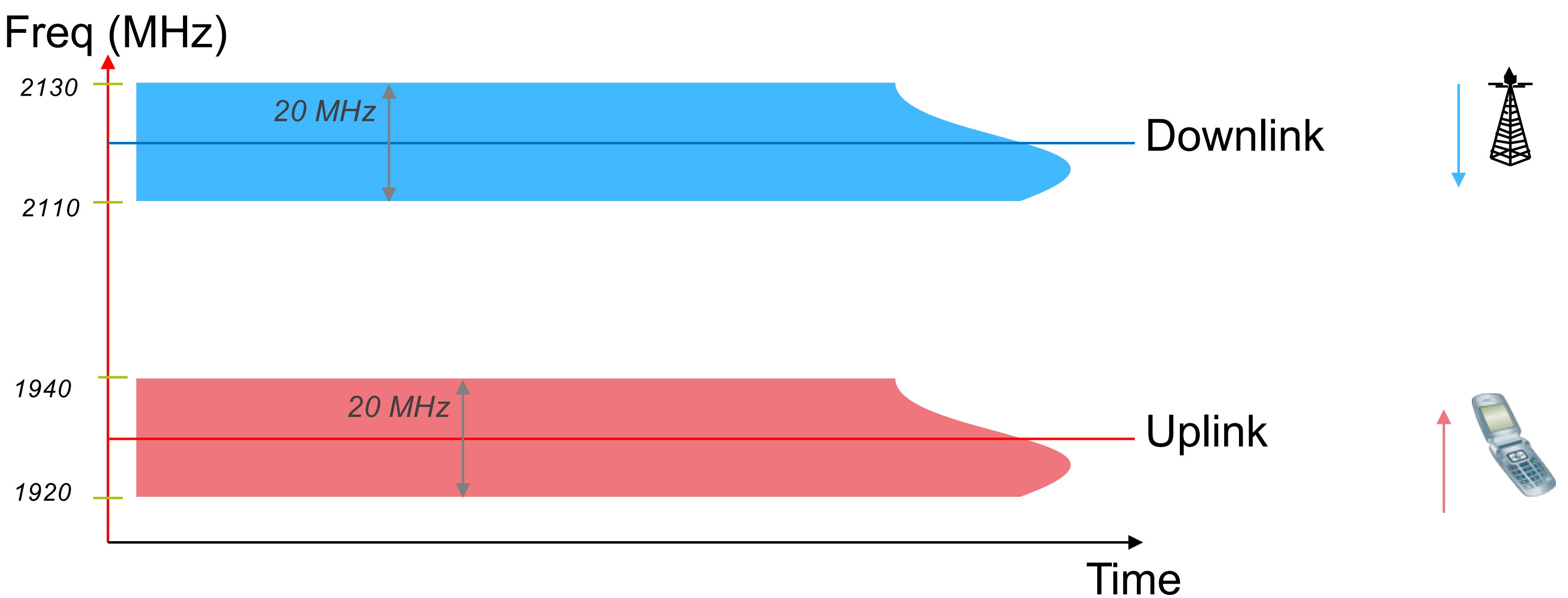
LTE Radio Primer

Irfan Ali

LTE Duplexing Scheme

- LTE supports two modes for UL and DL communication:
  - Frequency Division Duplexing (FDD)
  - Time Division Duplexing (TDD)



Frequency Division Duplexing

Our Quest

- T1: How does the UE know when to listen for transmissions to it in the DL direction?
- T2: How does the UE know when to transmit in the UL direction?
    - Signaling transmission
    - Data transmission

Top-down

- B7: How does a UE choose a particular eNodeB?
- B6: How does the UE synchronize to the frame structure in UL direction?
- B5: How does the UE synchronize to the frame structure in DL direction?
- B4: What is the frame-structure for LTE?
- B3: How is the bit information coded in OFDM signals?
- B2: How is OFDM signals transmitted in LTE?
- B1: What is OFDM and how does it work?

Bottom-up

What is OFDM?

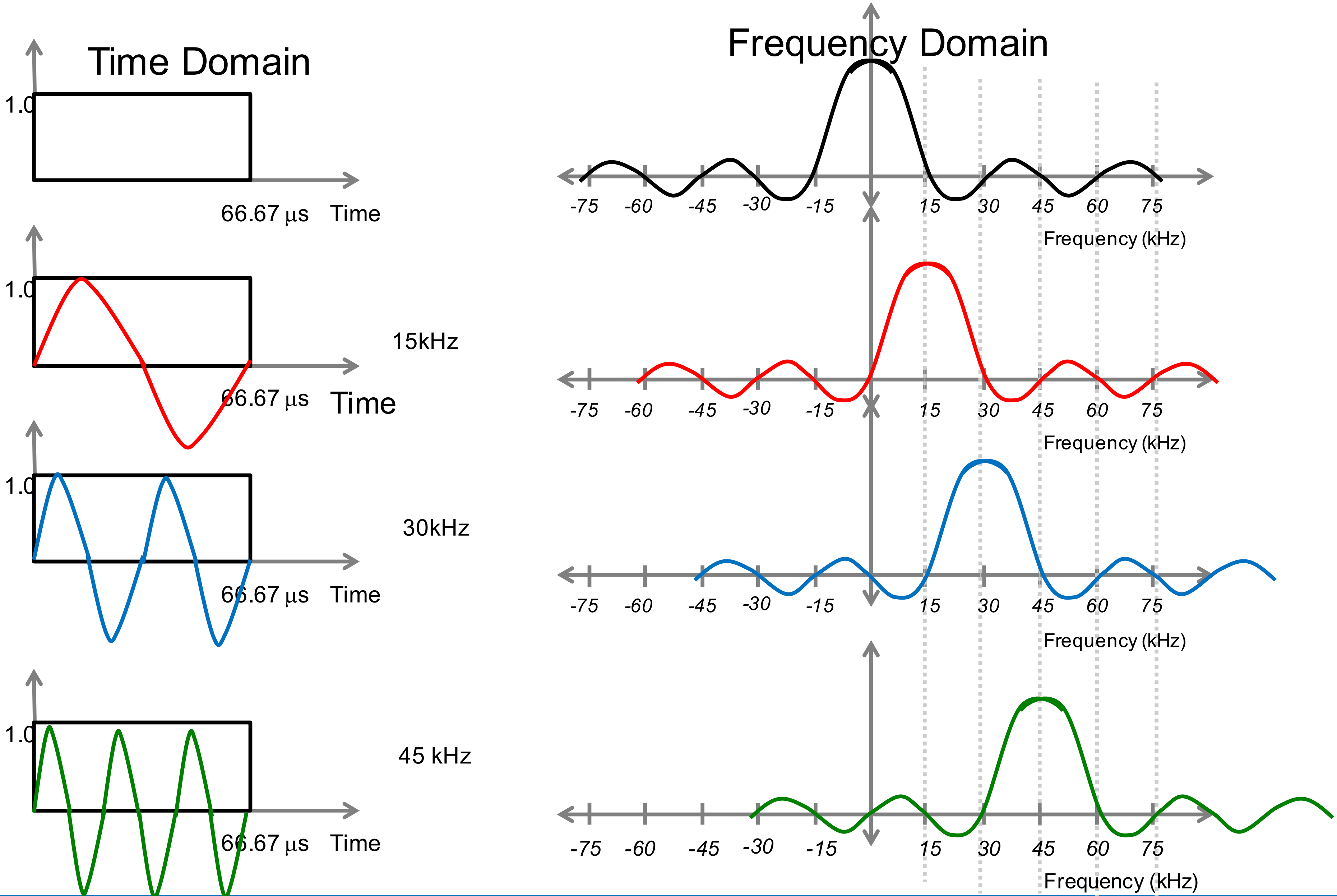
LTE Downlink

- B3: How is the bit information coded in OFDM signals?
- B2: How is OFDM signals transmitted in LTE?
- B1: What is OFDM and how does it work?

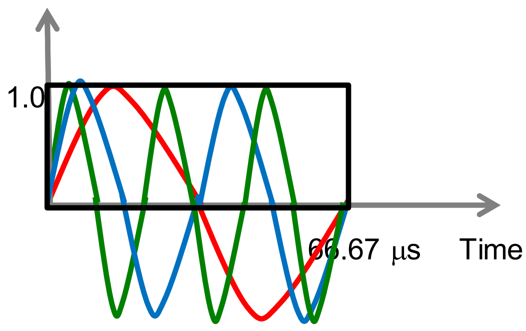
What is OFDM? What does Orthogonal mean?

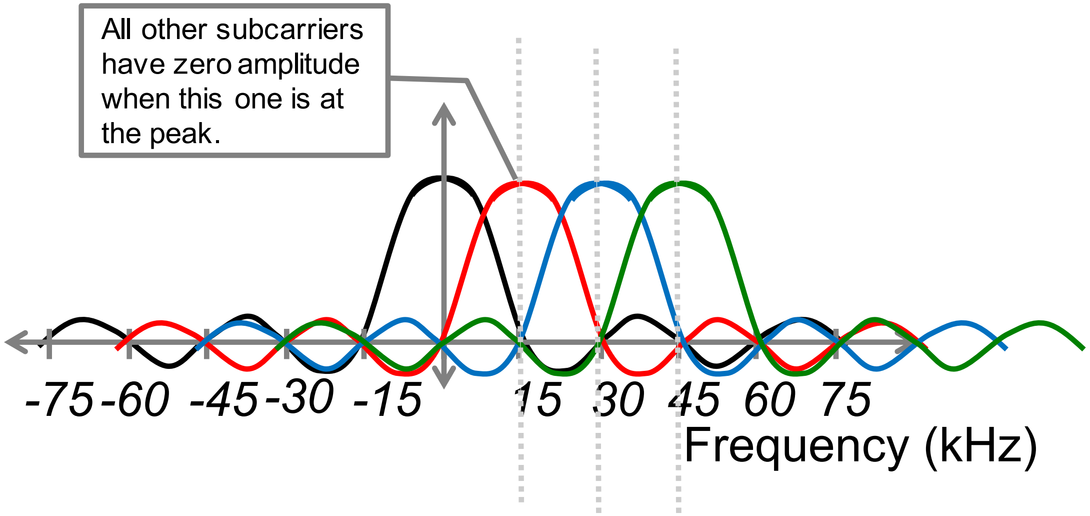
- OFDM: Orthogonal Frequency Division Multiplexing
- OFDM: Carrier frequencies are harmonics of each other:
  - f_0, 2 f_0, 3 f_0 ,…
- Basic property of harmonic signals is that they are “orthogonal” to each other, i.e., multiplication of one signal with the other leads to zero.
- x(t) and y(t) are said to be orthogonal to each other if:
  - Integral (0, inf) x(t).y(t). dt =0
  - Or for periodic signals with period T
  - Integral (0, T) x(t).y(t). dt =0
- By using orthogonal basis functions, an ideal receiver can completely reject an unwanted signal using a different basis function than the desired signal.
  - In Time Division Multiplexing, the orthogonal basis functions are non-overlapping time-slots.
  - In Code Division Multiplexing, the orthogonal basis function are the orthogonal chip sequences (eg. Walsh Codes)
  - In OFDM, the orthogonal basis functions are carrier frequencies that are harmonics (multiples) of each other.

OFDM for LTE: Illustration with 3 carriers at 15kHz



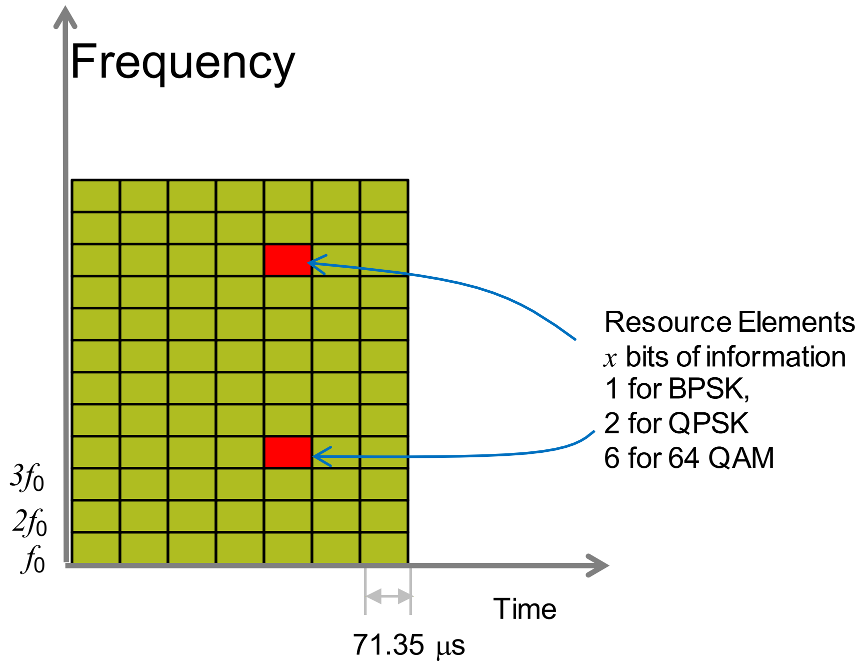
OFDM for LTE: Illustration: Composite





To detect if a particular sub-carrier is present in a symbol: Multiply the signal in the symbol by subcarrier and integrate for symbol period

Representing OFDM signal in time and frequency



Our Quest

- T1: How does the UE know when to transmit in the UL direction?
- T2: How does the UE know when to listen for transmissions to it in the DL direction?
    - Signalling transmission
    - Data transmission

Top-down

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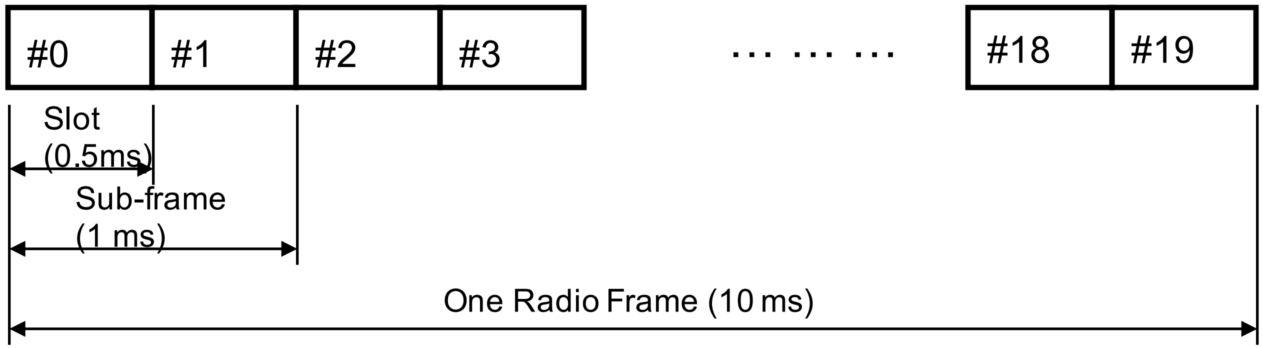
Bottom-up

DL Frame Structure – FDD

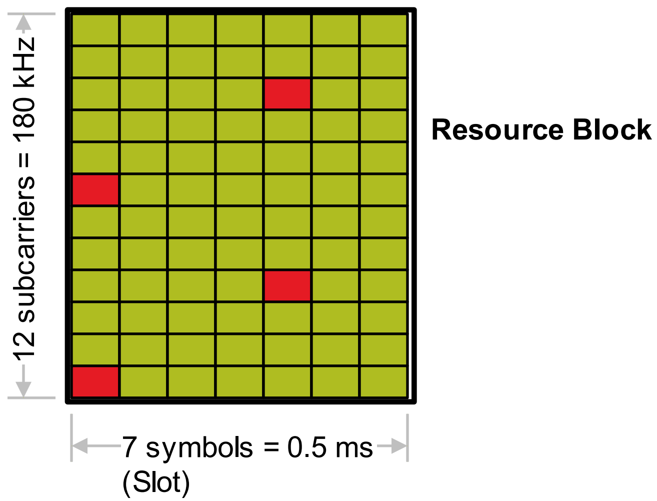


1 subframe = 1ms (subframe is defined as two consecutive 0.5 ms slots)

- *Minimum scheduling unit is 1subframe*

- 10 subframes make up Radio Frame

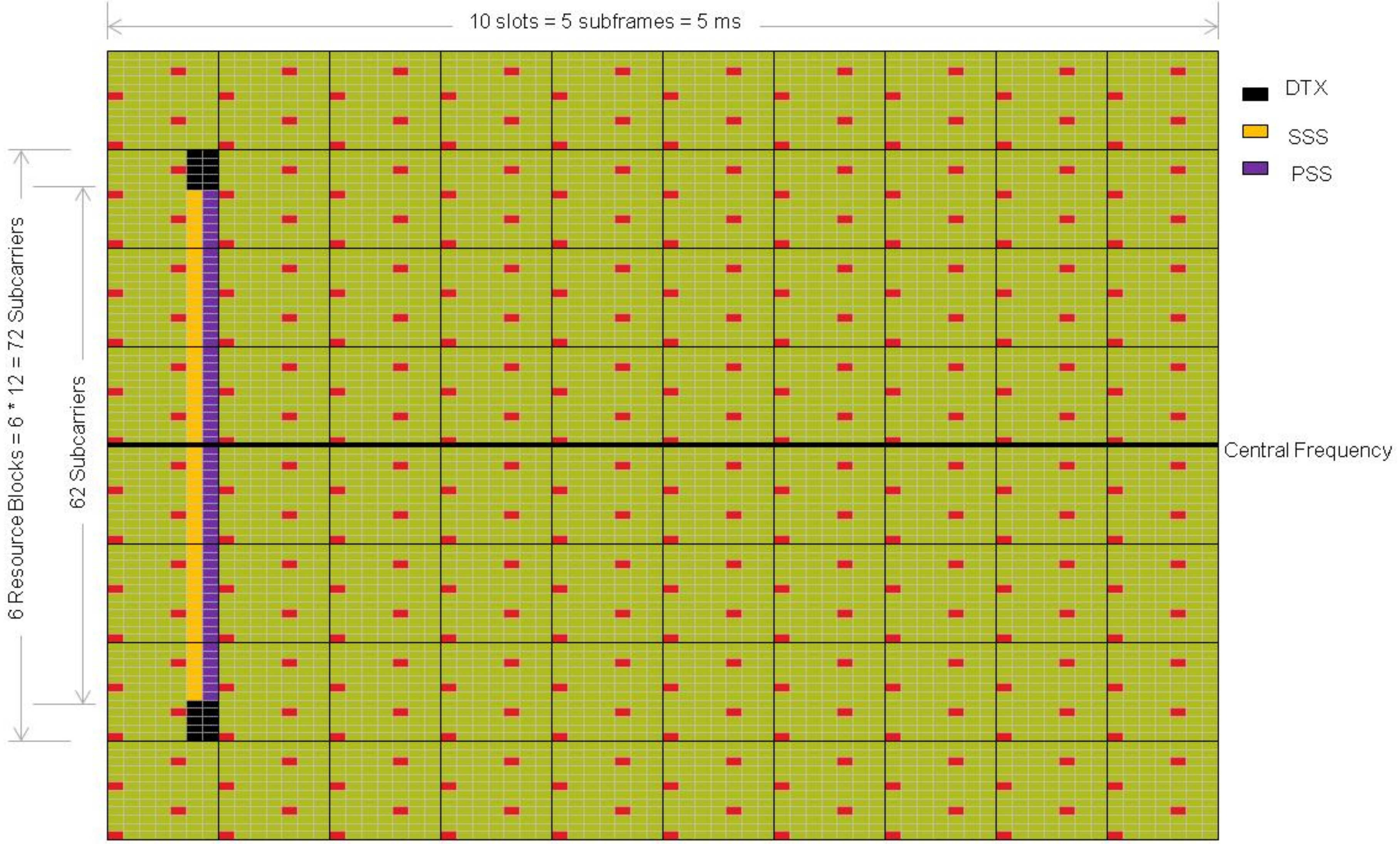
- In the frequency domain the downlink subcarriers are grouped into resource blocks, where each resource block consists of 12 consecutive subcarriers corresponding to a nominal resource-block bandwidth of 180 kHz



How does a UE figure out the DL frame-timings and read broadcast information of a cell?

Synchronization Signals

- To enable a UE to determine DL frame boundaries, Primary and Secondary Synchronization Signal (PSS and SSS), which are well known signal patterns are transmitted in well-known location in the DL channel.
  - These are transmitted in slots 0 and 10 of every radio frame, i.e., PSS and SSS are transmitted twice every 10 msec.



Synchronization Signals

- The Primary Synchronization Signal is allocated to the central 62 subcarriers belonging to the last symbol of slot 0 and slot 10 of every radio frame, i.e the PSS is transmitted twice every 10 ms radio frame. Both transmissions are identical.
- The Primary Synchronization Signal is used to:
  - Achieve symbol, slot and subframe synchronization
  - Determine the Physical Layer Cell Identity (PCI) from within the Physical Layer Cell Identity Group. There are three PCIs in each group so the PSS is generated using 1 of 3 different sequences.
- The Secondary Synchronization Signal is allocated to the central 62 subcarriers belonging to the second to last symbol of slot 0 and slot 10 of every radio frame, i.e the SSS is transmitted twice every 10 ms radio frame.
- The 2 SSS transmissions within each radio frame use different sequences to allow the UE to differentiate between the 1st and 2nd transmission, i.e. allowing the UE to achieve frame synchronization.
- The Secondary Synchronization Signal is used to:
  - Achieve frame synchronization
  - Determine the Physical Layer Cell Identity Group. There are 168 Physical Layer Cell Identity Groups so the SSS is generated using 1 of 168 different sequence-pairs.

Cell Search Procedure Used by UE

- UE uses matched filter to determine Primary Synchronization Signal
- UE detects frame boundaries to 5 msec ambiguity
- UE locks to carrier frequency
- UE detects (1-of-3) Physical cell identity (PCI) within the PCI Group.
- UE obtains knowledge of reference signal Structure

Use of Primary Synchronization Signal

↓

- UE determines frame boundary (i.e removes the 5 ms ambiguity)
- UE determines the cell identity group

Use of Secondary Synchronization Signal

↓

UE measures RSRP and RSRP

Use of Reference Signal

↓

UE decodes broadcast signal (eg. determine Tracking Area Ident.

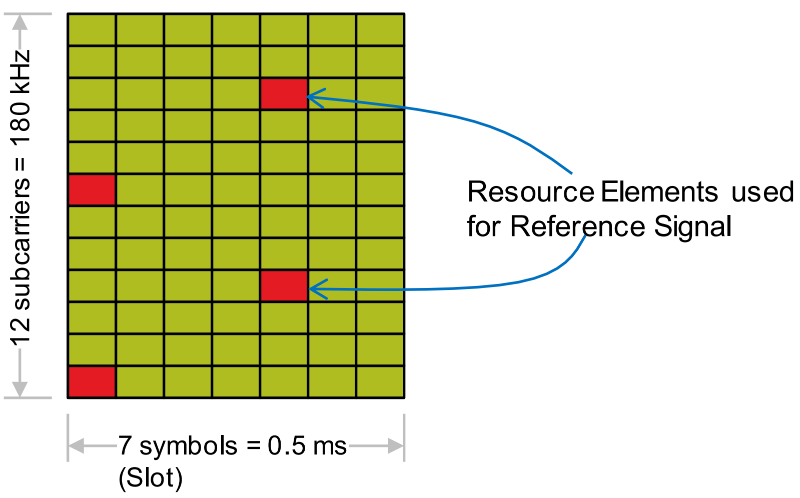
Use of Broadcast Channel

What does a UE measure to determine if it can camp on a cell?

Measurement-1: Reference Signal Receive Power (RSRP)

- Reference Symbol
  - In order for receiver to estimate the channel, known reference symbols also referred to as pilot symbols are inserted at regular intervals within the OFDM time-frequency grid.
  - Using knowledge of the reference symbols the receiver can estimate the frequency-domain channel around the location of the reference symbol
  - The reference symbols should have sufficient high density in time and frequency to provide estimates of the entire time/frequency grid.
  - There are four resource elements per resource block that are dedicated to Reference Signal.

- The location of Reference Signals depends on the Physical layer cell identity of the cell.
- Once the UE has decoded the Primary and Secondary Synchronization Signals and consequently identified the Physical Layer Cell Identity, the UE is able to deduce the resource elements allocated to the Reference Signal.



Reference Signal Received Power (RSRP)

- The RSRP is the average power (in watts) received from a single Reference Signal resource element
  - ➢ The power measurement is based upon the energy received during the useful part of the OFDMA symbol and excludes the energy of the cyclic prefix.
- Knowledge of absolute RSRP provides the UE with essential information about the strength of cells from which path loss can be calculated for power-control calculations.

Measurement 2: Reference Signal Received Quality (RSRQ)

- Although RSRP is an important measure, on its own it gives no indication of signal quality.
- RSRQ provides this measure and is defined as the ratio of RSRP to the E-UTRA carrier received signal strength indicator (RSSI).
- The RSSI parameter represents the entire received power including the wanted power from the serving cell as well as all cochannel power and other sources of noise.
- Measuring RSRQ becomes particularly important near the cell edge when decisions need to be made, regardless of absolute RSRP, to perform a handover to the next cell.

$$\boxed{RSRQ = \frac{RSRP}{(RSSI / N)}}$$

where *N* is the number of Resource blocks over which the RSSI is measured

Our Quest

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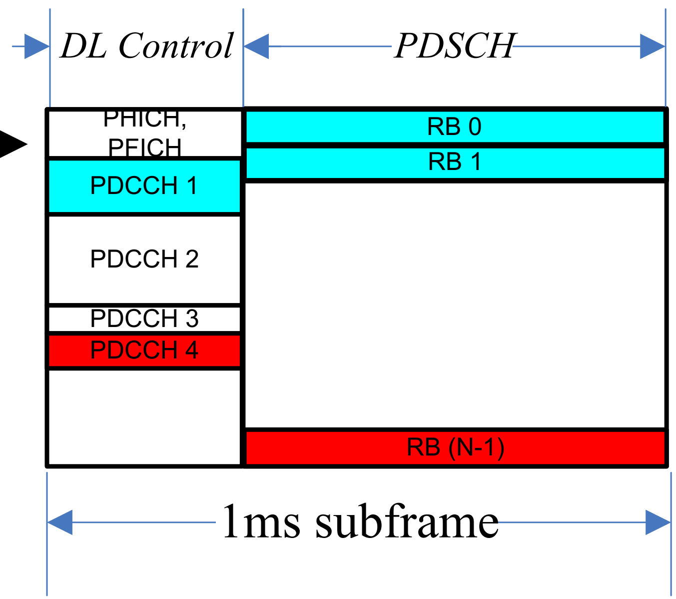
Bottom-up

MAC View of the Air Interface

- DL control signalling is in the first 1-3 symbols of every subframe or 1 ms
  - ➢ The rest of the symbols (11-13) are used for PDSCH
- DL scheduling occurs every subframe or 1ms
  - ➢ Each subframe is 14 symbols
- Depending of the MCS and the amount of data the UE is assigned a specific number of Resource Blocks (RBs)
- Logical RBs represented

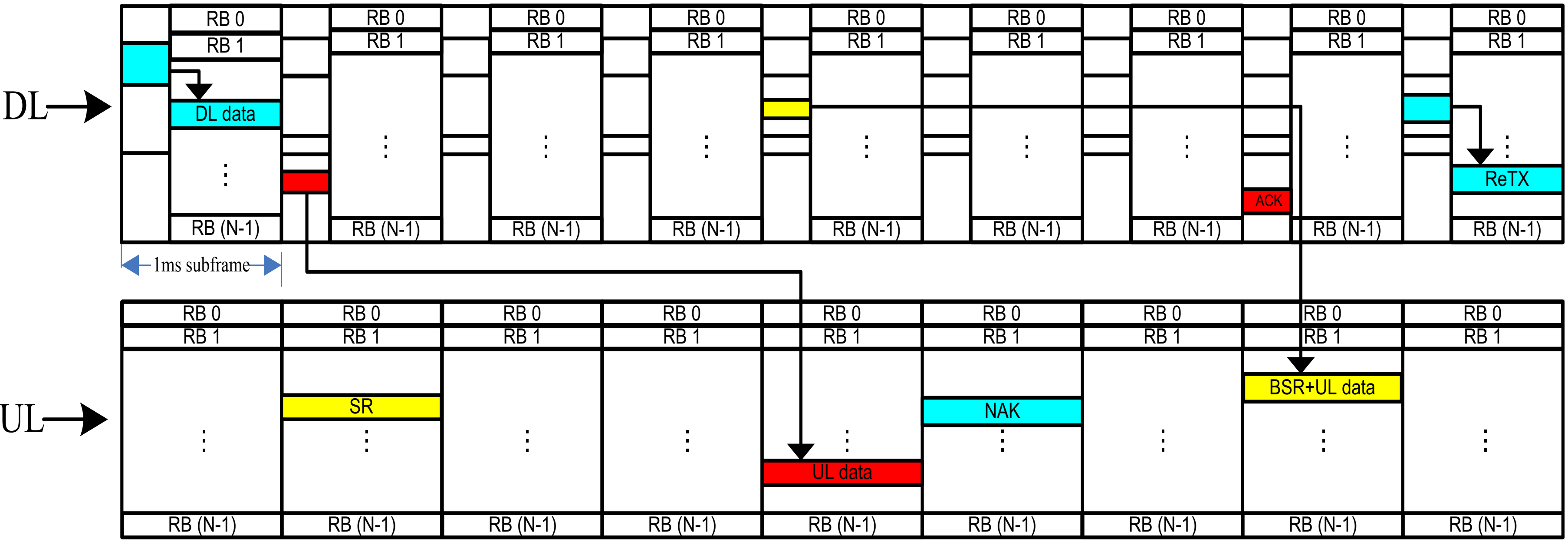
UE monitors PDCCH
For indication of DL/
UL assignment as
well as ACK/NAK



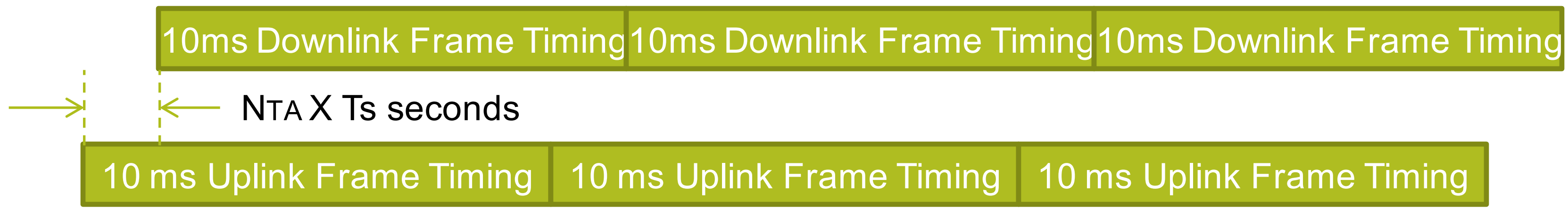
PDCCH	Physical Downlink Control Channel
PHICH	Physical Hybrid ARQ Indicator Channel
PDSCH	Physical Downlink Shared Channel

UL and DL Data Transmission

- DL data is scheduled in the same subframe
- UL data scheduled several (typically 4) subframes into the future
- Scheduling Request (SR) is used by the UE to request UL allocation
- Buffer Status Report (BSR) is sent by the UE to indicate the amount of queued up data
- Timing example is for illustration purpose



UL Frame Structure and Timing



$0 < N_{TA} < 20512$
$T_s = 1/30.72\ \mu s$

- The uplink frame timing <u>precedes</u> the downlink frame timing at the UE to allow for propagation delay from UE to eNB.
- The eNB generates timing advance values for each UE, such that the UL frames arrive synchronized at the eNB.
  - UEs at cell-edge are giving larger timing advance than UEs at center.
- UL Frame Structure is the same as DL Frame Structure (0.5 ms slot, 10 ms Frame).
  - Also Resource Block are the same (0.5 ms slot, 180 kHz in freq).
- (In Rel 8) UL, Resource blocks are allocated adjacent to each UE.
- In the UL direction, the Common Control Channel (PUCCH) is multiplexed along with data on the common control channel.

Random Access Procedure

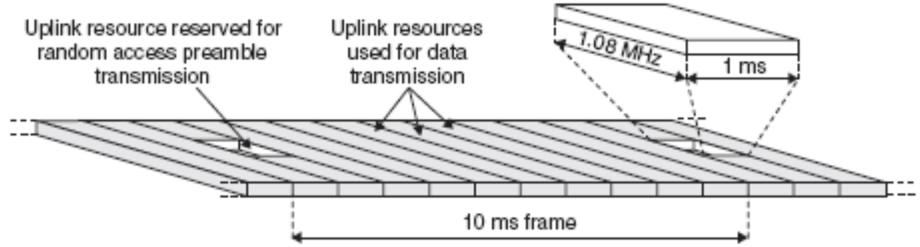


Figure 17.4 *Principal illustration of random-access-preamble transmission.*

- In the frequency domain, the random-access preamble has a bandwidth corresponding to six resource blocks (1.08 MHz).
    - This nicely matches the smallest bandwidth in which LTE can operate, which is six resource blocks.
- A terminal carrying out a random-access attempt has, prior to the transmission of the preamble, obtained downlink synchronization from the cell-search procedure. However, the uplink timing is not yet established.
- The start of an uplink frame at the terminal is defined relative to the start of the downlink frame at the terminal. With the LTE UL preamble length of approximately 0.9 ms, there is 0.1 ms guard time allowing for cell sizes up to 15 km

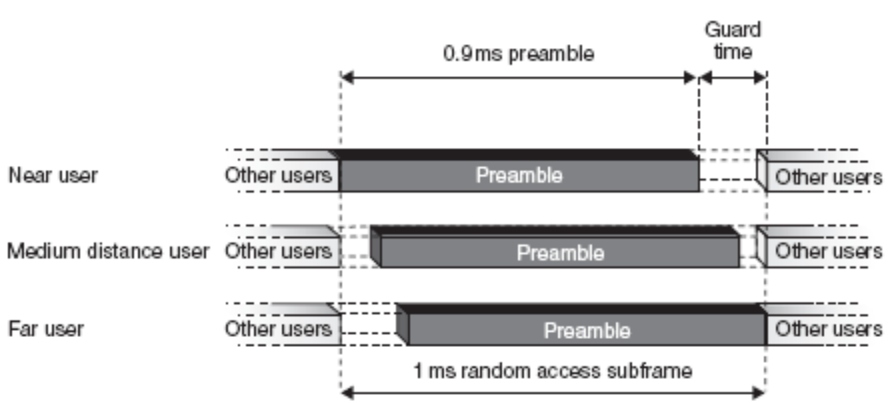
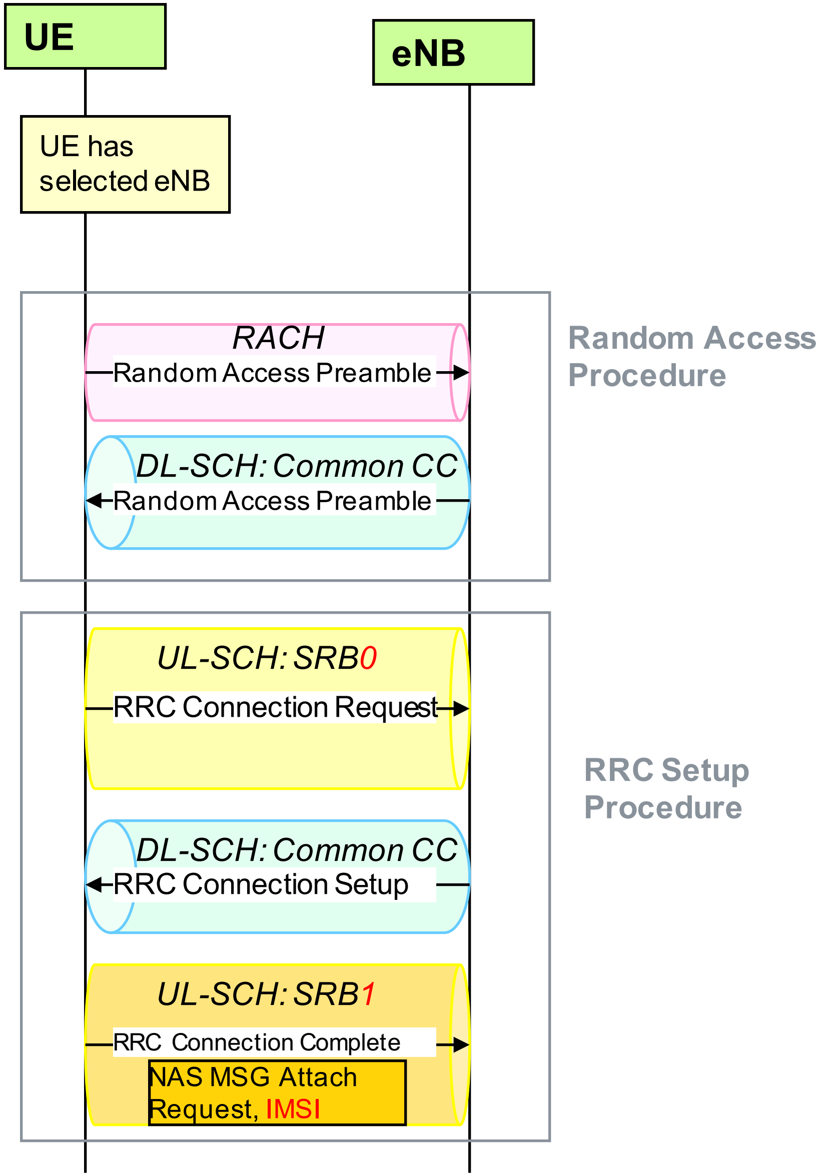


Figure 17.5 *Preamble timing at eNodeB for different random-access users.*

Random Access Procedure (during Attach)



UE has synchronized to the downlink frame of the eNB and hence knows the DL frame boundaries. The UE has also listened to the broadcast channel of the eNB and knows when the random access channel (RACH) slots are in the uplink direction.

UE transmits a specific preamble (sequence)in a RACH slot. Since multiple UEs could have transmitted on the same RACH slot, the UE listens on the downlink shared (DL-SCH) common control channel (CC) to see if the UE's preamble has been accepted by the eNB.

The eNB transmits the (a) index of the random access preamble detected, (b) the timing correction that the UE should use. (c) scheduling grant when the UE should transmit in the next message in UL direction, and (d) temporary identity (C-RNTI) used between UE and the eNB.
UE listens for the preambles in all the DL CCH slots.

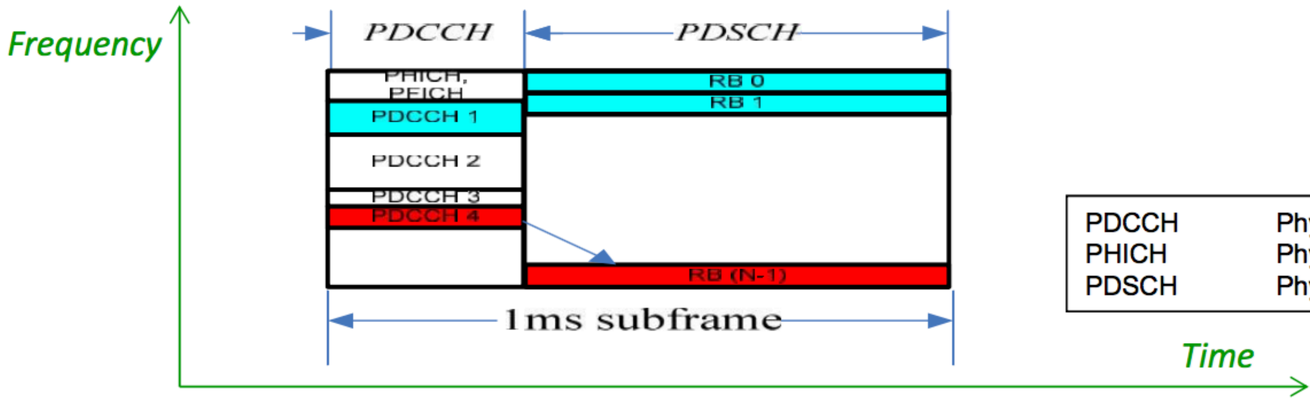
The UE now knows the UL frame boundaries and transmits request for RRC connection request. The UE includes the C-RNTI.

The eNB now transmits RRC Connection Setup message including the C-RNTI that was received from the UE. This step resolves any contention that could have occurred due to two UEs using the same preamble sequence in RACH access step.

The UE now transmits a message to the MME in the time-slot allocated in the previous step. The UE also includes its IMSI in the message.

How does the UE find out when the eNB is talking to it?

- To a first approximation (which is sufficient for these slides), the downlink channel for FDD appears as a sequence of 1 ms subframes, as shown below. The first few (typically 3) symbols are used for control signaling (PDCCH) and the remaining of the 14 symbols is the shared channel (PDSCH) which carries both signaling and data traffic.



PDCCH	Physical Downlink Control Channel
PHICH	Physical Hybrid ARQ Indicator Channel
PDSCH	Physical Downlink Shared Channel

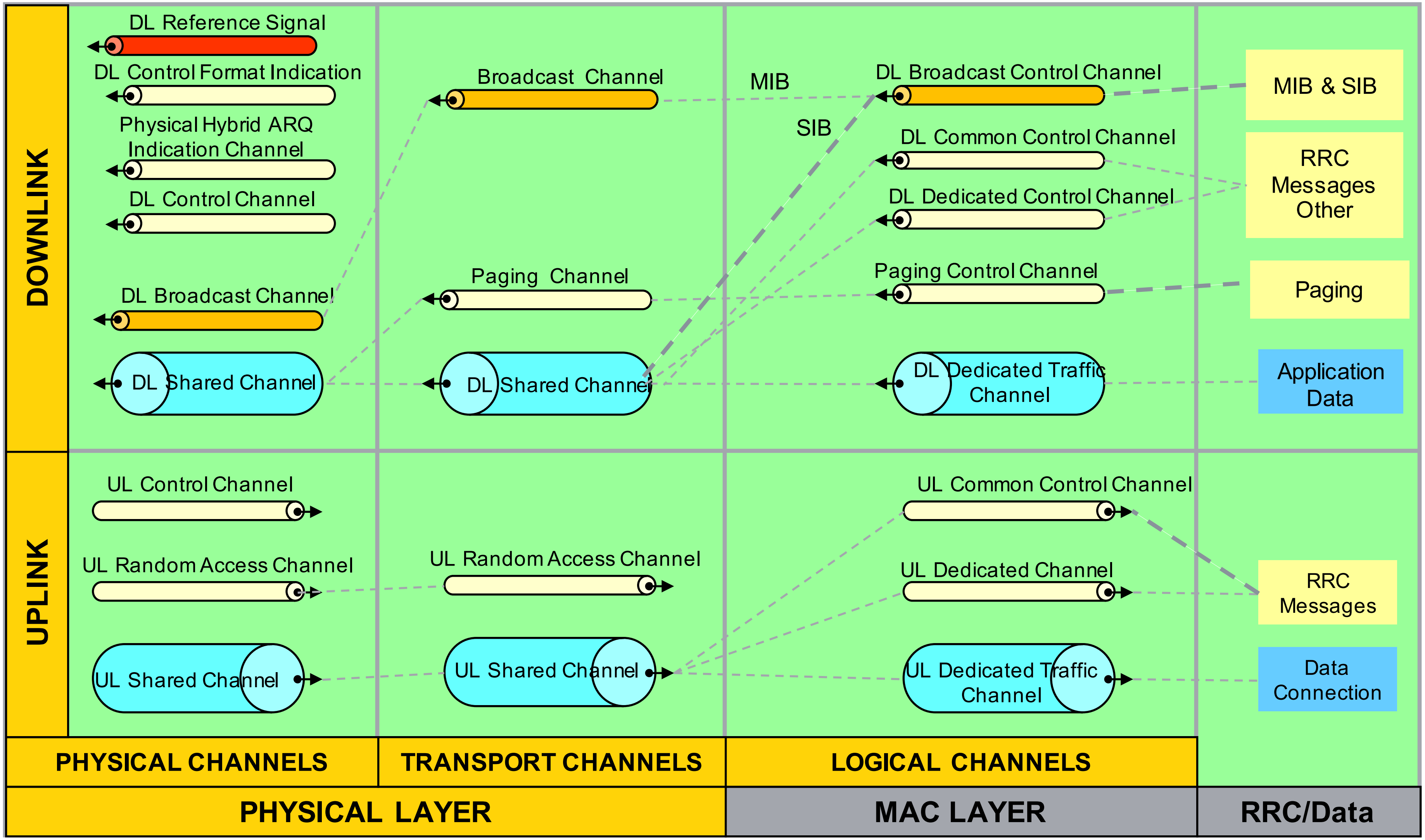
- The UE checks the PDCCH for its C-RNTI or P-RNTI (0xFFFE) or SI-RNTI (0xFFFF). The C-RNTI is unique to the UE in a cell. The P-RNTI and SI-RNTI are common to all UEs.
  - Technically speaking, the PDCCH has its 16 bit CRC scrambled by the appropriate RNTI.
  - The check for P-RNTI or SI-RNTI is not done in every PDCCH frame but only on selected, “paging occasion”, sub-frames (once every DRX cycle).
- If the UE finds its C-RNTI in the PDCCH channel, then it knows that there is a control plane (RRC) or user-plane (PDCP) message for it in the PDSCH portion (symbols 4-14) of the subframe. The PDCCH also points to which part of the PDSCH subframe contains the message for the UE.
- The UE then goes to that part of the PDSCH to find out what the message is.
- The MAC header in the PDSCH tells the UE whether it is an RRC message or a Data message.
  - Logical Channel ID 0 ➔ CCCH (SRB0)
  - Logical Channel ID 1, 2 ➔ DCCH (SRB1 and SRB2)
  - Logical Channel ID 3-10 ➔ DTCH

RNTI	Radio Network Temporary Identity
C-RNTI	Cell RNTI
P-RNTI	Paging RNTI
SI-RNTI	System Information RNTI

LTE Channels

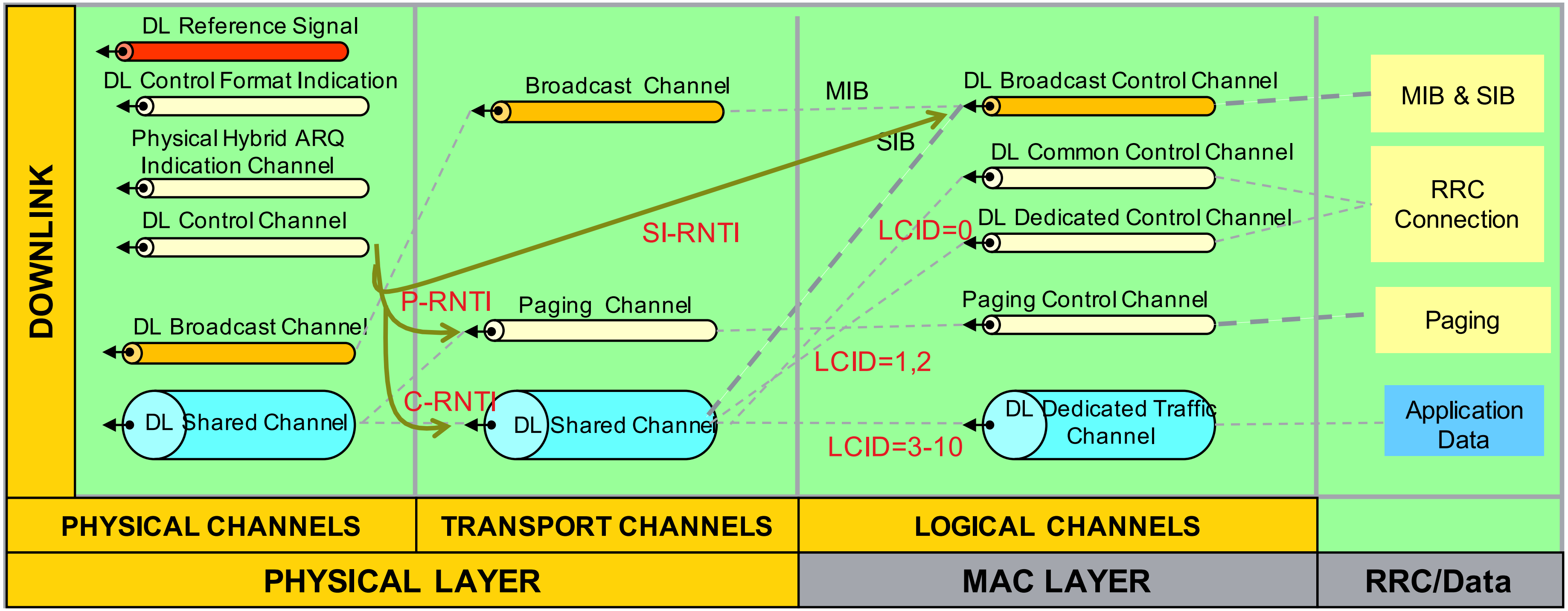
- Same as in UMTS defines three types of channels:
  - ➢ **Logical Channels**
    - Transfers data between the RLC and MAC
  - ➢ **Transport Channels**
    - Transfers data between the MAC and Physical Layer
  - ➢ **Physical Channels**
    - Transfers data across the air-interface

Mapping of Channels



NOTE: Not including multicast channels

UE asks "What data is being sent to me in DL?"



- If there is data for UE, the DL Control Channel provides information if the data is for paging channel or of the Shared Channel.
  - This is done by using a specific type of RNTI, i.e P-RNTI indicated PCH data, whereas C-RNTI and SI-RNTI indicated DL-SCH data.
- When UE receives data on DL-SCH, the MAC header indicated whether the data belongs to CCCH, DCCH or DTCH (BCCH is identified by SI-RNTI).
  - Logical Channel ID 0 ➔ CCCH (SRB0)
  - Logical Channel ID 1, 2 ➔ DCCH (SRB1 and SRB2)
  - Logical Channel ID 3-10 ➔ DTCH

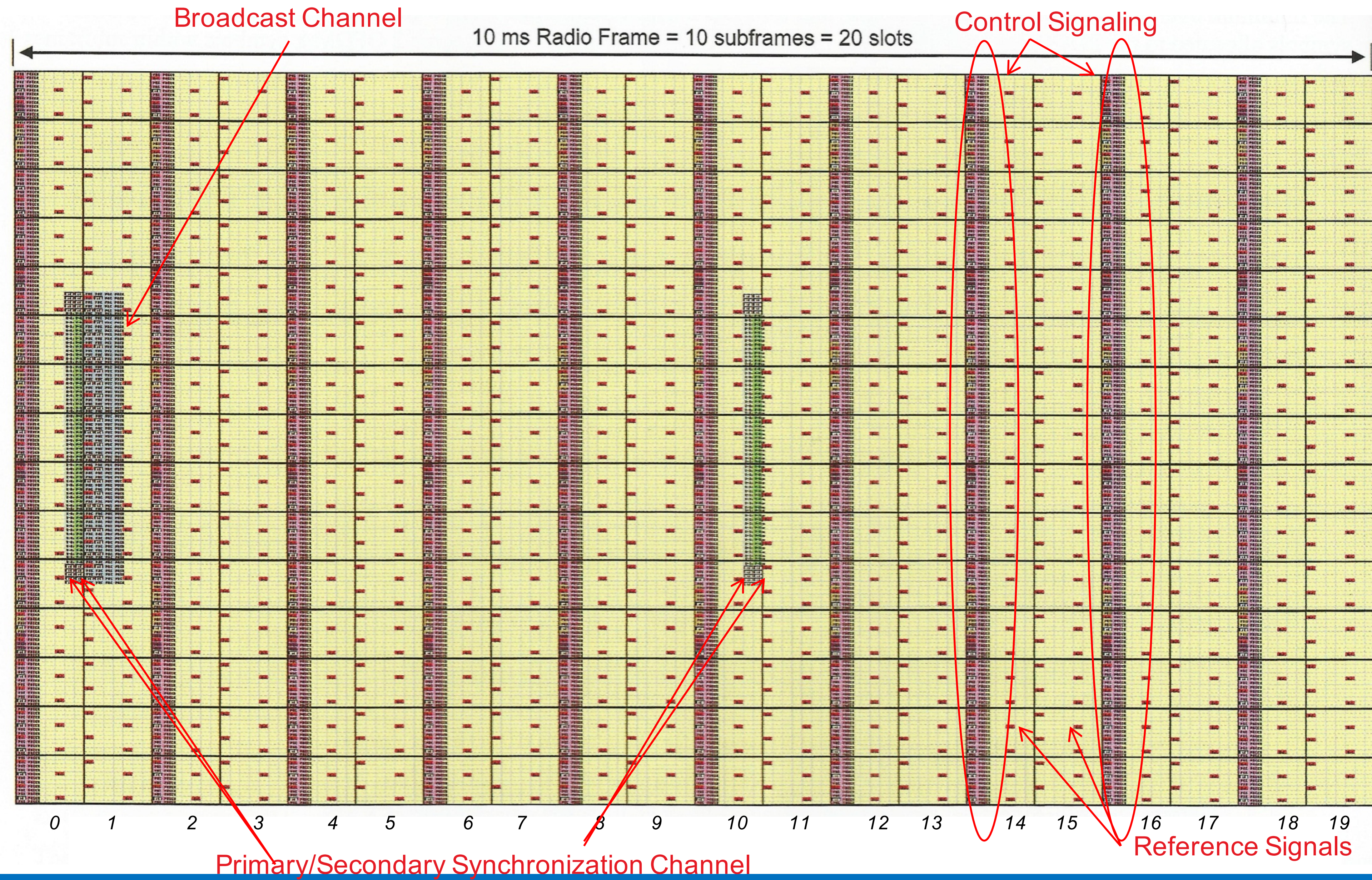
How does the UE find out what RRC message is being sent to it in DL direction? (2of2)

- If Logical Channel ID == 0 (SRB0): The "Message Type" field in the RRC message tells the UE what the message is:
  - DL-CCCH-MessageType ::= CHOICE {
  - rrcConnectionReestablishment RRCConnectionReestablishment,
  - rrcConnectionReestablishmentReject RRCConnectionReestablishmentReject,
  - rrcConnectionReject RRCConnectionReject,
  - rrcConnectionSetup RRCConnectionSetup
  - }
- If Logical Channel ID == 1, 2 (SRB1 and SRB2): The "Message Type" field in the RRC message tells the UE what the message is:
  - DL-DCCH-MessageType ::= CHOICE {
  - csfbParametersResponseCDMA2000 CSFBParametersResponseCDMA2000,
  - dlInformationTransfer DLInformationTransfer,
  - handoverFromEUTRAPreparationRequest HandoverFromEUTRAPreparationRequest,
  - mobilityFromEUTRACommand MobilityFromEUTRACommand,
  - rrcConnectionReconfiguration RRCConnectionReconfiguration,
  - rrcConnectionRelease RRCConnectionRelease,
  - securityModeCommand SecurityModeCommand,
  - ueCapabilityEnquiry UECapabilityEnquiry,
  - counterCheck CounterCheck,
  - ueInformationRequest-r9 UEInformationRequest-r9,
  - spare6 NULL, spare5 NULL, spare4 NULL,
  - spare3 NULL, spare2 NULL, spare1 NULL
  - }

How does the UE find out what RRC message is being sent to it in DL direction? (3of3)

- If Logical Channel ID == 3-10 (DRBs): The message is a data traffic channel (user plane message) belonging to a particular Data Radio Bearer. It is a PDCP message and the PDCP headers apply.’

DL Frame Structure



Uplink Direction

Single-Carrier FDMA (SC FDMA)

OFDMA Pro and Con

PROs

- Suited to multi-path propagation
  - ➢ Frequency selective channel divided into flat-fading sub-channel
  - ➢ Fast serial data stream divided into slow parallel data streams
    - Symbol duration long compared with channel delay spread
  - ➢ Avoid need for equaliser
- Efficient signal processing possible with FFT/IFFT
- Low out of band emissions

CONs

- High peak to mean ratio
  - ➢ Techniques to reduce peak/mean required
- Cyclic prefix required to avoid inter-symbol interference from multi-path
  - ➢ Reduces efficiency
- Sensitive to synchronisation errors
  - ➢ Use of dedicated pilots reduces efficiency

OFDM and SC-FDMA

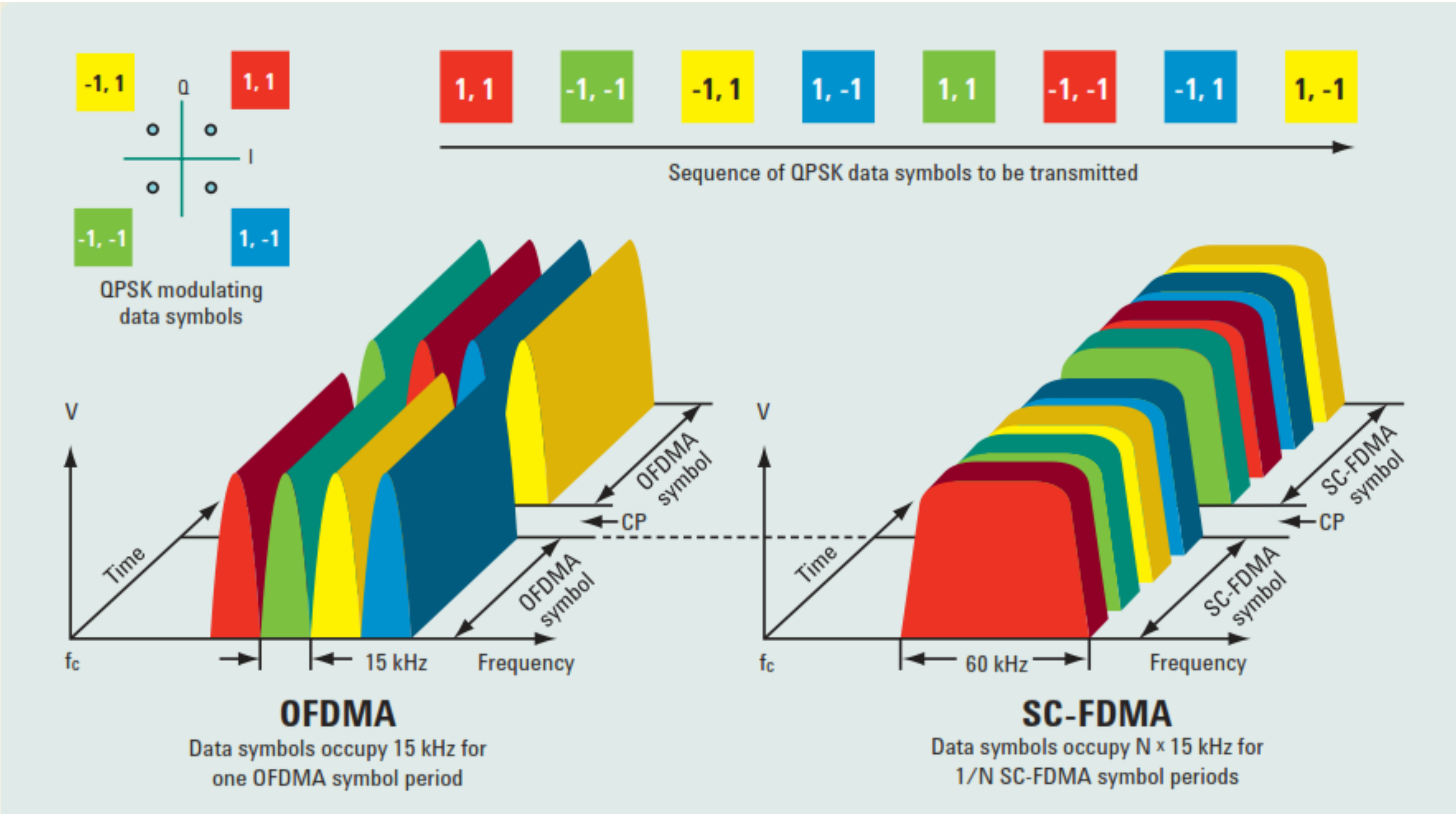
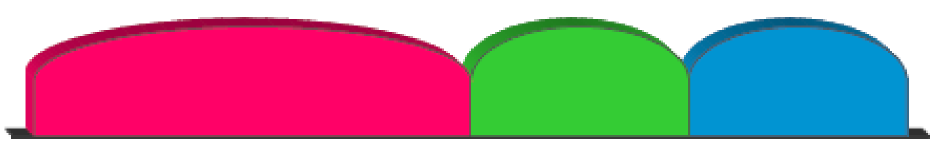


Figure 2. Comparison of how OFDMA and SC-FDMA transmit a sequence of QPSK data symbols

Source: 3GPP Introducing SC-FDMA, Agilent Tech Notes

3G LTE – *Uplink radio access*

- ***Single-carrier FDMA***
- **"Single-carrier"** ⇨ *Improved power-amplifier efficiency*
  ⇨ *Reduced terminal power consumption and cost, and improved coverage*
- **FDMA** ⇨ *Intra-cell orthogonality in time* ***and*** *frequency domain*
  ⇨ *Improved uplink coverage and capacity*
- **High degree of commonality with LTE downlink access**
  – *Same basic transmission parameter (frame length, "sub-carrier spacing", …)*



SC-FDMA

Source: Eric Dahlman, Ericsson.