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An introduction to cellular IoT: Signal processing aspects of NB-IoT

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NEON
Network of Competence on Internet of Things
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Outline

Introduction – motivation

IoT applications and challenges
IoT proprietary (LoRa) and/or licensed solutions (NB-IoT)

OFDM

OFDM system- Discrete model – Spectral efficiency – Characteristics
OFDM Sensitivity to synchronization errors.
Downlink time and CFO synchronization

3GPP LTE Characteristics

Network architecture
LTE layer functions
Physical channel characteristics
Congestion control and power efficiency

NB-IoT basics

Physical Layer numerology - Design Principles
DL and UL Physical Channels and Signals

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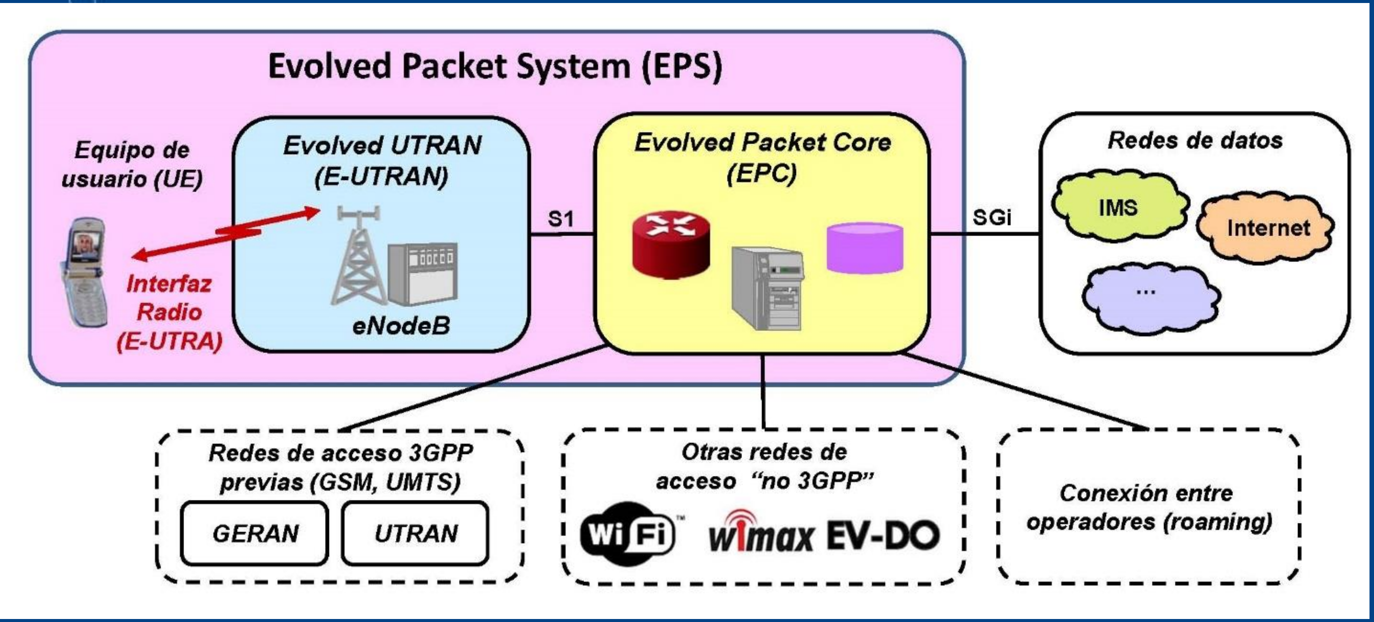
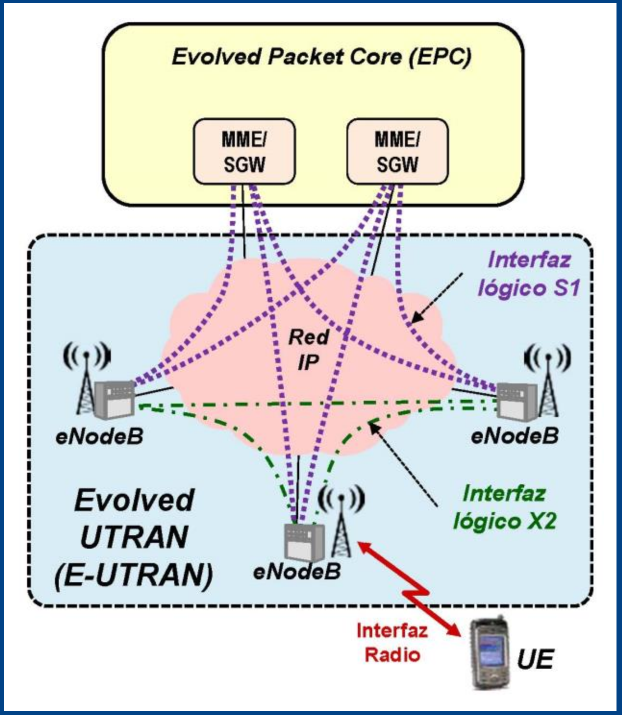
3GPP LTE system

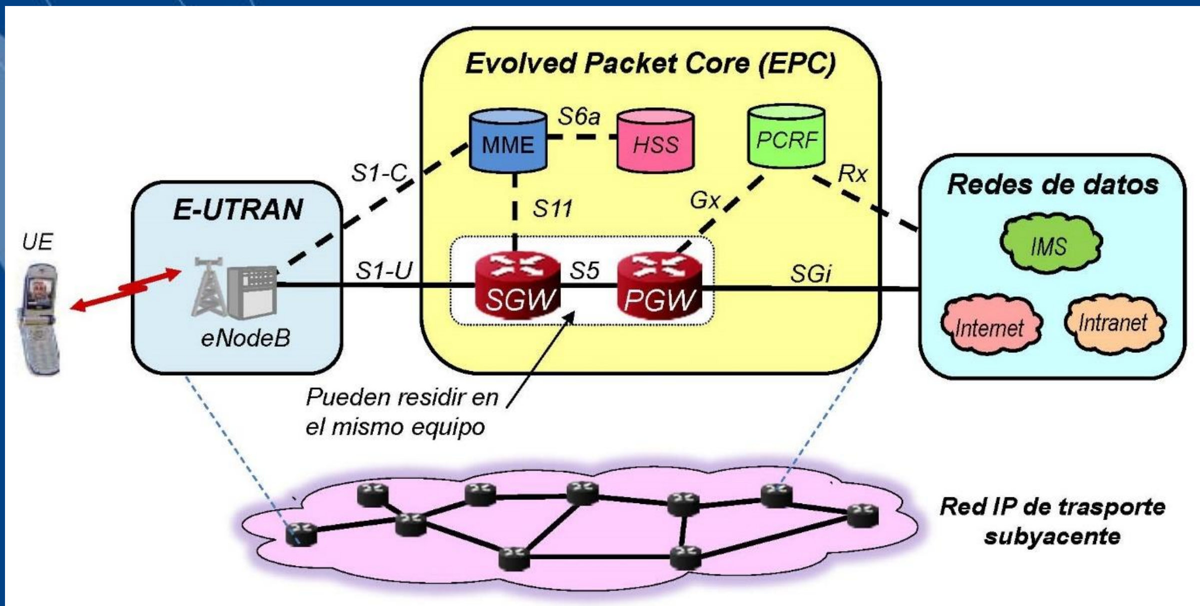


3GPP LTE: E - UTRAN

- Unique functional element e-NodeB (enhanced node B): Hybrid between base station and radio controller.
- Connected to EPC using IP network (mobile backhaul) by means of logic interfaces: S1 and X2.
- Functions
  - Physical (Modem, coding. Radio link control: error detection and correction).
  - Radio resource control (allocation, change, release).
  - Mobile handover (measurement control).
  - Traffic control between EPC and mobile (SGW user plane and MME control plane).



3GPP LTE: Evolved Packet Core (EPC)



eNodeB	Evolved Node-B	- Único elemento funcional de la red de acceso. - Híbrido de estación base y controlador
MME	Mobility Management Entity	- Servidor de señalización (funciones de control) - Gestión de movilidad y de sesiones: act. posición, paging, ...
SGW	Serving Gateway	- Intercambio de tráfico de usuario entre red de acceso y núcleo de red IP - Ancla para traspasos entre con otras redes 3GPP
PGW	Packet Data Network Gateway	- Intercambio de tráfico con redes externas (Packet Data Networks) - Clave para "policy enforcement" y recogida de datos de tarifación - Ancla para traspasos con redes no 3GPP
HSS	Home Subscriber Server	- Base de datos central de usuarios del sistema EPS - Identidades, datos de servicio y localización de usuarios
PCRF	Policy Charging and Rules Function	- Gestión de políticas de QoS y tarifación

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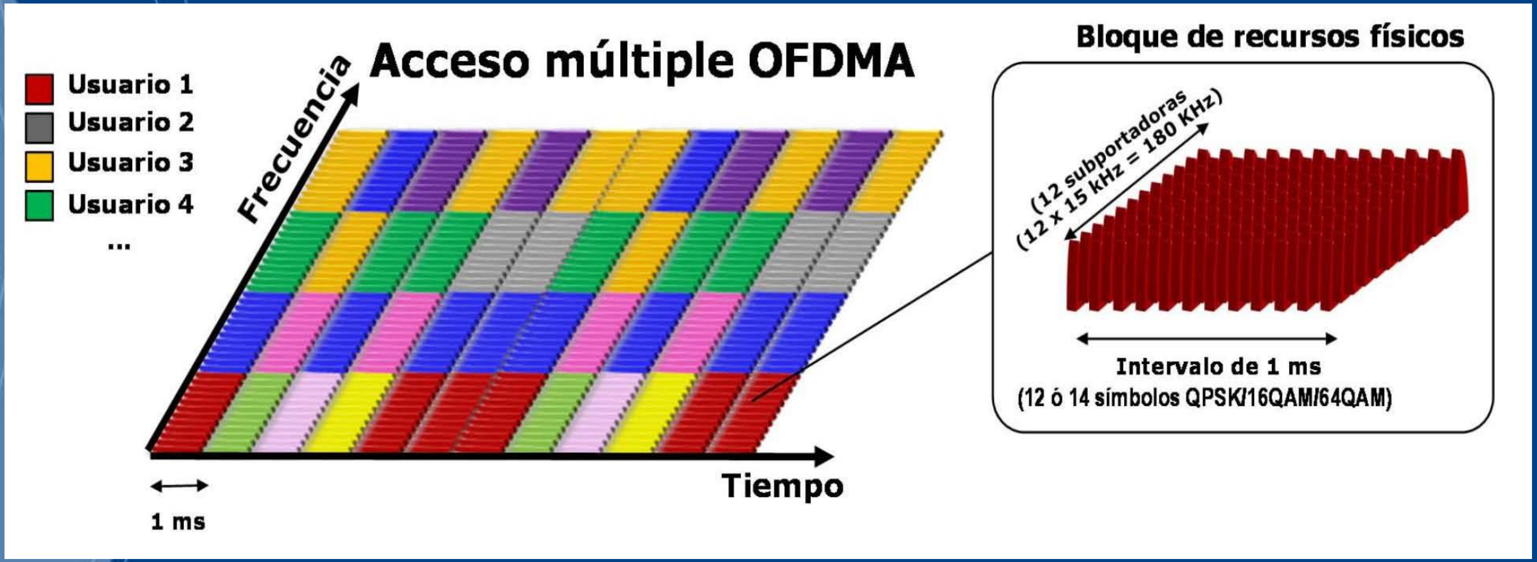
3GPP LTE channel characteristics

Design requirements and tradeoffs

- Main objective in OFDMA: scalable structure in terms of FFT size and bandwidth, maintaining subcarrier spacing fixed.
- To that purpose it is required to choose admissible values for Doppler spread (coherence time) and delay spread (coherence bandwidth) of the channel.

3GPP LTE…


Acceso múltiple OFDMA
Usuario 1
Usuario 2
Usuario 3
Usuario 4
...
Frecuencia
Tiempo
1 ms
Bloque de recursos físicos
(12 subportadoras
(12 x 15 kHz = 180 KHz)
Intervalo de 1 ms
(12 ó 14 símbolos QPSK/16QAM/64QAM)

3GPP LTE channel characteristics…

- Multipath fading channels are often defined by four key parameters:
  - Delay Spread (Td) and the Coherence Bandwidth (Wc) defining the multipath characteristics of the wireless channel;
  - Doppler Spread (Ds) and the Coherence Time (Tc) defining the fading characteristics of the wireless channel.

3GPP LTE…

Channel bandwidth [MHz]	1.4	3	5	10	15	20
Number of resource blocks (N_{RB})	6	15	25	50	75	100
Number of occupied subcarriers	72	180	300	600	900	1200
IDFT(Tx)/DFT(Rx) size	128	256	512	1024	1536	2048
Sample rate [MHz]	1.92	3.84	7.68	15.36	23.04	30.72
Samples per slot	960	1920	3840	7680	11520	15360

*3GPP TS 36.104

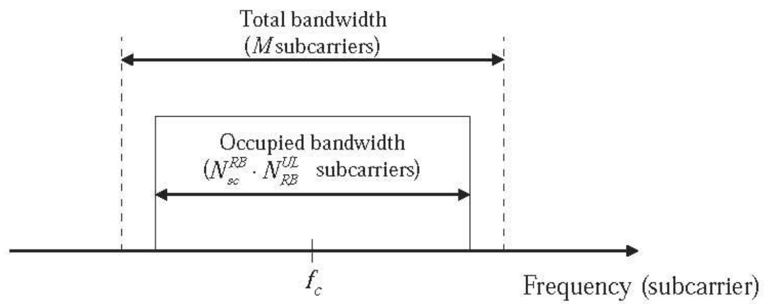


Figure 4.7 Physical mapping of a block in RF frequency domain (*fc*: carrier center frequency)

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3GPP LTE…

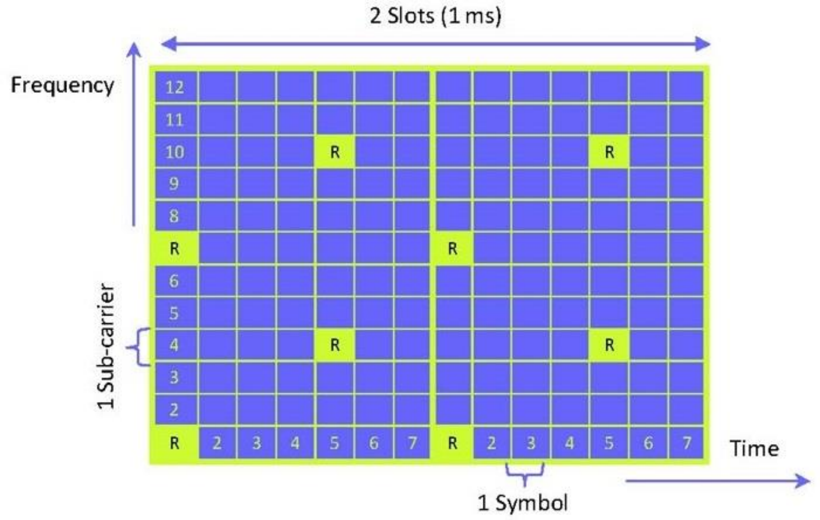
3GPP-LTE defines the system parameters for OFDMA based physical layer downlink signal. For example:

- Bandwidth (for example): 10 MHz, Sampling rate: 15.36 MHz, FFT size: 1024
- Subcarrier Spacing: 15 KHz
- Normal mode CP Length: 72 (72/15.36 MHz = 4.6875 μs),
- Duration of one OFDM symbol: (1024+72)/15.36 MHz ≈ 71.35 μs

- Frequency domain spacing between reference symbol subcarriers: 6

  ΔW = 15 KHz x 6 = 0.09 MHz
- Time domain spacing between reference OFDM symbols: 4

  ΔT ≈ 71.35 μs x 4 = 285.42 μs



3GPP LTE…

- 3GPP-LTE defines multipath fading channel models to be used for design, for example: the Extended Typical Urban model (ETU), delay spread of Td= 5 μs and maximum Doppler frequency of 300 Hz.
- Therefore, the coherence bandwidth is $W_c \approx 1/2T_d = 0.1$MHz.
- Since $\Delta W < W_c$, the spacing of the reference subcarriers is less than the coherence bandwidth of the channel. Hence, we can assume a flat fading channel for all subcarriers between the reference subcarriers.
- This implies that channel estimates obtained using the known reference subcarriers can also be used for equalization of the other subcarriers.

3GPP LTE…

- The ISI due to the multipath components of the channel is compensated by the cyclic prefix (CP).

- The CP length in the normal mode (4.6875 µs) is slightly less than the worst case delay spread (5 µs).

- However, LTE also supports an extended mode of CP where the length of the CP is 16.67 µs (256 samples / 15.36 MHz) and this is sufficient to handle the worst case delay spread of the ETU channel.

3GPP LTE…

- The Doppler spread of the channel model is calculated from the maximum Doppler frequency as $D_s = 300 - (-300) = 600$ Hz
- Therefore, the coherence time is $T_c \approx 1/4D_s = 416.67$ μs
- That is $\Delta T < T_c$, that is the spacing of the reference symbols in time domain is less than the coherence time of the channel.
- Hence, we can assume that the channel does not change during the time interval corresponding to ΔT.
- This implies that the channel estimates obtained using the known reference symbols can also be used for equalization of the other non-reference OFDM symbols.

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3GPP LTE…

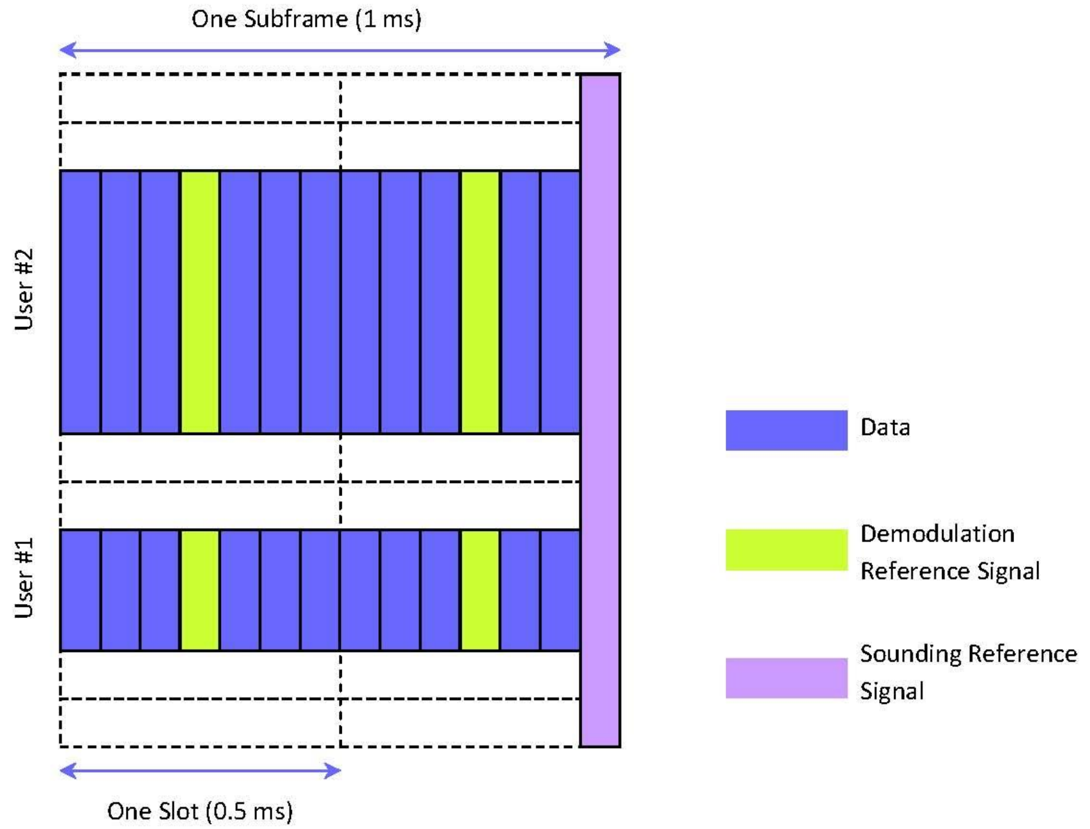
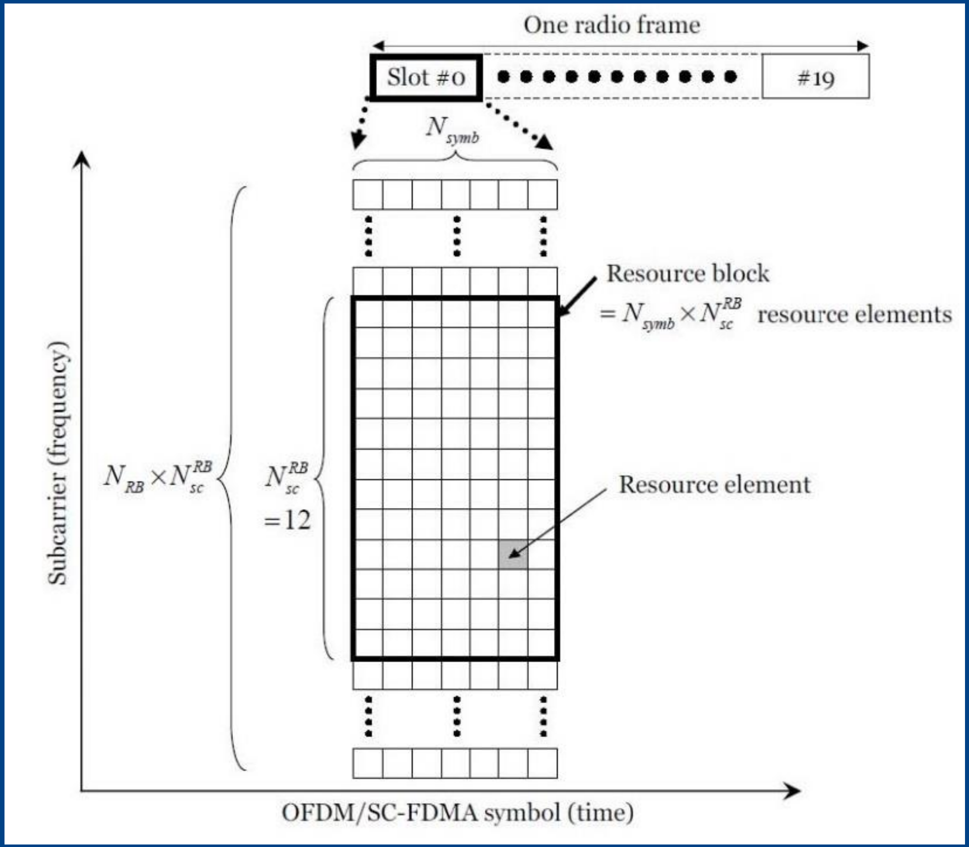


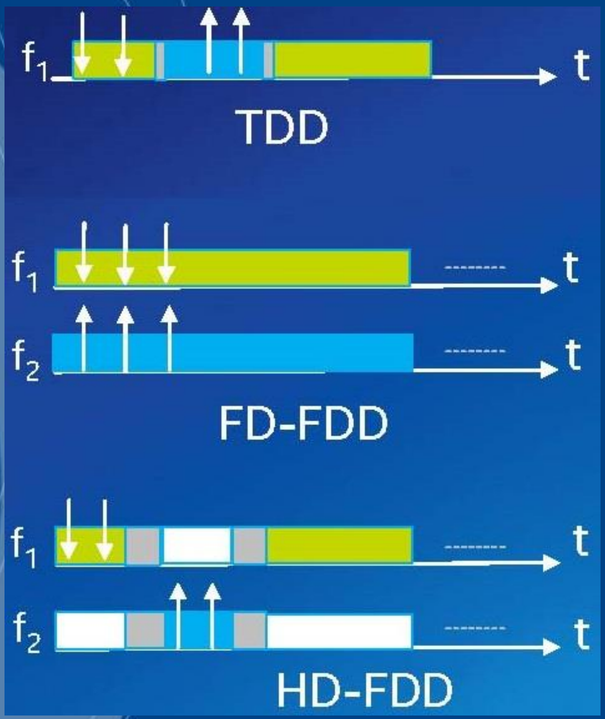
FIGURE 7 UPLINK DEMODULATION AND SOUNDING CHANNEL REFERENCE SIGNALS (NORMAL CP MODE).

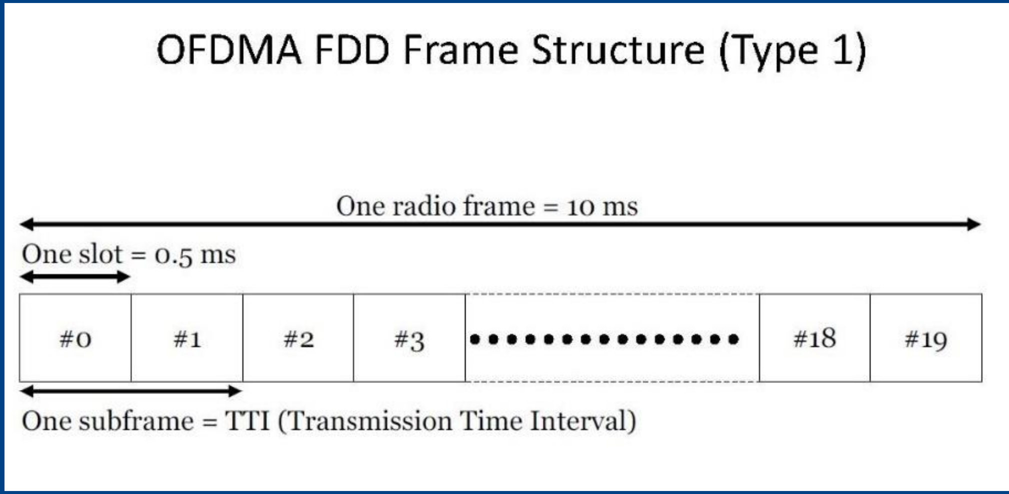
3GPP LTE…

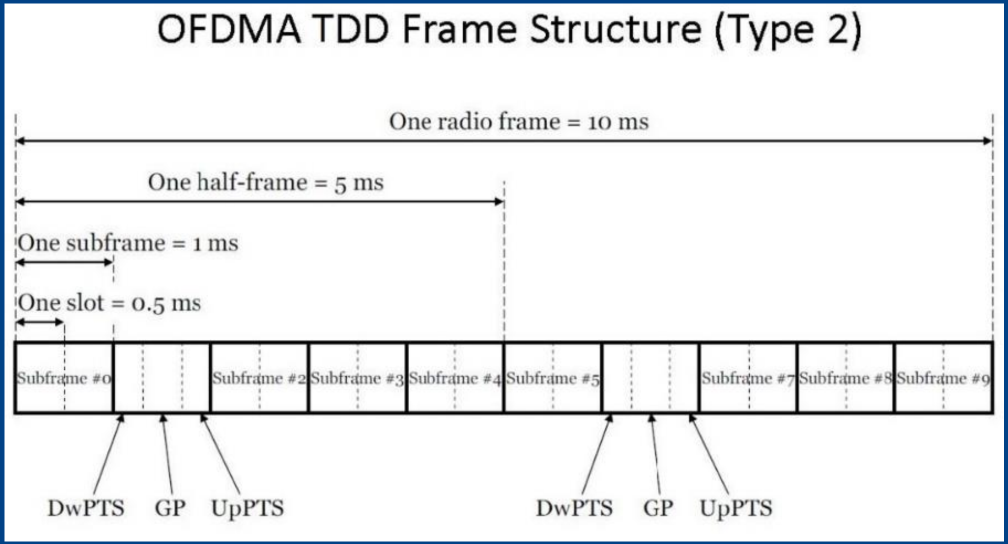
OFDMA Resource block structure



3GPP LTE…







DwPTS: DL pilot time slot
GP: Guard period
UpPTS: UL pilot time slot

3GPP LTE…

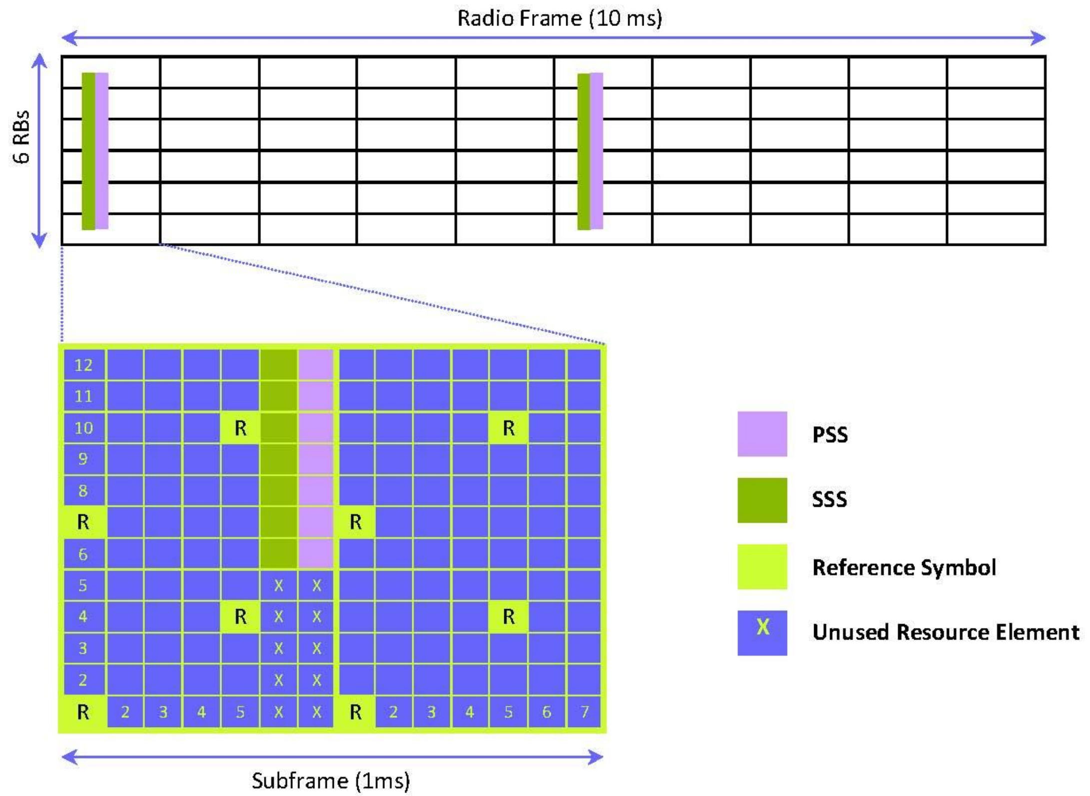


FIGURE 9 SYNCHRONIZATION SIGNALS FRAME STRUCTURE IN FREQUENCY AND TIME DOMAIN.

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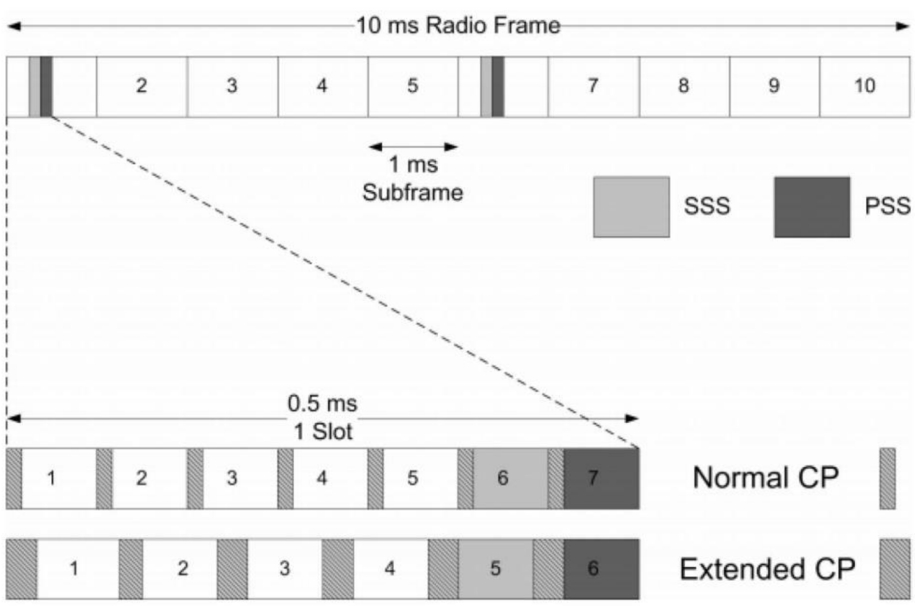
3GPP LTE…

PSS and SSS frame and slot structure in time domain in the FDD case



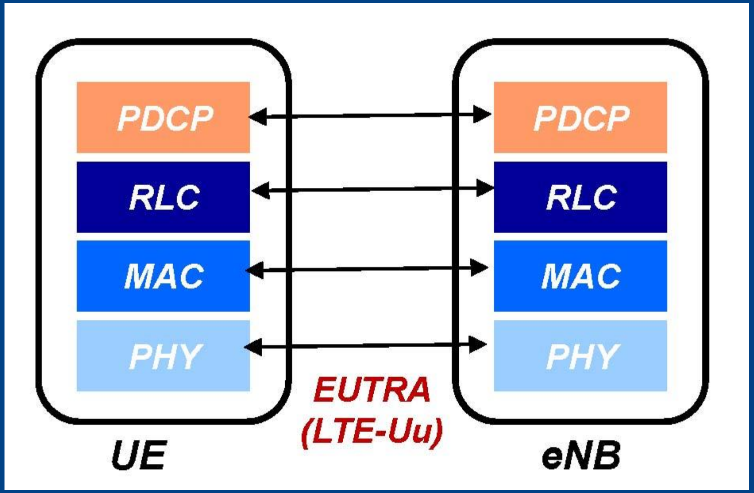
3GPP LTE: Radio interface protocols

- PDCP (Packet Data Convergence Protocol):
  Header compression, protection, etc.

- RLC (Radio Link Control):
  DRX command
  Error correction for H-ARQ (Hybrid ARQ).
  Segmentation, concatenation, retransm., etc.

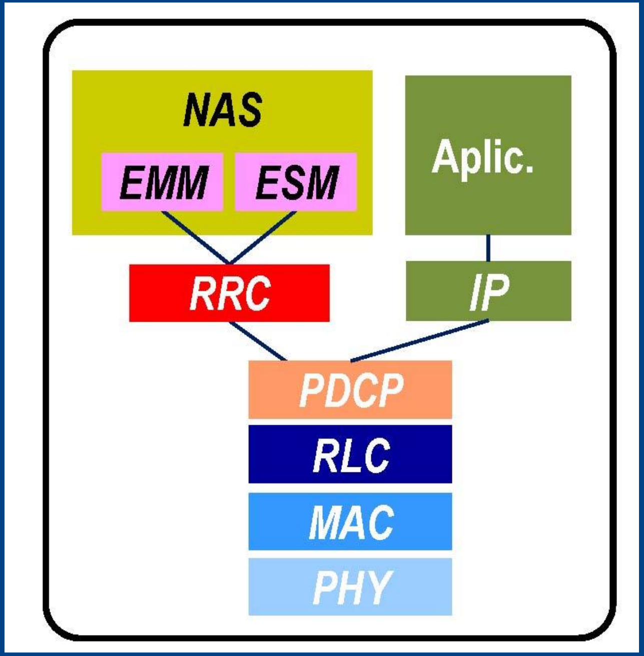
- MAC (Medium Access Control):
  Scheduling among shared physical resources management (UL-SCH y DL-SCH).
  Power control.
  Random access.
  Hybrid retransmissions H-ARQ, etc.

- PHY (Physical layer):
  Modulation, coding, etc.



3GPP LTE: Radio interface signaling

Gestión de Recursos Radio (RRM)	Gestión de sesiones radio (RRC)	Establecimiento, modificación y liberación de sesión RRC
	Traspasos	Con o sin cambio de SGW/MME, con o sin soporte de X2.
Gestión de movilidad (EMM)	Attach / Detach	Procedimientos de registro y desregistro en la red.
	Tracking Area Update	Actualización de posición por cambio de Tracking Area (similar Routing Area de GPRS/UMTS)
	Authentication	Autenticación y negociación de claves (similar a UMTS).
	Service request	Reanudación de intercambio de tráfico por móvil tras inactividad
	Paging	Reanudación de intercambio de tráfico por red tras inactividad
Gestión de sesiones (ESM)	Gestión de portadoras EPS	Establecimiento, modificación y liberación de portadoras EPS (por defecto y dedicadas), siempre a instancias de la red.
	Gestión de conexiones PDN	Establecimiento, modificación y liberación de sesiones de datos con redes externas a instancias del terminal (estilo GPRS/UMTS)



Sublevel RRC (Radio Resource Control)

Sublevel NAS (Non-Access Stratum):

– *EMM (EPS Mobility Management)*
– *ESM (EPS Session Management)*

3GPP LTE: Logical, transport and physical channels

Table 4.4 Logical channels

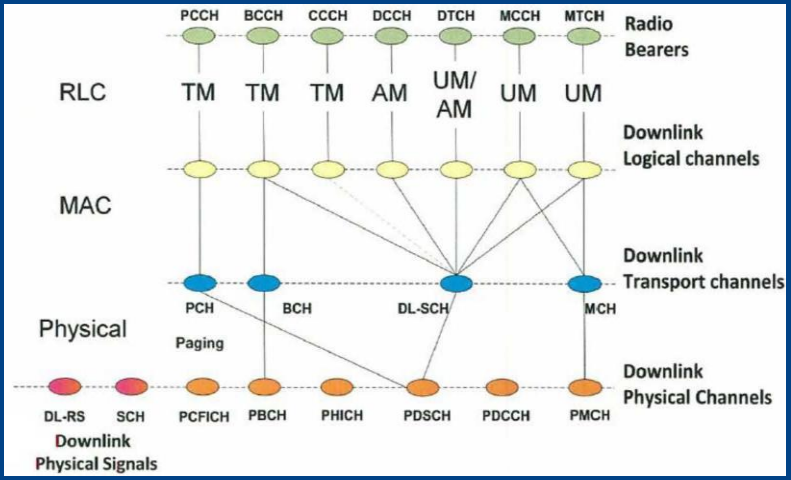
Logical channel name	Acronym	Control channel	Traffic channel
Broadcast control channel	BCCH	x	
Paging control channel	PCCH	x	
Common control channel	CCCH	x	
Multicast control channel	MCCH	x	
Dedicated control channel	DCCH	x	
Dedicated traffic channel	DTCH		x
Multicast traffic channel	MTCH		x

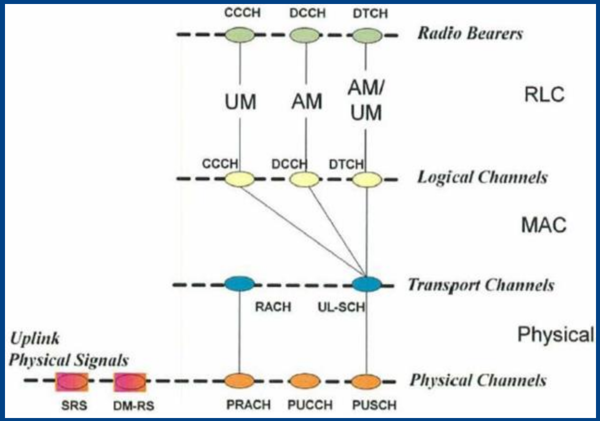
Table 4.3 Transport channels

Transport channel name	Acronym	Downlink	Uplink
Broadcast channel	BCH	x	
Downlink shared channel	DL-SCH	x	
Paging channel	PCH	x	
Multicast channel	MCH	x	
Uplink shared channel	UL-SCH		x
Random access channel	RACH		x

Table 4.2 Physical channels

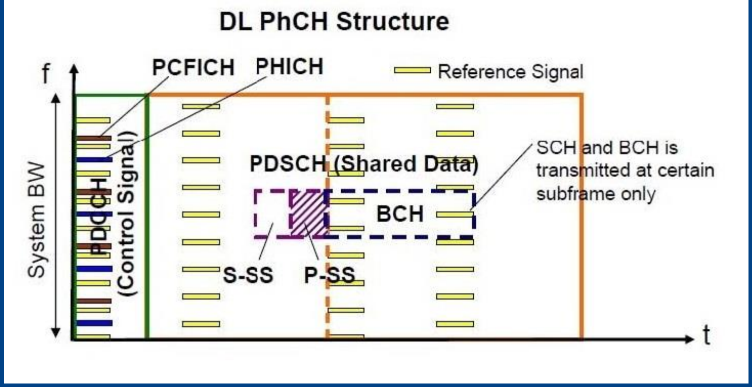
Physical channel name	Acronym	Downlink	Uplink
Physical broadcast channel	PBCH	x	
Physical control format indicator channel	PCFICH	x	
Physical downlink control channel	PDCCH	x	
Physical hybrid ARQ indicator channel	PHICH	x	
Physical downlink shared channel	PDSCH	x	
Physical multicast channel	PMCH	x	
Physical uplink control channel	PUCCH		x
Physical uplink shared channel	PUSCH		x
Physical random access channel	PRACH		x



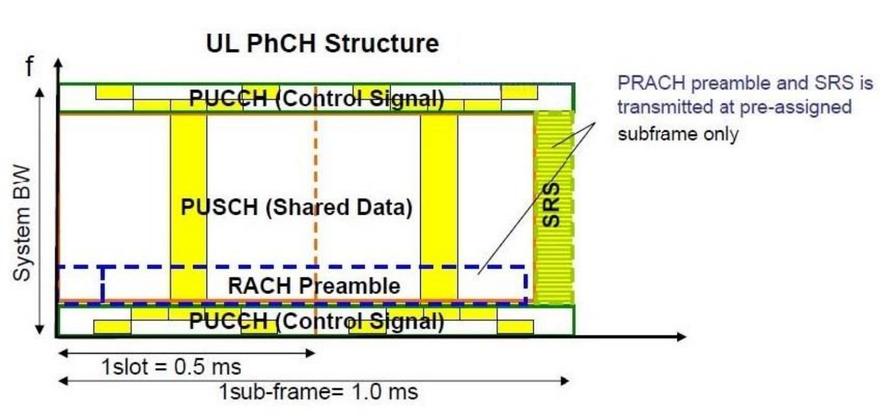


3GPP LTE: Physical channel structure…

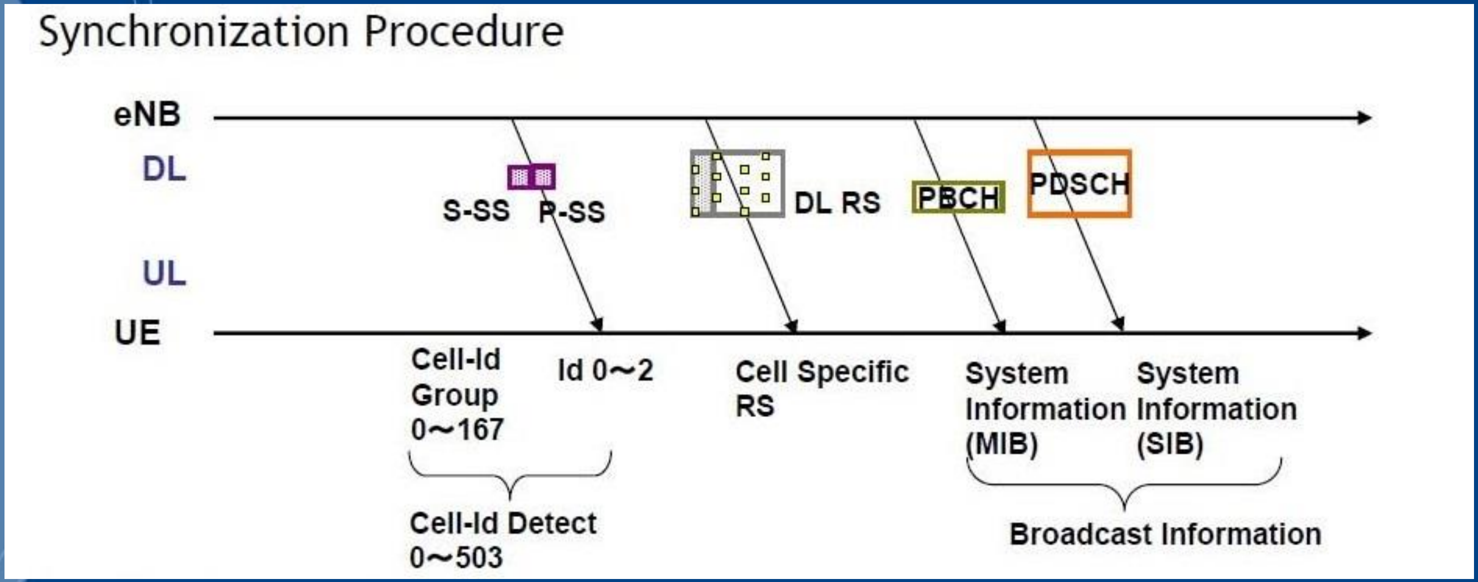
Downlink
PBCH: Transmit broadcast channel
PCFICH: Indicate PDCCH symbol
PDCCH: Assign PDSCH/PUSCH
PHICH: Indicate HARQ-ACK for UL
PDSCH: DL data
PMSCH: Transmit multicast channel
P-SS and S-SS: UE synchronization



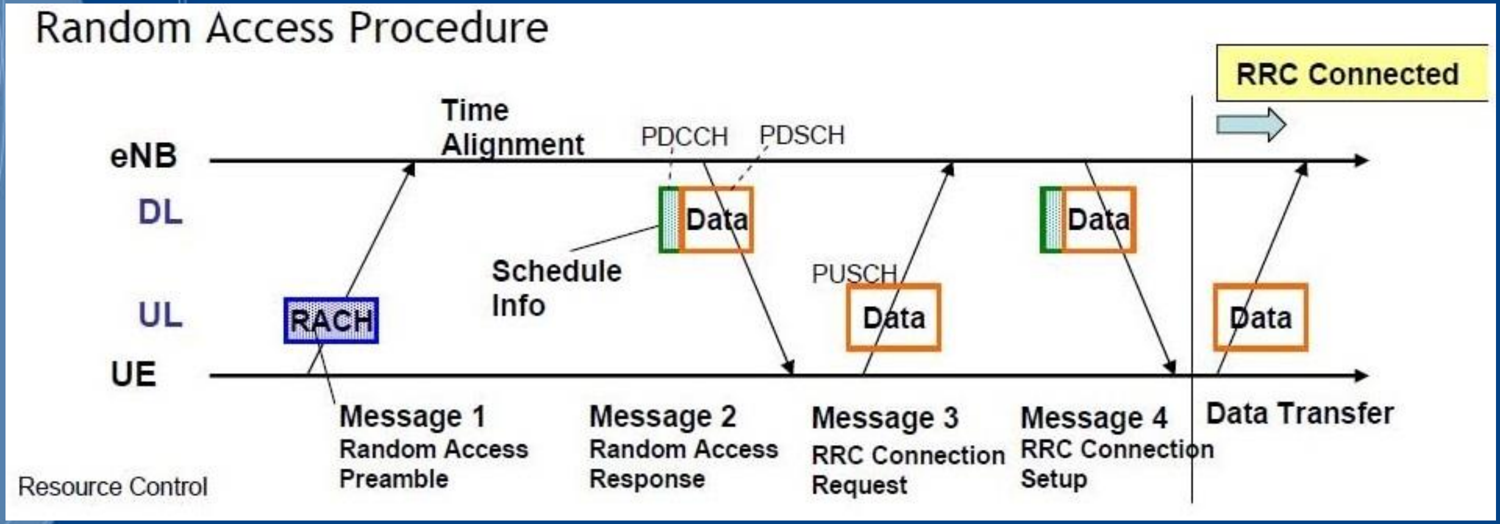
Uplink
PUCCH: Transmit ACK/NACK, CQI, SR
PUSCH: UL data
PRACH: Transmit random access preamble
SRS: For UL CQI measurement



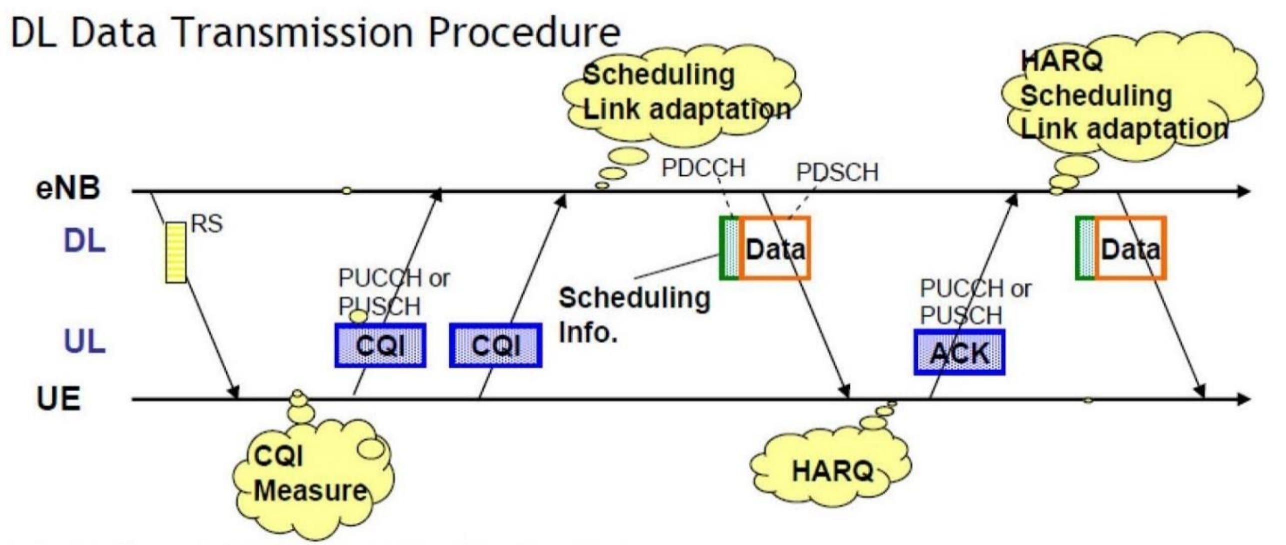
3GPP LTE: Synchronization procedure



3GPP LTE: Random access procedure

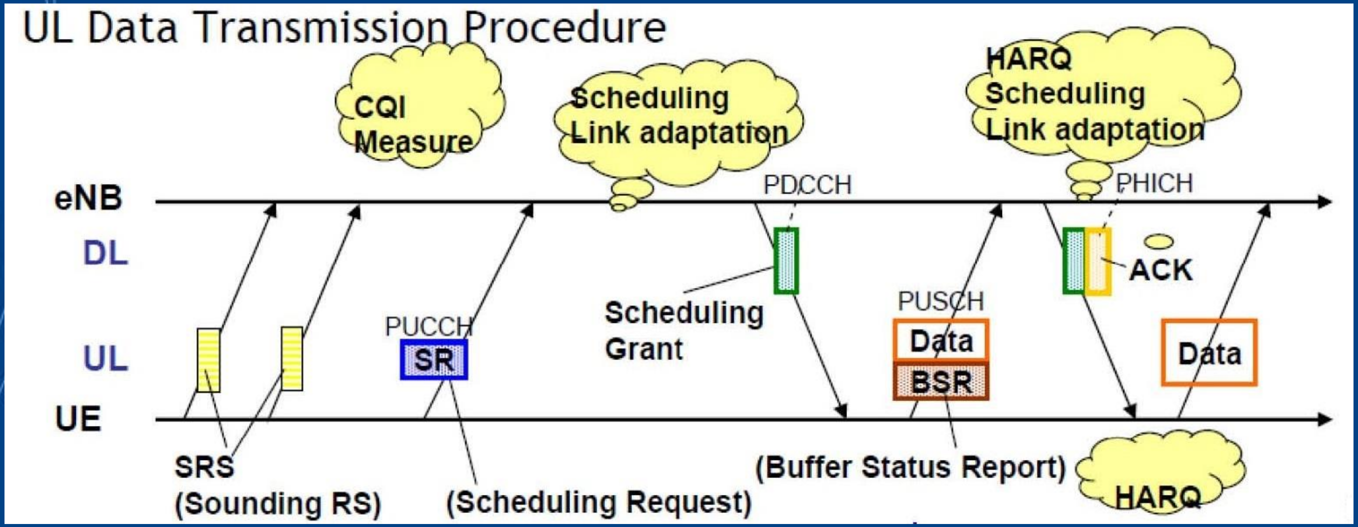


3GPP LTE: DL data transmission procedure



CQI: channel quality indicator (depends on modulation and code rate)

3GPP LTE: UL data transmission procedure



3GPP LTE: Congestion control

Basic access control techniques:

Separate RACH resources for MTC - PRACH resources can be separated into two groups, H2H and M2M traffic.

Backoff Schemes - In overload conditions, the network can request the M2M devices to back off. This scheme is less suitable for massive batch arrivals than other schemes.

Slotted Access - resources are assigned by the network for exclusive use by individual or groups of M2M devices.

Pull-based Schemes - a paging scheme, where eNodeB triggers the M2M devices to transmit.

Access Class Barring - consists of separating users into groups: access classes. Is used by eNodeB to control the load. It does so by blocking one or several user classes. The number of classes is optional, and depends on the required granularity.

3GPP LTE: Congestion control

Random access:

Random access attempts are allowed in predefined time/frequency resources called RA opportunities (RAOs).

In LTE, two types:

- **Contention free** (critical situations such as handover, downlink data arrival or positioning). There is a coordinated assignment of PRACH preambles, so collision is avoided.

- **Contention – based** (standard mode for network access, it is used by UEs to change the Radio Resource Control state from idle to connected, to recover from radio link failure, to perform uplink synchronization or to send scheduling requests).

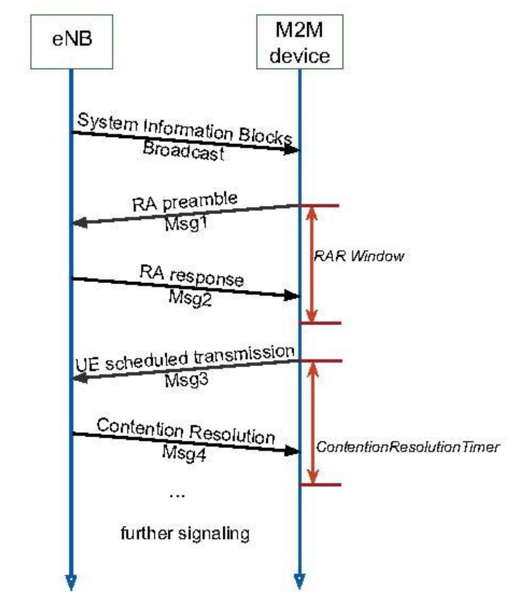


Figure 1. LTE-A Contention-based RA Procedure

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3GPP LTE: Access class barring (ACB)

ACB redistributes the access requests of UEs through time to reduce the number of access requests per RAO.

ACB is applied to UEs before RA: UEs are divided into access classes (AC) 0 to 15 according to its traffic characteristics (each UE can belong to one out of 10 ACs and to one or more out of 5 special categories).

ACB is useful when RA requests occur in a bursty manner, i.e., a large number of UEs attempt transmission at a given time but the system is usually not congested.

In other words, ACB spreads the load offered through time, but in the long run, the total offered load is kept the same.

3GPP LTE: ACB…

If ACB is not operating, all classes are allowed to access the PRACH.

When ACB is operating, eNB broadcasts (through SIB Type 2) mean barring times, TACB = {4, 8, 16, . . . , 512 s}, and barring rates, PACB = {0.05, 0.1, . . . , 0.95}, that are commonly applied to ACs 0-9. Then, at the beginning of RA, each UE generates a random number between 0 and 1, U[0, 1).

If this number is less than or equal to PACB, the UE sends its preamble. Otherwise, the UE waits

Tbarring = (0.7+0.6×rand)×TACB; where rand = U[0, 1).

This process is repeated until the UE generates a random number lower than PACB and sends its preamble.

3GPP LTE: Enhanced Access Barring (EAB)

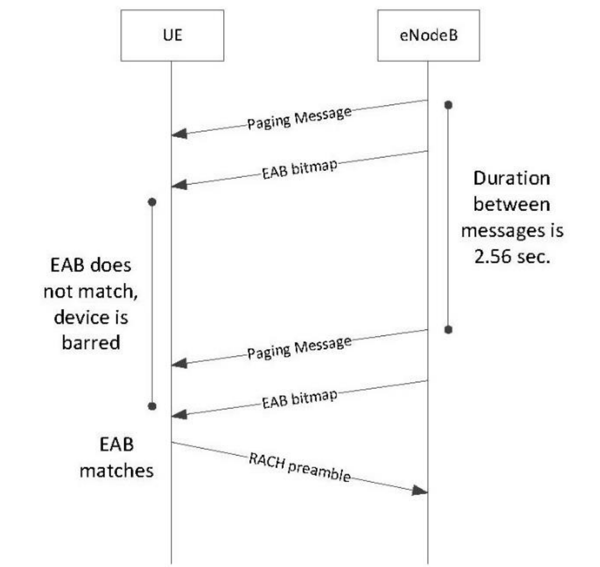
After broadcasting paging information, eNodeB sends a barring bitmap, consisting of 10 bits numbered 0-9, representing different AC.

The devices do the barring check by comparing the detected bitmap to the AC of the device.

If the AC and the broadcasted bitmap match, the device will not initiate any communication until the EAB SIB is changed.

The network rotates AC, by broadcasting a different EAB bitmap each time.

The duration of barring varies. If the bitmap matches, the device proceeds with the communication.



Extended Access Barring mechanism used in 3GPP LTE/LTE-A networks.

3GPP LTE: Discontinuous reception (DRX)

- During DRX, UE maintains a DRX cycle that is defined as a number of subframes.

- UE monitors PDCCH for on-duration subframes (1~200 subframes) and may turn off its receiver for rest of the DRX cycle.

- eNB does not schedule transmissions during off-period of the DRX cycle.

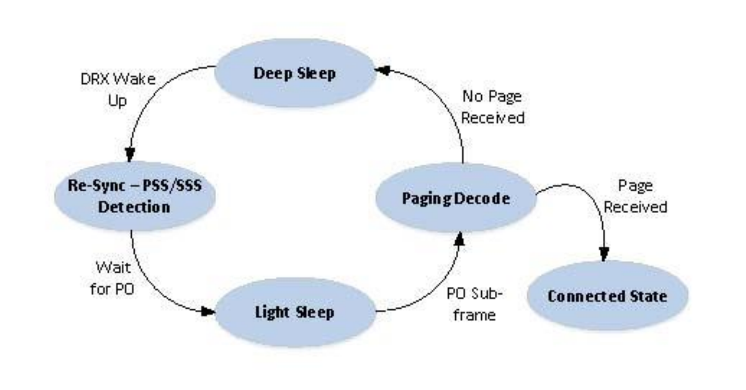
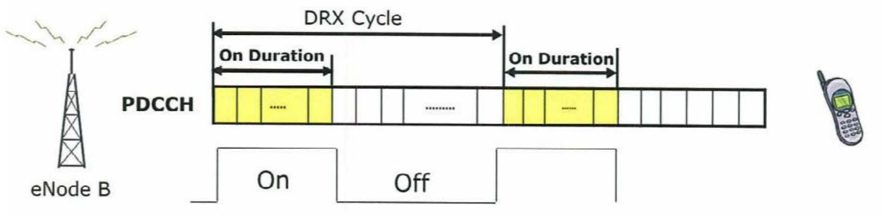


Figure 1.3: Current DRX model in LTE/LTE-A.



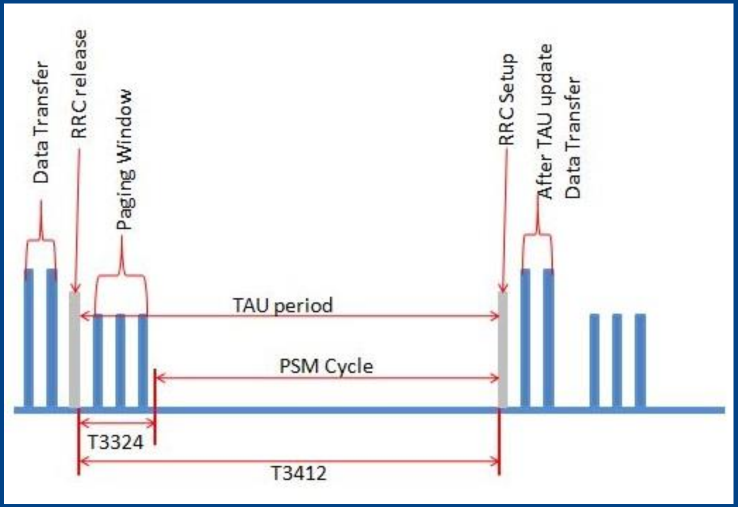
3GPP LTE: Power saving mode (PSM)

A UE is PSM enabled when it sends T3324 active and T3412 extended timers in TAU request.

Network provides two options: accept UE requested values or MME configured values for these timers.

The T3324 active timer is an integer value ranging from 0 to 11160 seconds.

The T3412 extended timer is an integer value ranging from 0 to 35712000 seconds.



Conclusions

- 3GPP cellular LTE architecture design concept is based on the separation of data-plane and control-plane signaling.
- From the multiple access technique perspective, OFDMA is the choice due to its scalable structure in terms of FFT size and bandwidth.
- The network layer protocols are related to logical signaling NAS (RRC, PDPC, RLC) and physical signaling AS (MAC, PHY).
- Congestion control is performed base on ACB.
- PSM and DRX techniques are used to save energy in the different UE cycles.