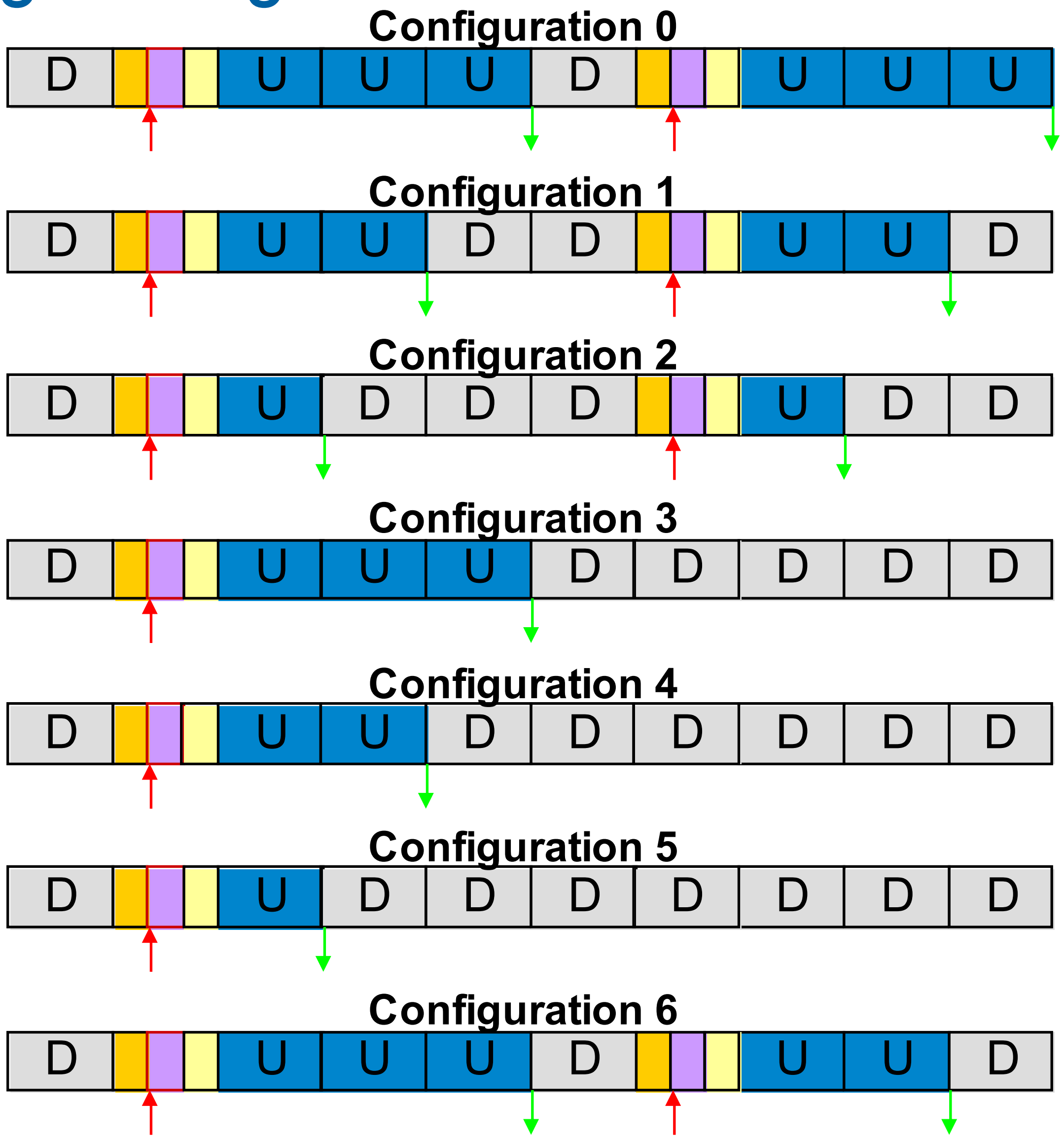
D = the subframe is reserved for downlink transmissions

U = the subframe is reserved for uplink transmissions

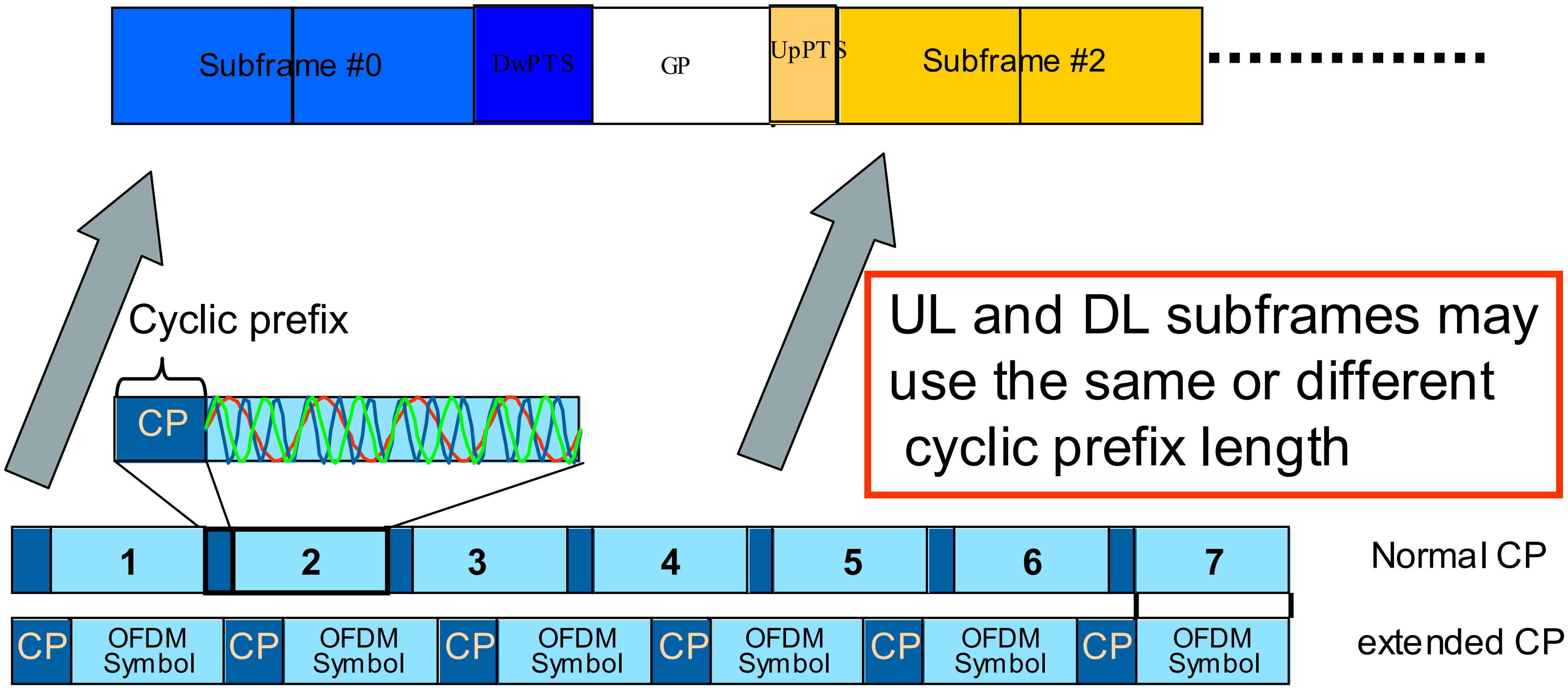
S = a special subframe containing DwPTS, GP and UpPTS

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



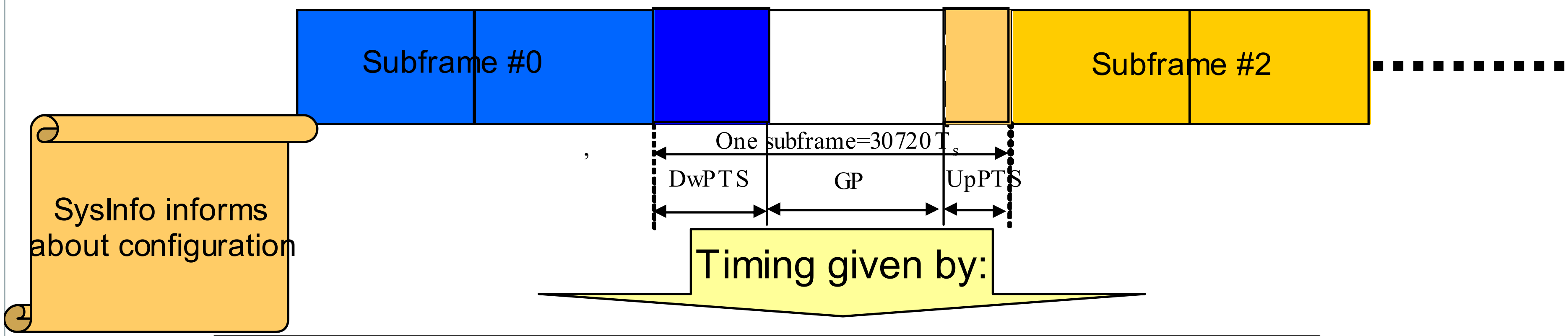
LTE TDD: cyclic prefix used in UL and DL



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?



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	$6592 \cdot T_s$			$7680 \cdot T_s$		
1	$19760 \cdot T_s$			$20480 \cdot T_s$		
2	$21952 \cdot T_s$	$2192 \cdot T_s$	$2560 \cdot T_s$	$23040 \cdot T_s$	$2192 \cdot T_s$	$2560 \cdot T_s$
3	$24144 \cdot T_s$			$25600 \cdot T_s$		
4	$26336 \cdot T_s$			$7680 \cdot T_s$		
5	$6592 \cdot T_s$			$20480 \cdot T_s$	$4384 \cdot T_s$	$5120 \cdot T_s$
6	$19760 \cdot T_s$	$4384 \cdot T_s$	$5120 \cdot T_s$	$23040 \cdot T_s$		
7	$21952 \cdot T_s$			-	-	-
8	$24144 \cdot T_s$			-	-	-

Table from TS 36.211

DwPTS, GP, UpPTS

Transmitted content

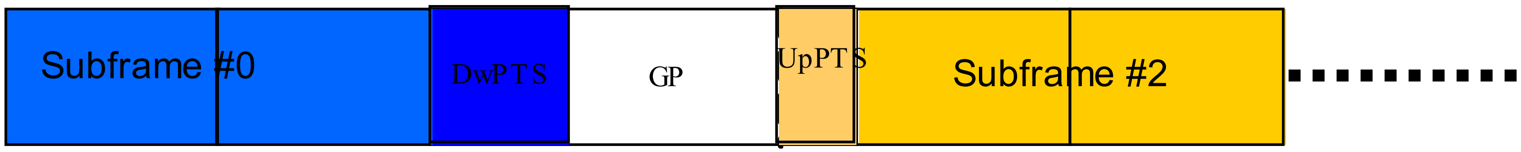
- **DwPTS – Downlink Pilot Time Slot,**
  - PDCCH → 1, 2 OFDM symbols beginning of subframe,
  - Primary synchronization signal → 3. OFDM symbol in DwPTS,
  - Reference signal → 1. OFDM symbol in DwPTS,
  - User data,

- **GP – Guard Period,**
  - Length: $L_{GP}=T_{DU}+T_{UD}+\mathit{Propagation\ Delay}$
  - $T_{DU/UD}$: The guard period at DL to UL switch, respectively UL to DL switch,

- **UpPTS – Uplink Pilot Time Slot,**
  - PRACH Format 4,
  - Sounding Reference Signal.

LTE TDD: special subframe configurations

Special subframe configuration = maximum cell size



Timing given by:

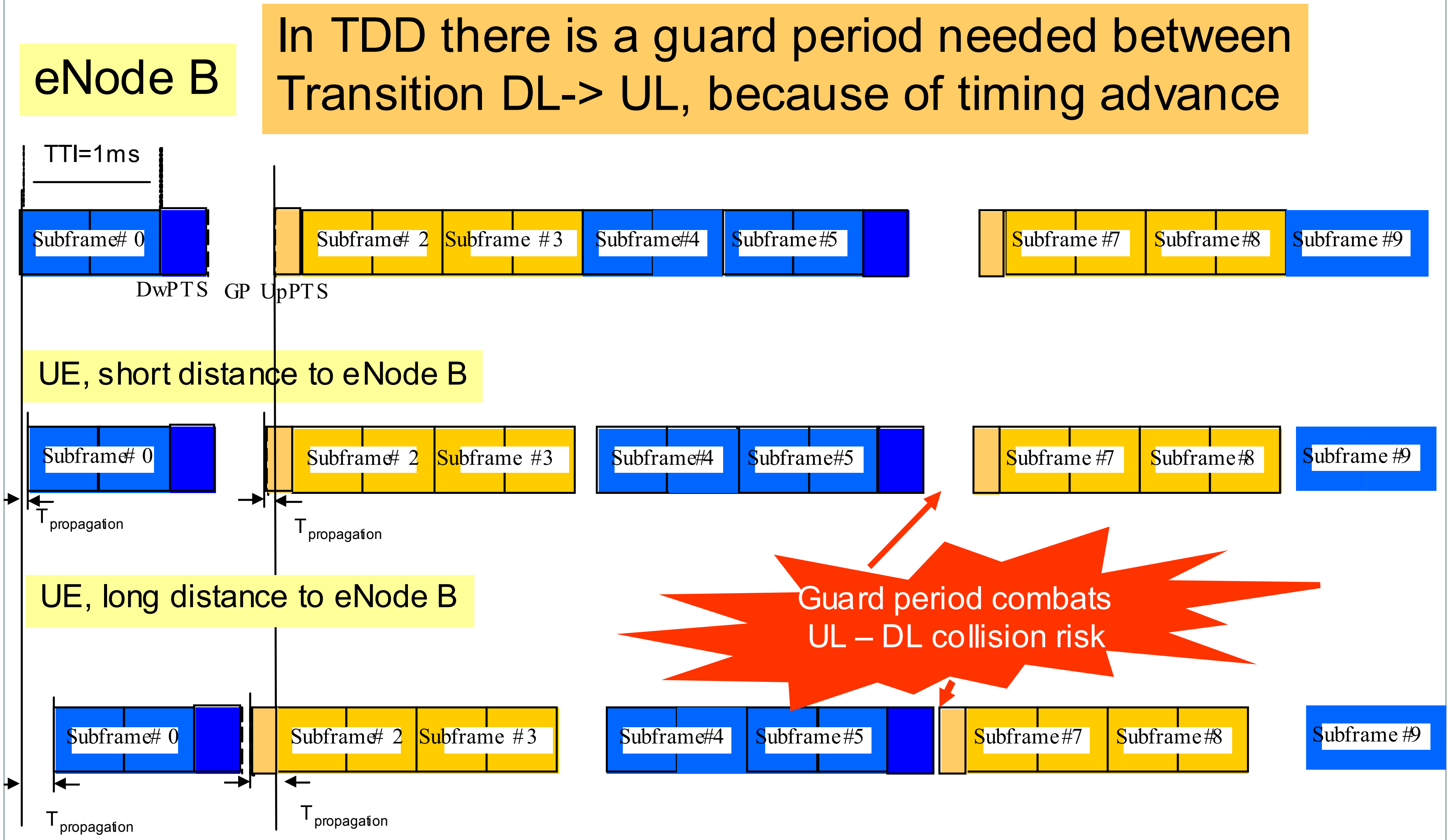
Example for timing

Number basis = 2192*T_s

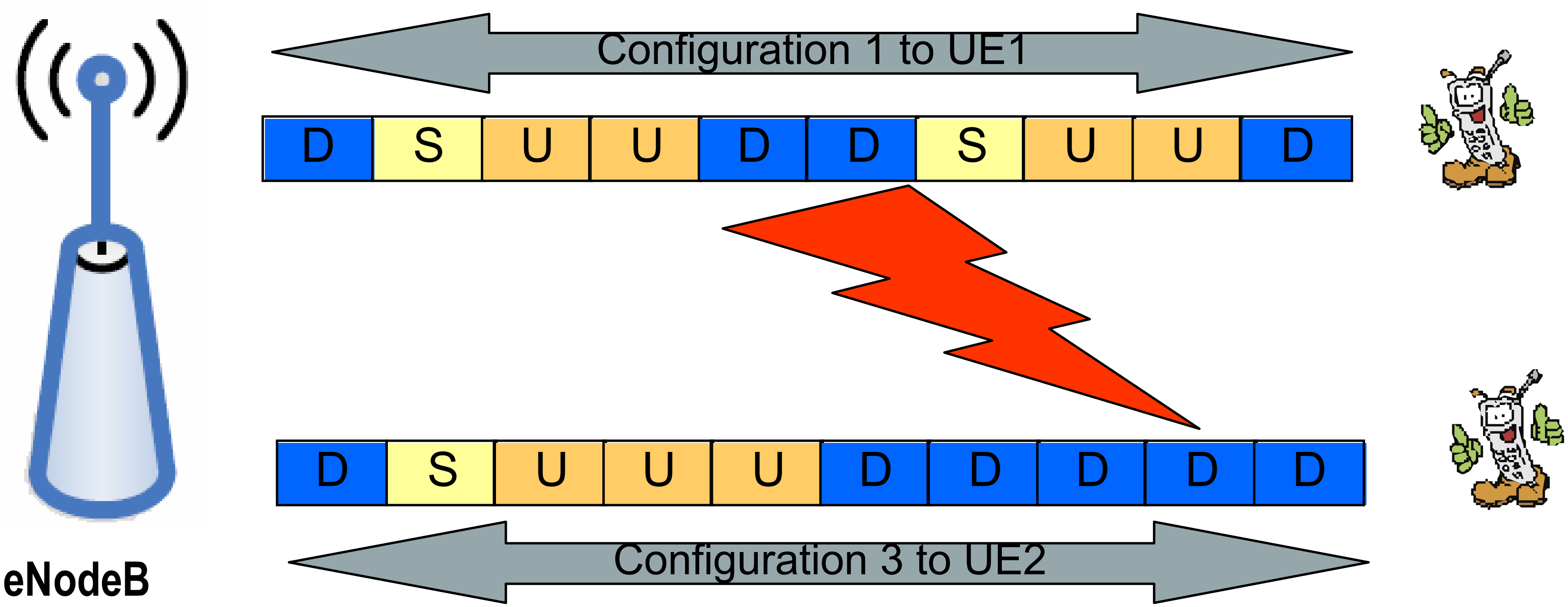
Special subframe configuration	Normal Cyclic prefix in DL and UL			Max Cell size
	DwPTS	Guard Period	UpPTS	
0	3	10	1	100 km
1	9	4	1	40 km
2	10	6	1	60 km
3	11	2	1	20 km
4	12	1	1	10 km
5*	3	9	2	90 km
6	9	3	2	30 km
7*	10	2	2	20 km
8	11	1	2	10 km

*: first requirements

LTE TDD: timing advance and guard period

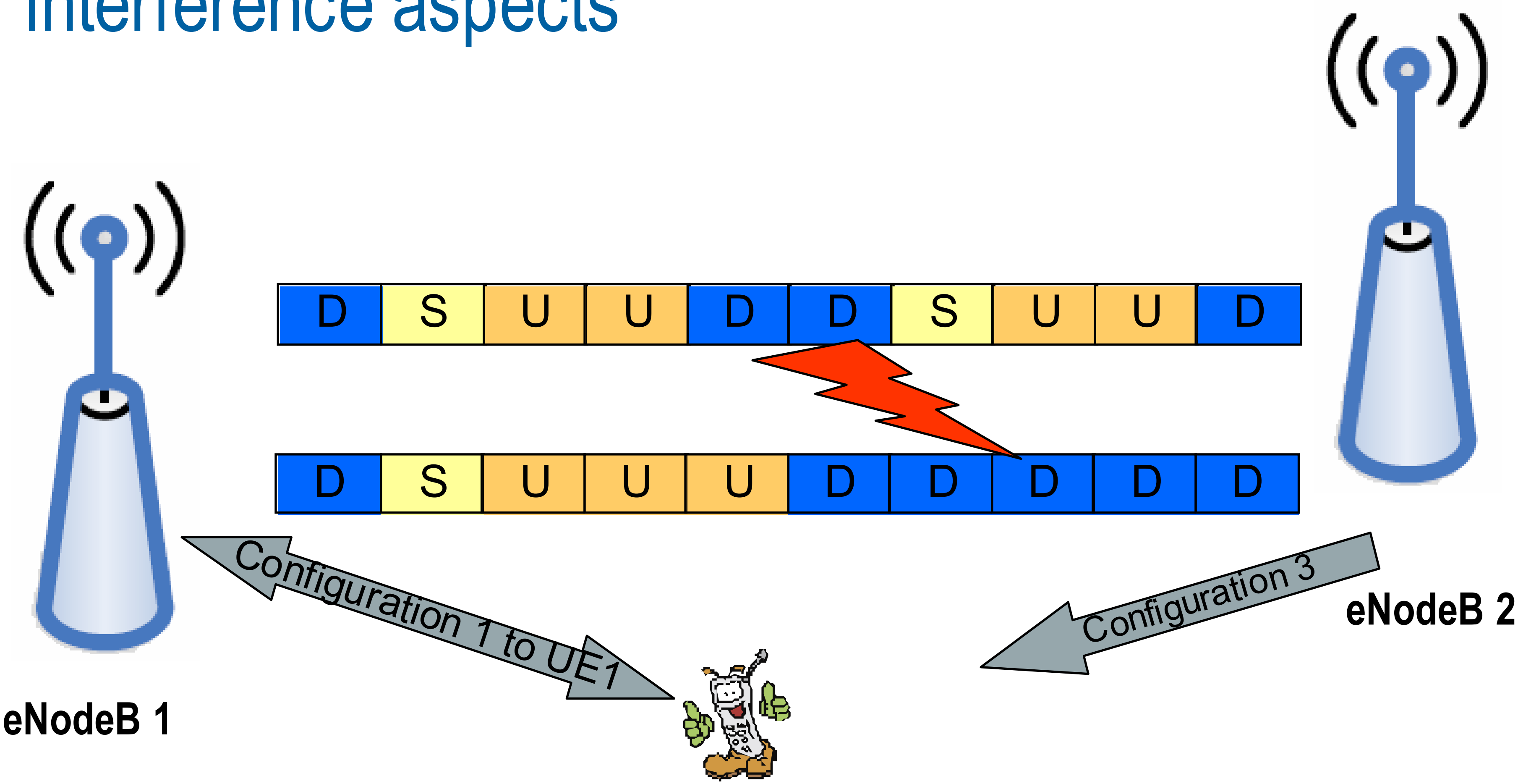


Interference aspects



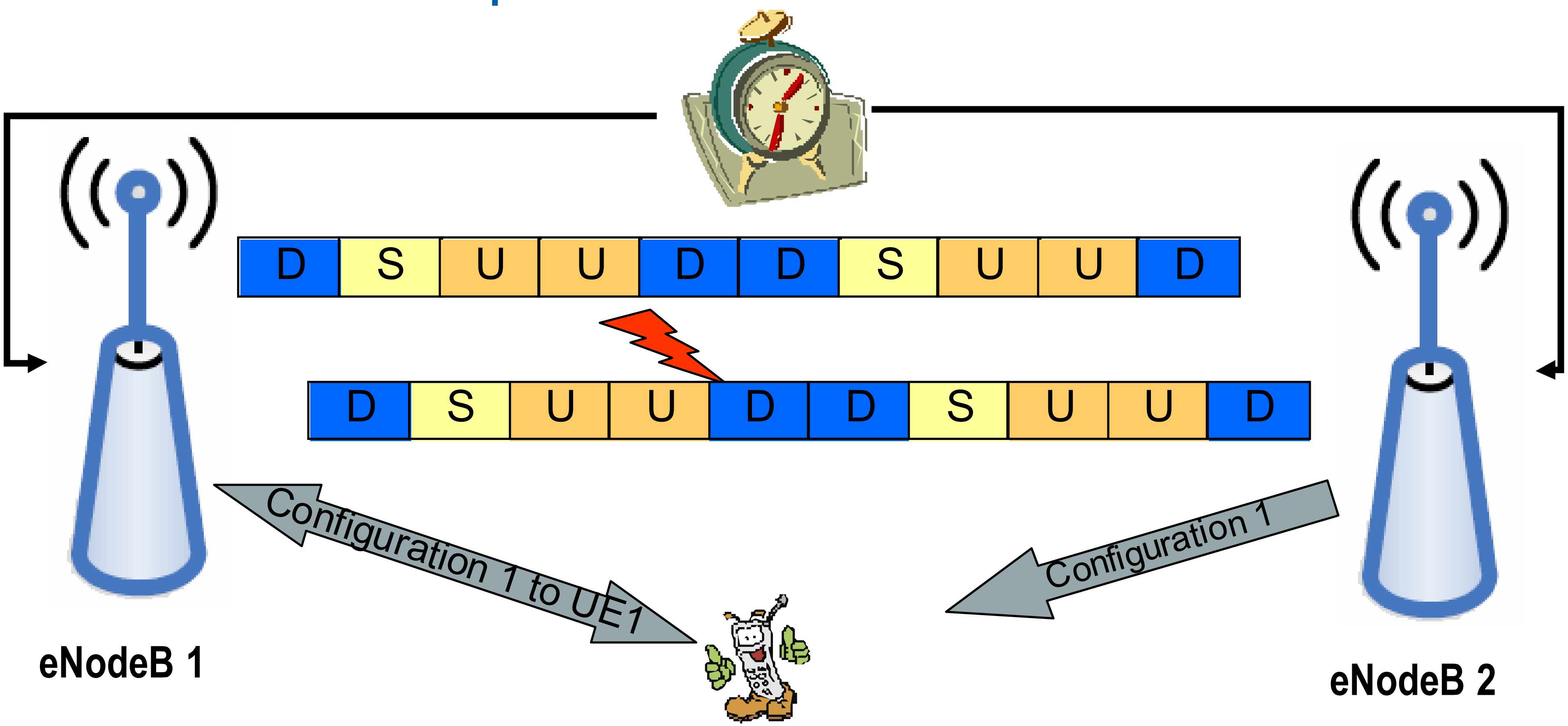
The UL/DL configuration can not vary dynamically between the UEs within a node B

Interference aspects



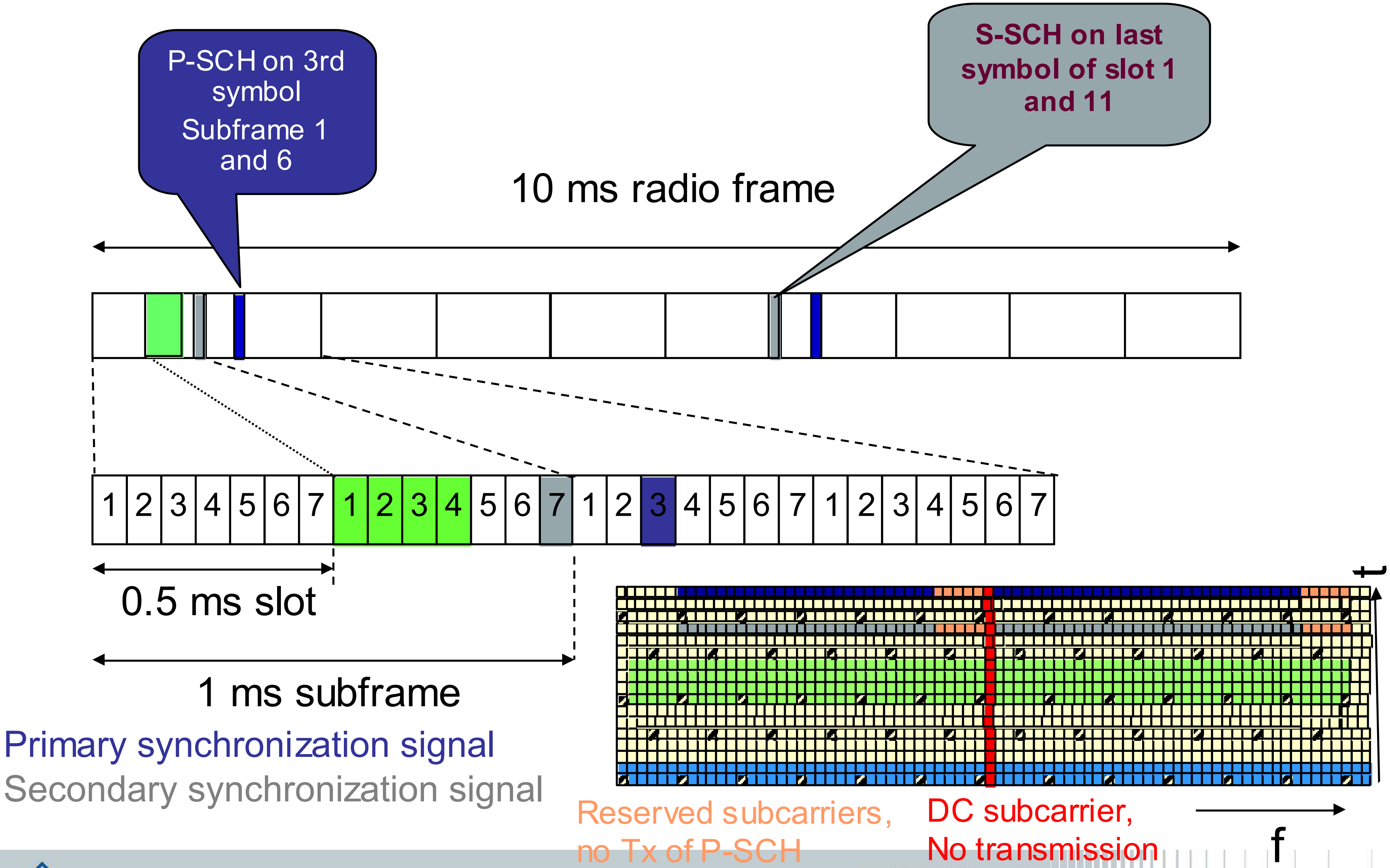
Neighbour cells should have the same UL/DL configurations

Interference aspects

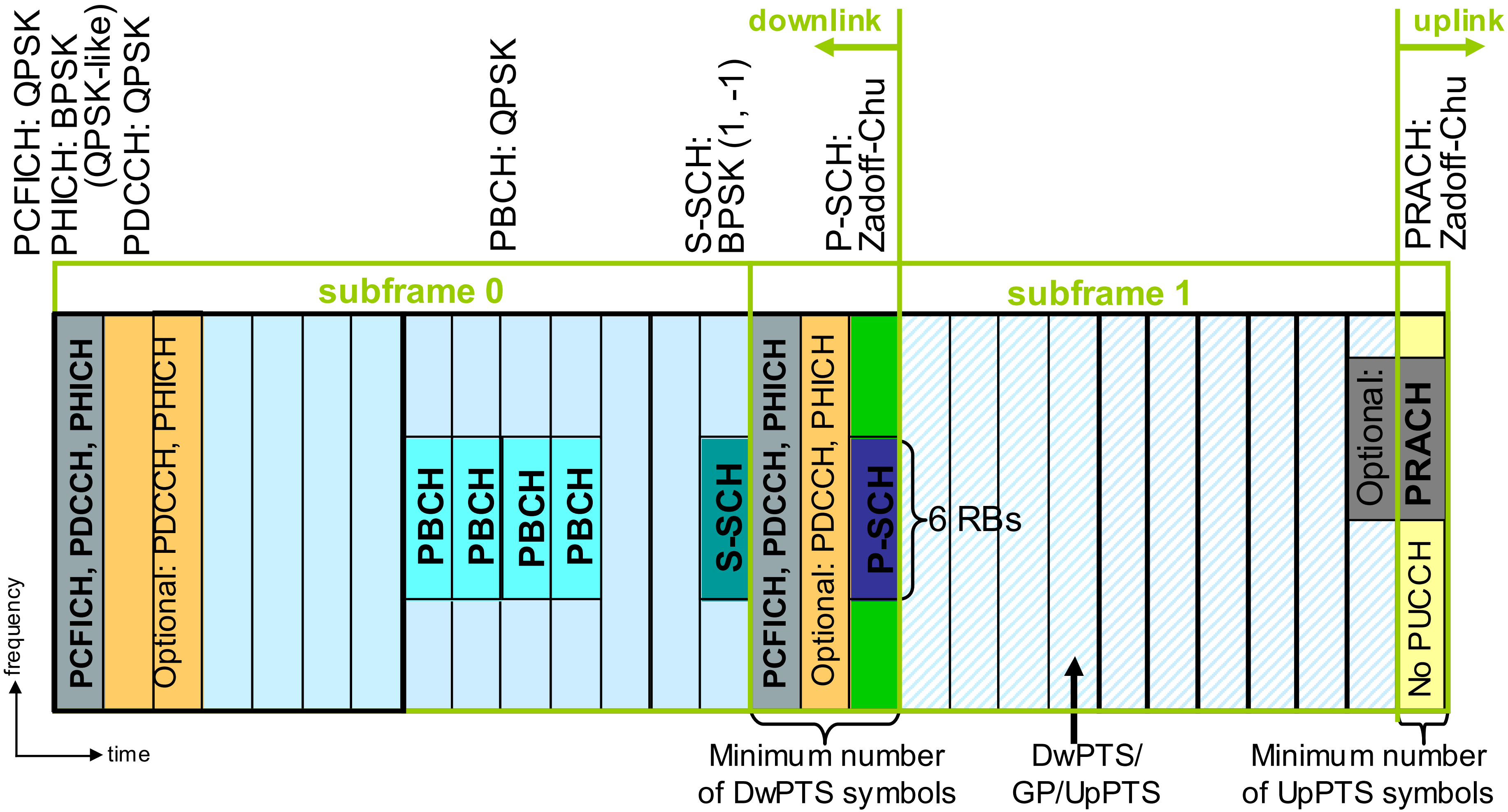


Neighbour cells should have the same Frame timing. Synchronisation required

LTE TDD: P-SCH and S-SCH position

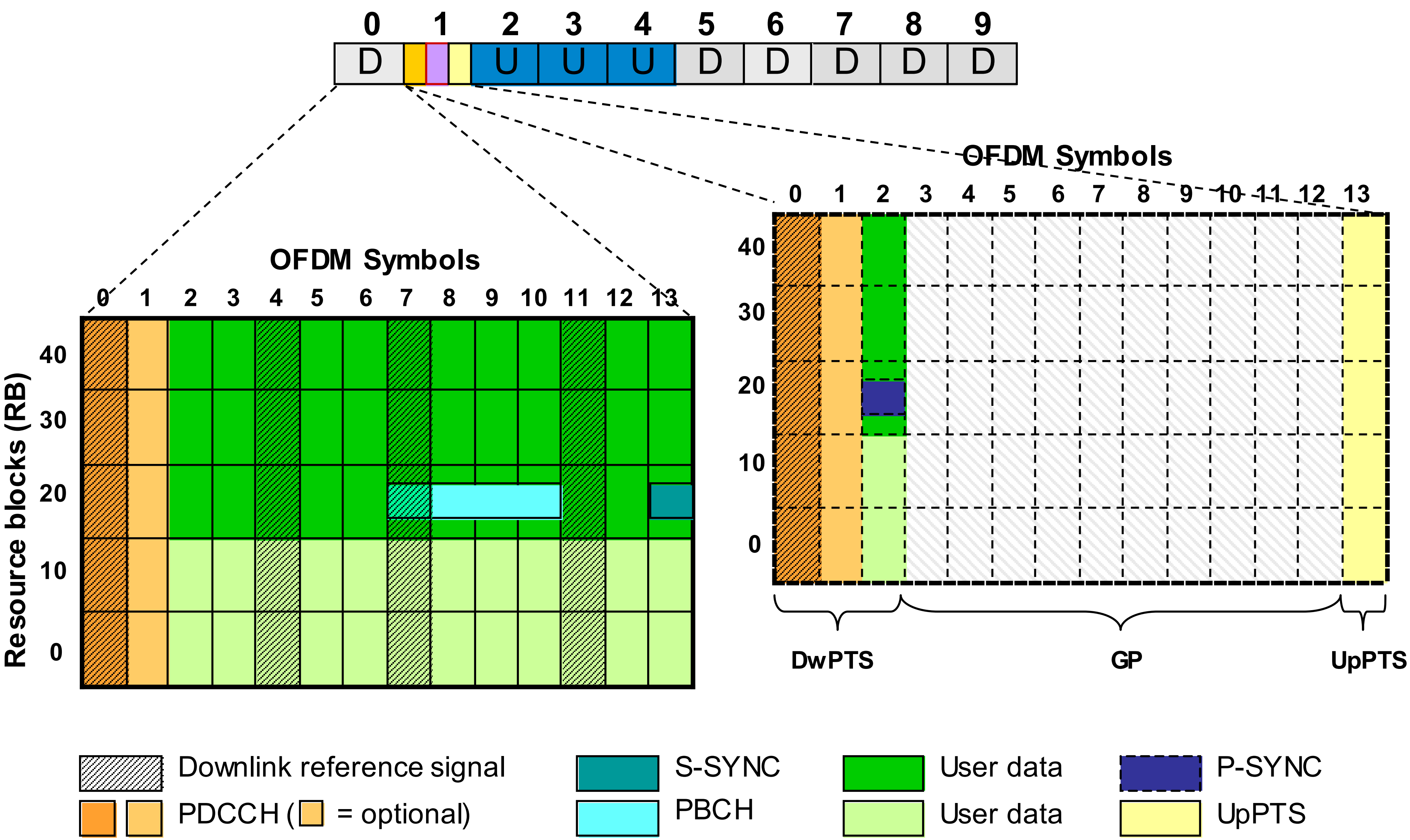


TDD: First Downlink Subframes



- PCFICH, PDCCH, PHICH, PBCH, Reference Signals are transmitted on all antenna ports.
- Antenna port for P-SCH is not specified. Antenna port of S-SCH is identical to P-SCH.

TDD: Allocations in Subframes 0 and 1



Signalization of UL-DL configuration and special subframe configuration

- Special subframe configuration as well as UL-DL configuration is signaled to the UE via system information,
  - *SIB Type 1* → *TDD-Config* information element.

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},
    systemInfoValueTag                  INTEGER (0..31),
    nonCriticalExtension                SEQUENCE {}                 OPTIONAL    -- Need OP
}

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

TDD-Config **information element**

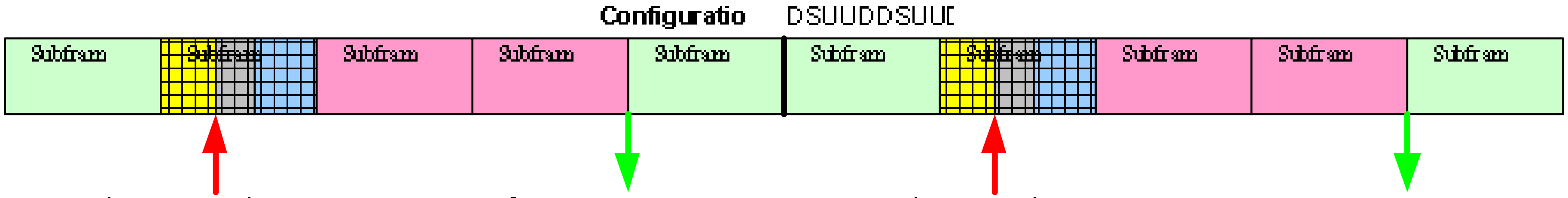
```
-- ASN1START

TDD-Config ::=                  SEQUENCE {
    subframeAssignment              ENUMERATED {
                                        sa0, sa1, sa2, sa3, sa4, sa5, sa6},
    specialSubframePatterns         ENUMERATED {
                                        ssp0, ssp1, ssp2, ssp3, ssp4,ssp5, ssp6, ssp7,
                                        ssp8}
}

-- ASN1STOP
```

UL-DL configuration, special subframe configuration can not be changed dynamically!

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) (0,0,0,1) (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			
	(1,0,0,0)			(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 TDD timing aspects: what to consider?

- **Aspects of timing in LTE TDD mode:**

1
- **PDCCH -> PDSCH, when receive PDSCH?**

2
- **PDSCH -> PUSCH/PUCCH, when transmit feedback?**

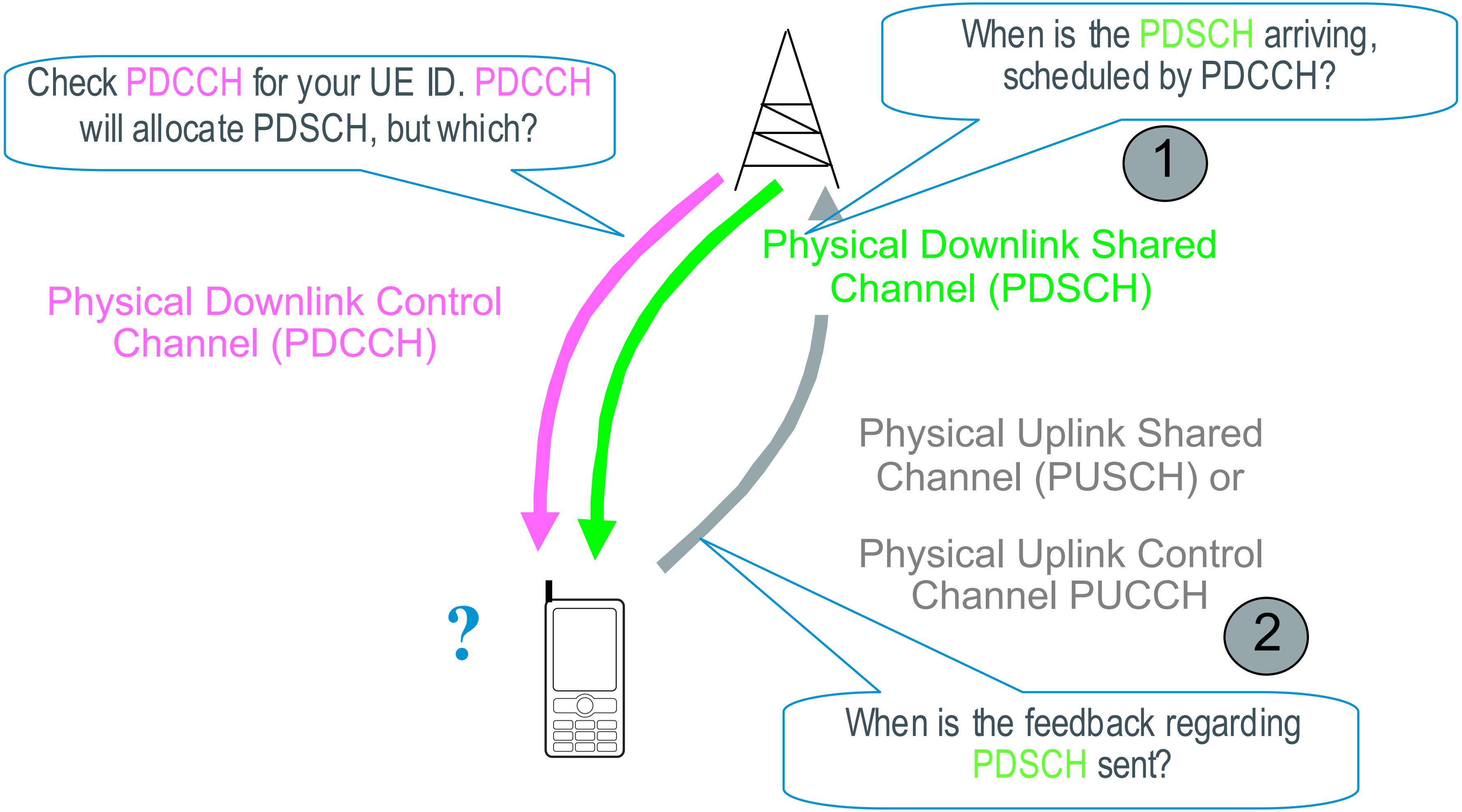
3
- **PDCCH -> PUSCH, when transmit PUSCH?**

4
- **PUSCH -> PHICH, when receive feedback?**

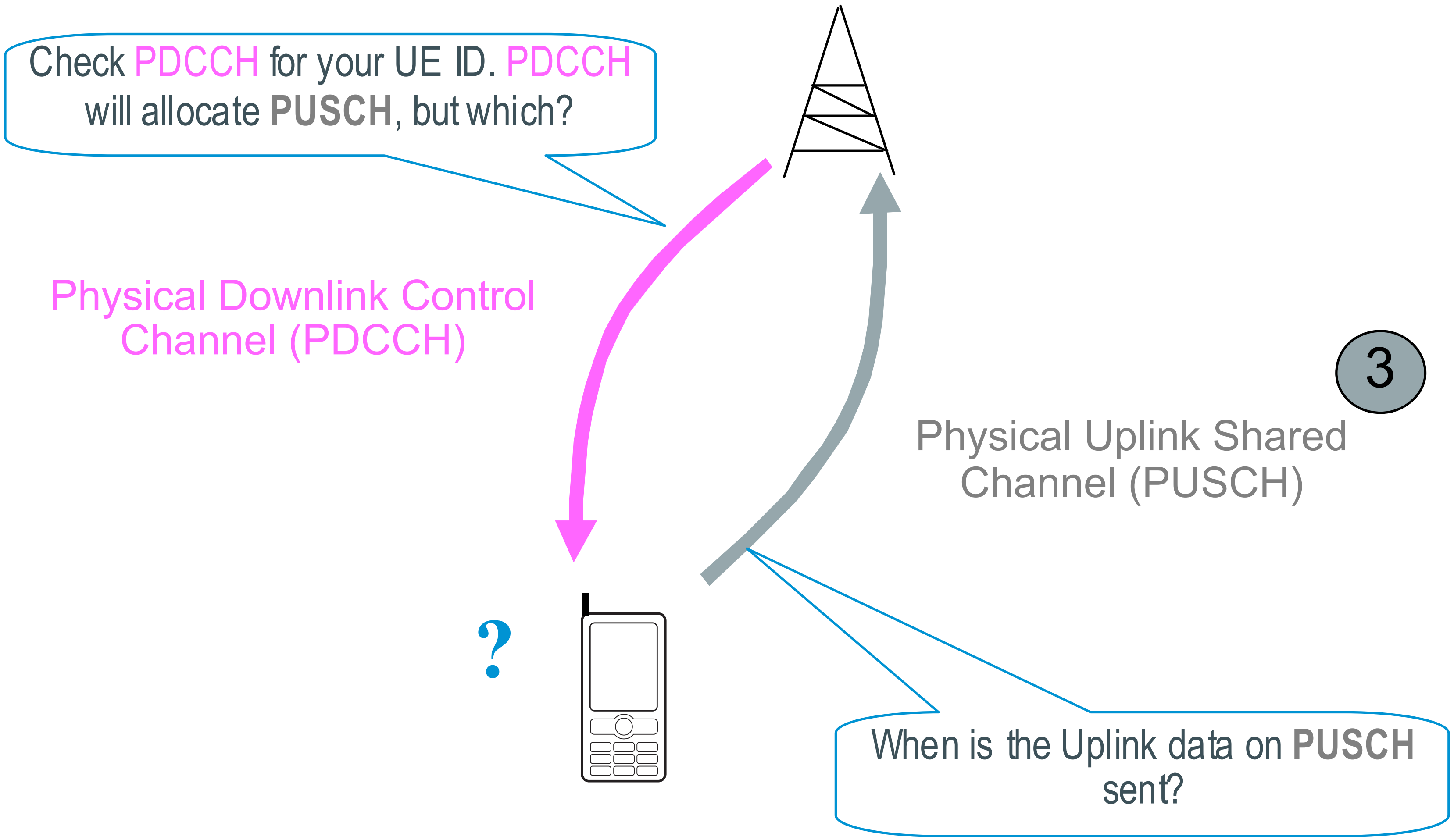
5
- **PHICH with NACK, when retransmit?**

6
- **PUSCH/PUCCH with NACK, when expect retransmission?**

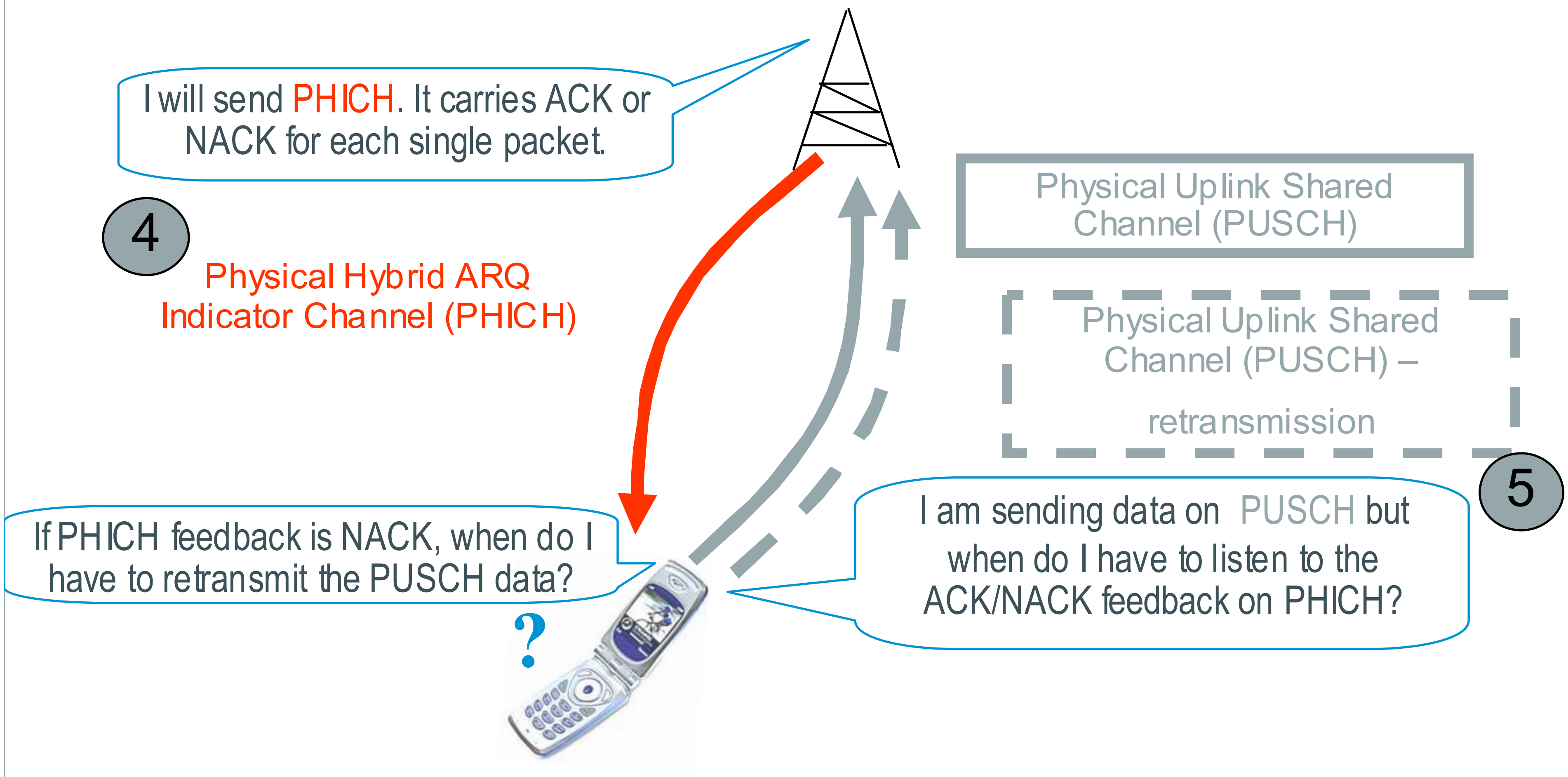
LTE TDD timing aspects: what to consider?



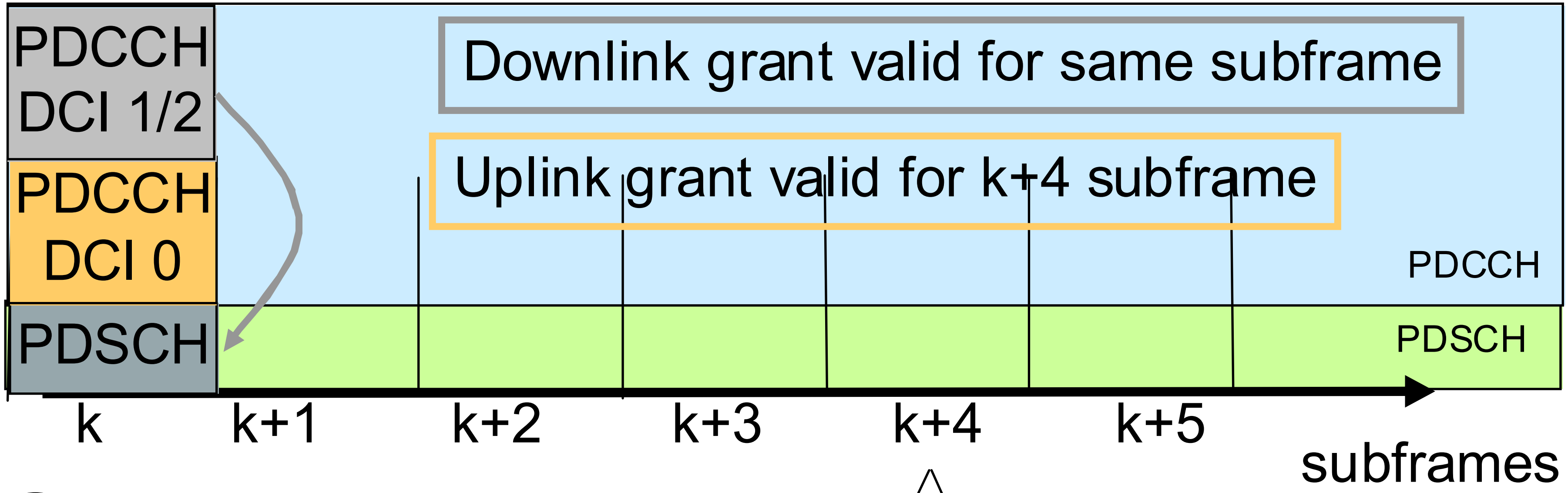
LTE TDD timing aspects: what to consider?



LTE TDD timing aspects: what to consider?

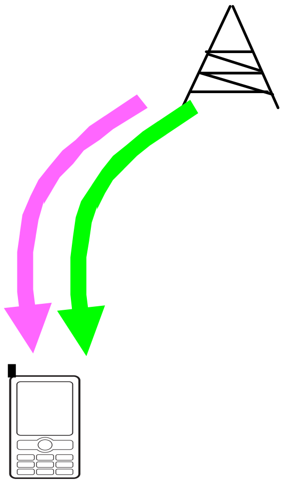


LTE TDD – timing aspects



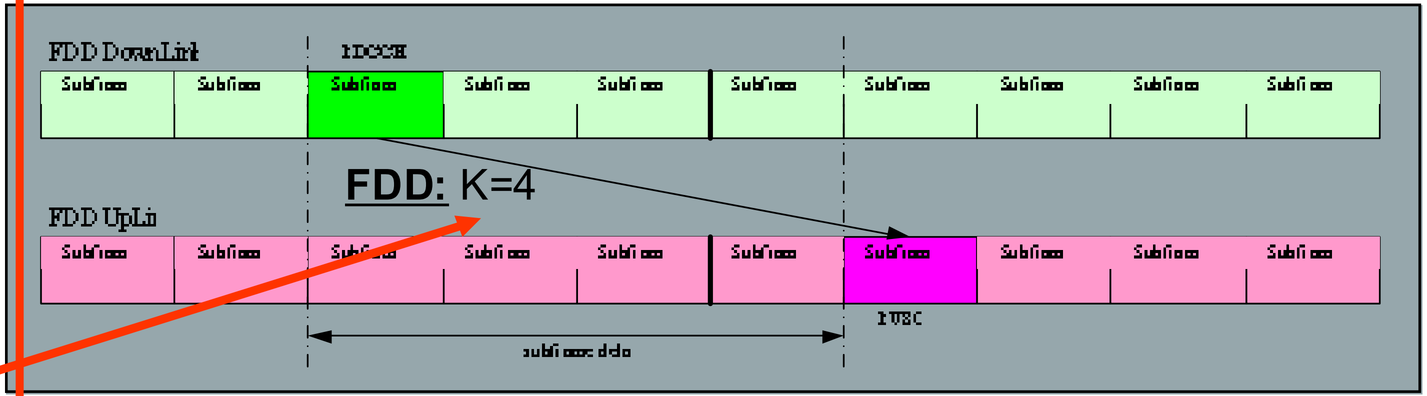
1

PDCCH and PDSCH
are sent in same subframe



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

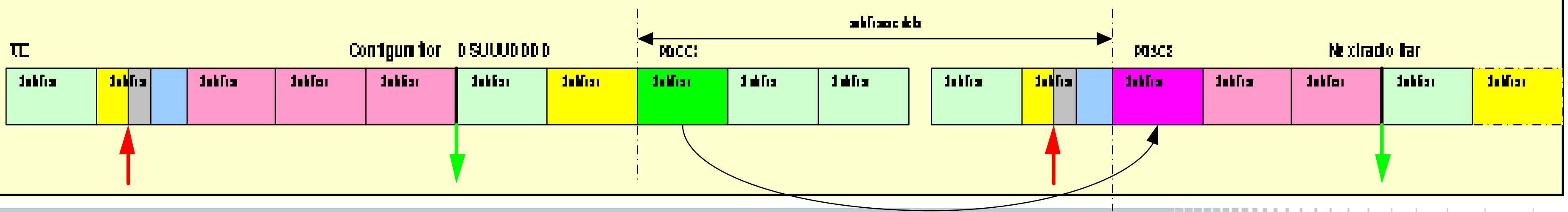


3

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



PUSCH and PDCCH Timing Relation

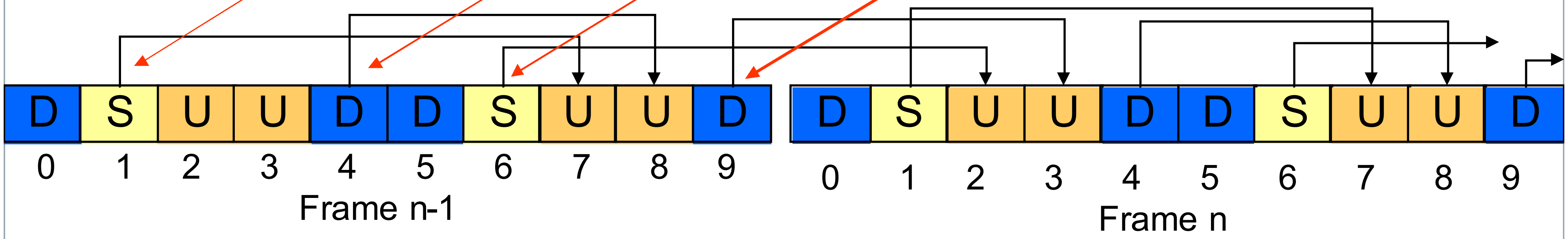
TDD: PUSCH timing relation depends on TDD frame configuration

3

(*)= for UL/DL configuration 0 there is normal HARQ operation and bundling HARQ operation. Latter is described in TS36.213

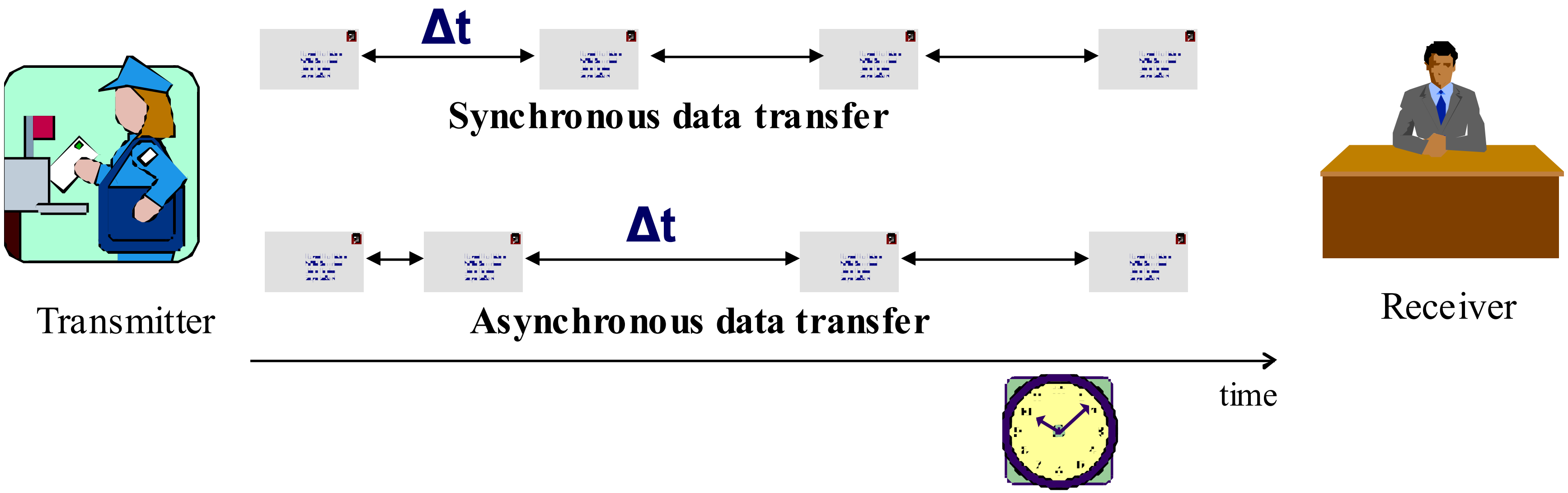
TDD UL/DL Configuration	Delay K for DL subframe number *n*									
	0	1	2	3	4	5	6	7	8	9
0	4(*)	6(*)				4(*)	6(*)			
1		6			4		6			4
2				4					4	
3	4								4	4
4									4	4
5									4	
6	7	7				7	7			5

Example:
Configuration 1



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

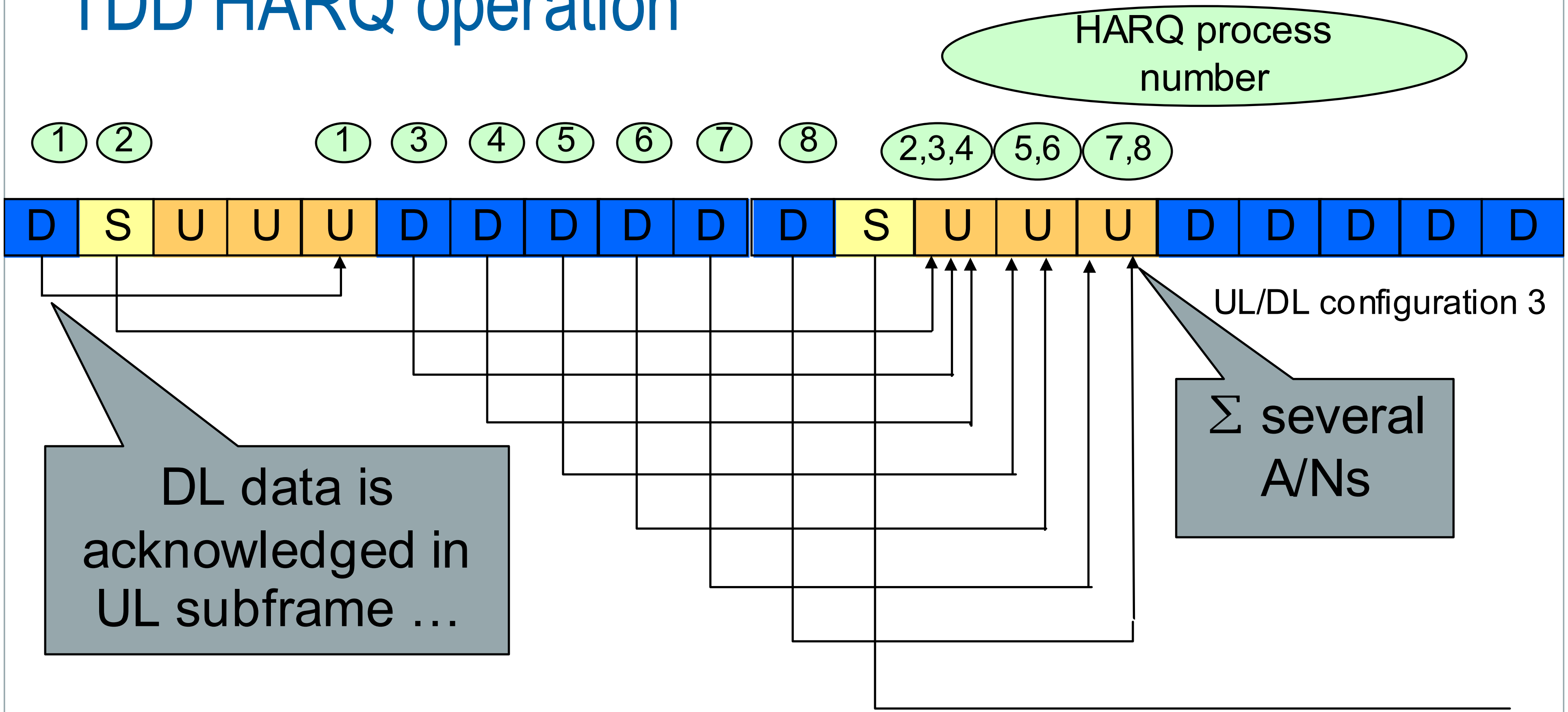
LTE TDD: HARQ processes in UL and DL

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

FDD=8 HARQ

TDD HARQ operation



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

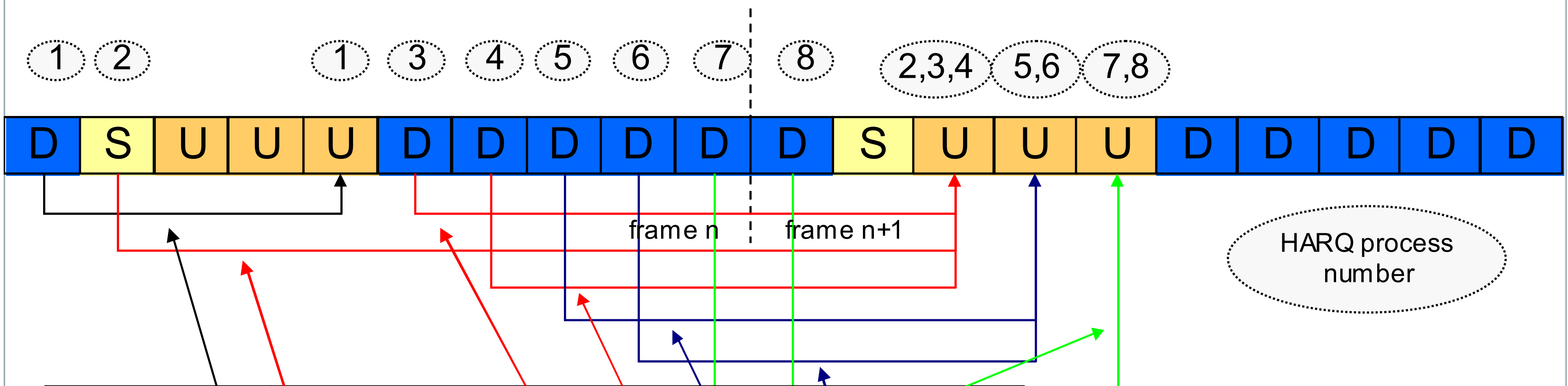
LTE TDD HARQ operation

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

TD-LTE vs. LTE FDD

HARQ processes in TD-LTE – Downlink (i.e. UL-DL configuration 3)



TDD 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

- **DL HARQ processes are asynchronous so they are signaled to the device with DCI format 1x, 2x,**
  - HARQ info (4 bit).

LTE TDD HARQ processes

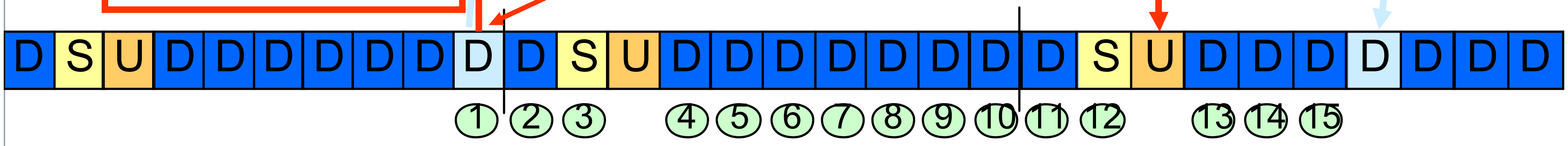
Downlink LTE TDD mode HARQ processes are non-synchronous and therefore they are signaled to the UE

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

Example:
ACK/NACK
timing

PDSCH in Subframe n will be acknowledged in Subframe n+k

e.g. here NACK
->retransmission
in k+4



HARQ process identifier.
Here 15 HARQ processes are needed

HARQ Info
= 4 bits

TDD ACK/NACK Bundling and Multiplexing

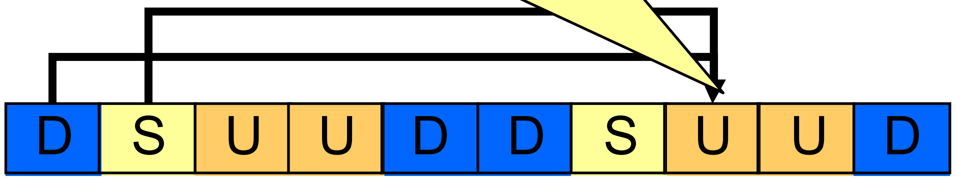
2 modes for feedback supported

ACK/NACK Bundling
for all UL-DL configurations

ACK/NACK Multiplexing
for all UL-DL configurations,
except configuration 5 (8 DL, 1 UL)

Example:
Configuration 1

Logical AND of all the ACK / NACKs

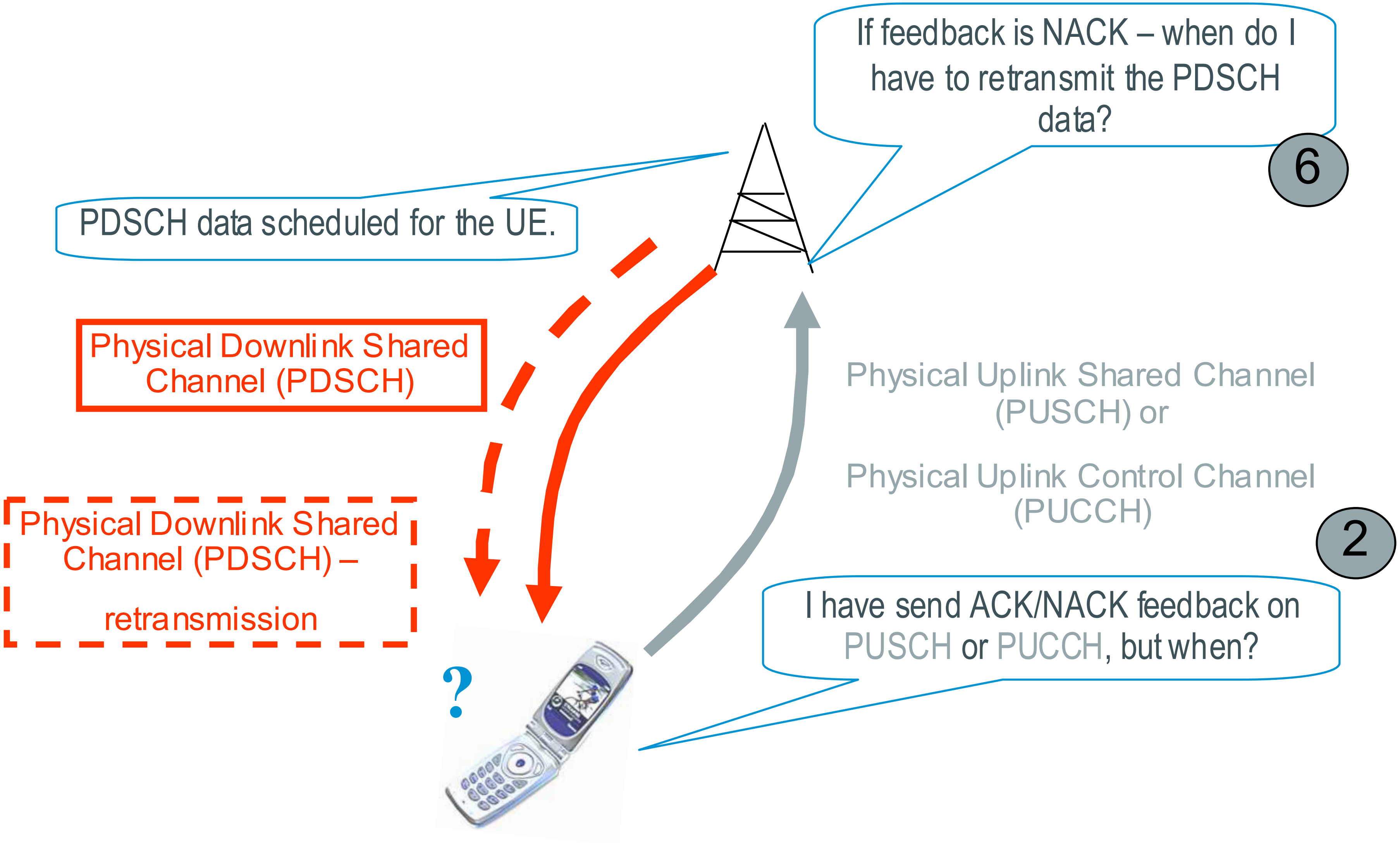


HARQ-ACK(0), HARQ-ACK(1), HARQ-ACK(2)	$n^{(1)}_{\mathrm{PUCCH}}$	$b(0),b(1)$
ACK, ACK, ACK	$n^{(1)}_{\mathrm{PUCCH},0}$	1, 1
ACK, ACK, NACK/DTX	$n^{(1)}_{\mathrm{PUCCH},1}$	1, 1
ACK, NACK/DTX, ACK	$n^{(1)}_{\mathrm{PUCCH},2}$	1, 1

⋮

Those bits are sent on PUCCH resource to indicate ACK/NACK

PDSCH ACK/NACK timing aspects



PDSCH-ACK/NACK Timing

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

2

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	-	-	13, 12, 9, 8, 7, 5, 4, 11, 6	-	-	-	-	-	-	-
6	-	-	7	7	5	-	-	7	7	-

LTE TDD: PDSCH-ACK/NACK feedback

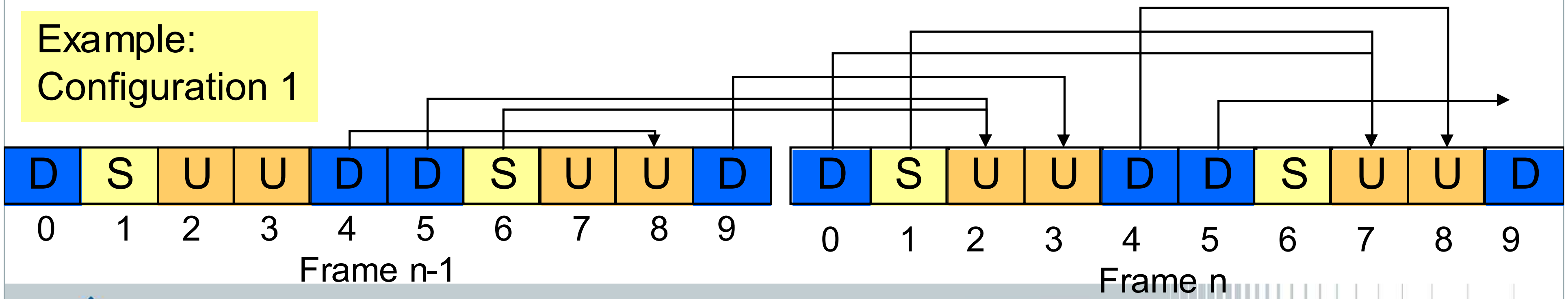
UE receiving data in subframe n-k sends ACK/NACK in subframe n

Value of k given as (TS36.213)

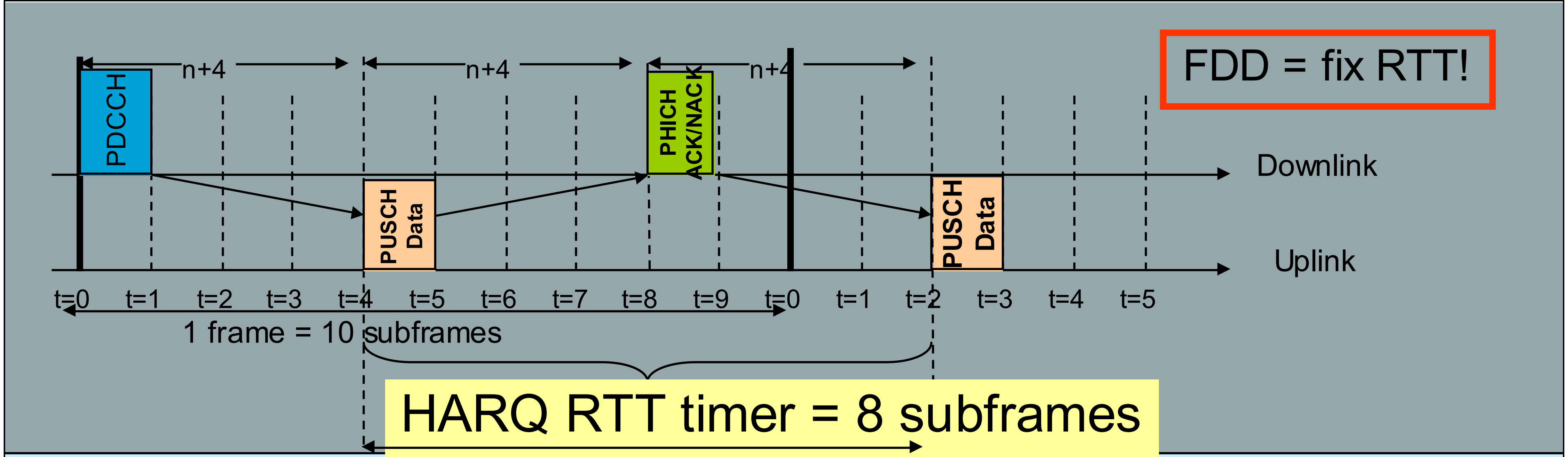
UL-DL Configuration	Subframe *n*									
	0	1	2	3	4	5	6	7	8	9
0	-	-	6	-	4	-	-	6	-	4
1	**-**	**-**	**7, 6**	**4**	**-**	**-**	**-**	**7, 6**	**4**	**-**
2	-	-	8, 7, 4, 6	-	-	-	-	8, 7, 4, 6	-	-
3	-	-	7, 6, 11	6, 5	5, 4	-	-	-	-	-
4	-	-	12, 8, 7, 11	6, 5, 4, 7	-	-	-	-	-	-
5	-	-	13, 12, 9, 8, 7, 5, 4, 11, 6	-	-	-	-	-	-	-
6	-	-	7	7	5	-	-	7	7	-

2

Example:
Configuration 1



HARQ Round Trip Time aspects, RTT timer



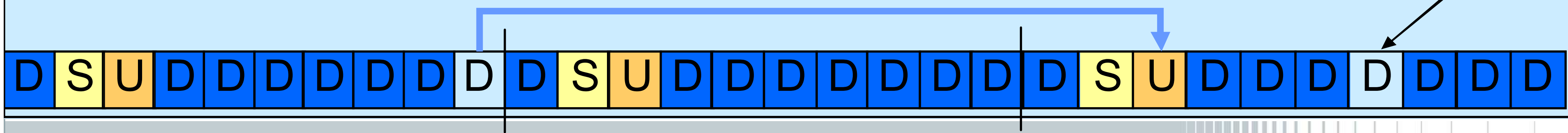
TDD = variable RTT!

PDSCH in Subframe n - k will be acknowledged in Subframe n

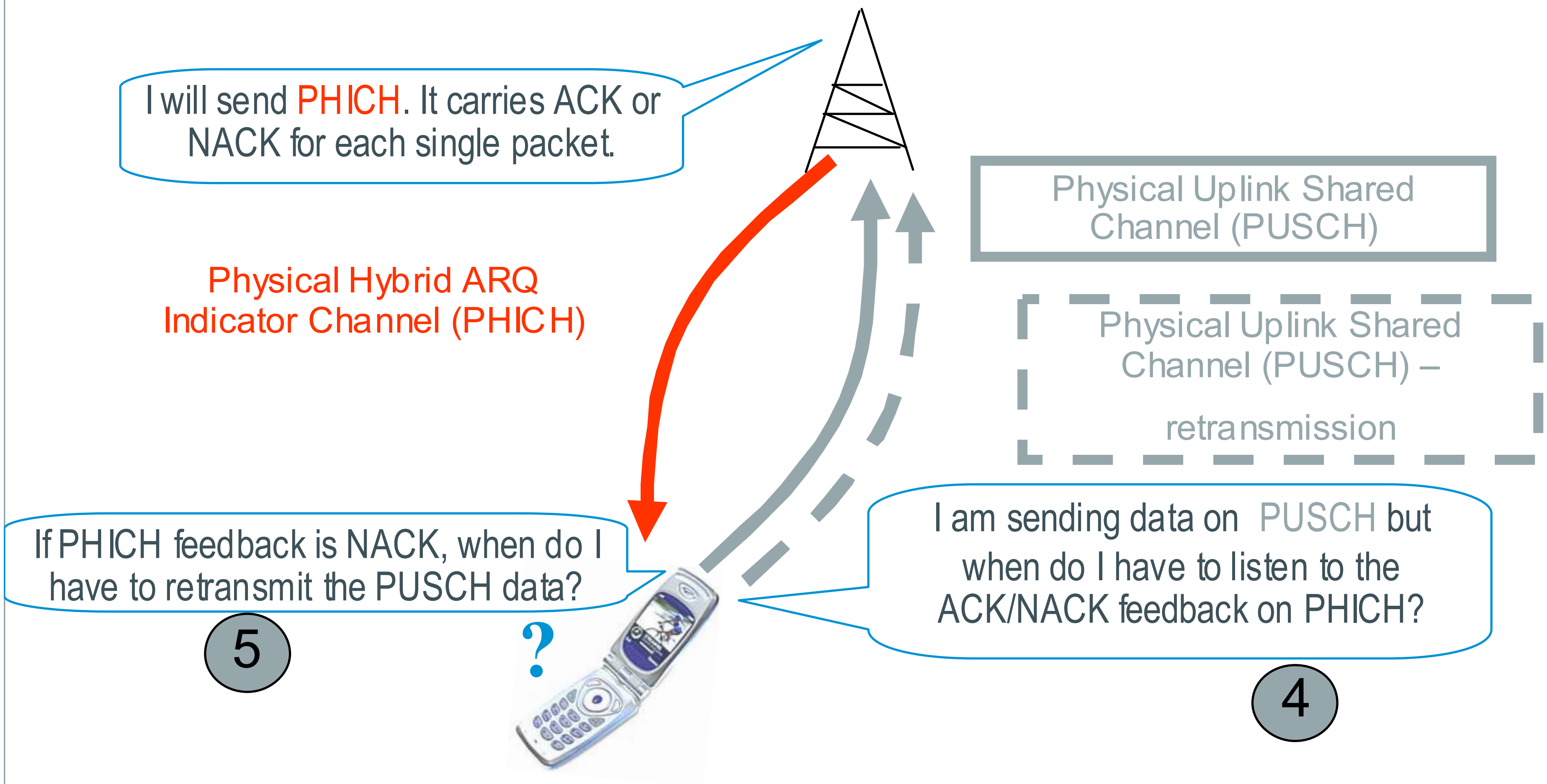
UL-DL Configuration	Subframe *n*									
	0	1	2	3	4	5	6	7	8	9
0	-	-	6	-	4	-	-	6	-	4
1	**-**	**-**	**7,6**	**4**	**-**	**-**	**-**	**7,6**	**4**	**-**
2	-	-	8,7,4, 6	-	-	-	-	8,7,4, 6	-	-
3	-	-	7,6,11	6,5	5,4	-	-	-	-	-
4	-	-	12,8,7,11	6,5,4, 7	-	-	-	-	-	-
5	-	-	13,12,9,8, 7,5, 4,11,6	-	-	-	-	-	-	-
6	-	-	7	7	5	-	-	7	7	-

6

HARQ RTT timer = k+4



PUSCH ACK/NACK timing aspects



PUSCH-ACK/NACK 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

4

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 TDD: PUSCH-ACK/NACK feedback

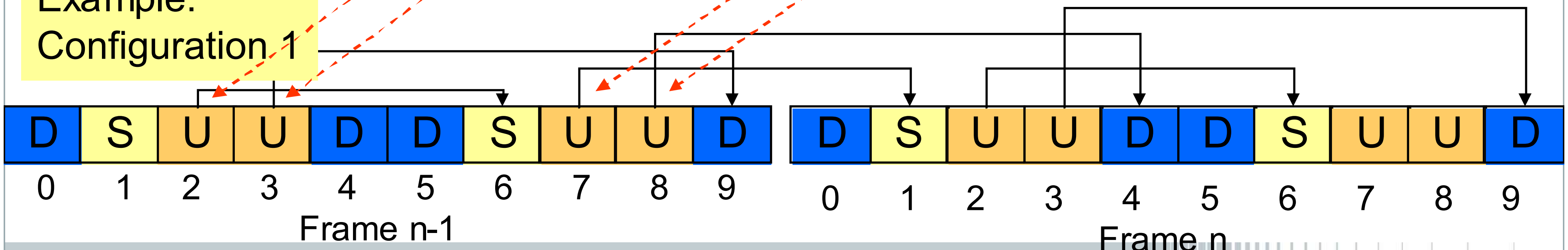
4

UE transmitting data in subframe n listens to PHICH ACK/NACK in subframe n+k

Value of k given as (TS36.213)

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	

Example:
Configuration 1

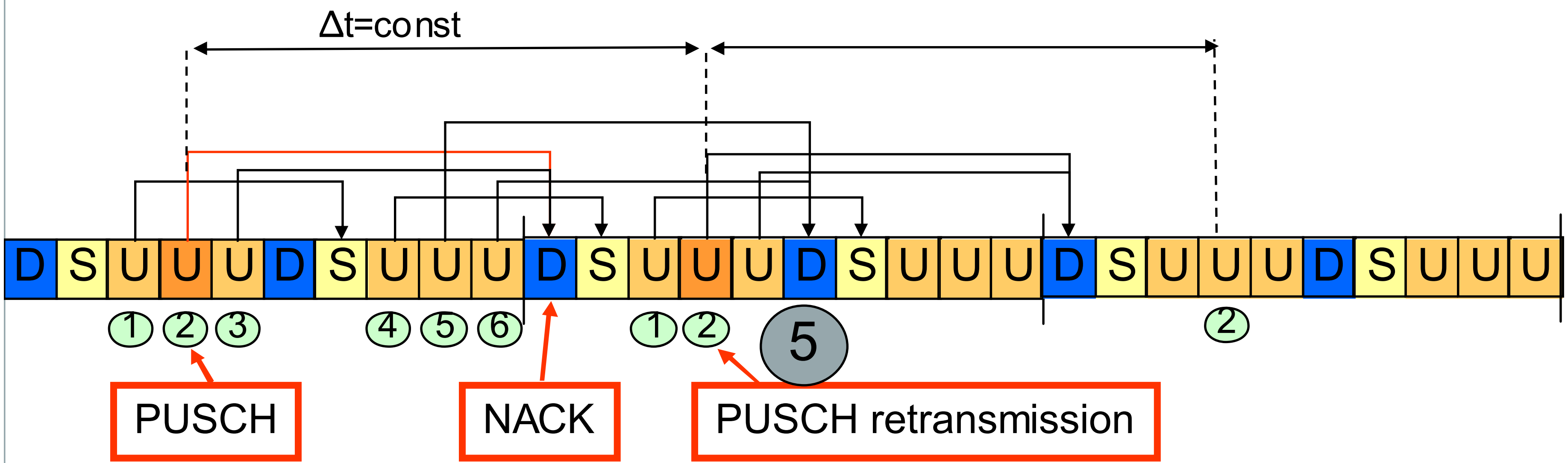


PUSCH-ACK/NACK Timing

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

4

Uplink HARQ processes are synchronuous, no indication needed



There will be enough topics

for future trainings ☺

Thank you for your attention!

Comments and questions welcome!