Long Term Evolution : PHY, MAC and RLC

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Outline I

Outline II

- Random access
- Timing advance

Section 1

Introduction

Introduction

- A new 3GPP standard frozen in Dec. 2008 : LTE
- Many concepts are coming from the preceding standards
- Important changes however :
    - Multi-carrier transmission
    - Simplified architecture
- Not yet 4G : LTE-Advanced fulfills the requirements of IMT-Advanced
- Standardization is evolving in parallel with the evolutions of HSPA+ (releases R7 and R8)

3GPP standard evolution

Release	Date	Main evolutions
R99	March 2000	WCDMA radio interface UTRAN radio access network ATM transport network
R4	March 2001	IIP in the transport network of UTRAN SIGTRAN and MEGACO in the circuit domain
R5	June 2002	HSDPA on the downlink IMS phase 1 Interface I_u-Flex
R6	March 2005	HSUPA on the uplink IMS phase 2 GAN
R7	Dec. 2007	HSPA+ and MIMO techniques IMS and TISPAN convergence
R8	Dec. 2008	HSPA+ evolutions LTE definition
R9	Dec. 2009	SON MBMS for LTE
R10	March 2011	LTE-Advanced definition

Table : Evolution of 3GPP releases. (source : `http:www.3gpp.org/specs/releases.htm`).

Objectives of the LTE standardization

- Peak rates : 100 Mbps (DL), 50 Mbps (UL) on 20 MHz
- In practice : 150 Mbps (DL), 75 Mbps (UL) on 20 MHz
- Average rate : HSPA $\times$ 3
- RAN latency : $<$ 5 ms for a small IP packet between the RAN and a UE at low load
- RRC latency : $<$ 100 ms to switch from Idle to Connected modes
- Mobility : maximum performances should be guaranteed at low mobility and the service should guaranteed at 350 Km/h
- Coverage : maximum performances up to 5 Km of cell radius
- Coexistence : measurements and handovers towards 2G, 3G and non 3GPP technologies like WiMAX or cdma2000

Section 2

How to reduce latency ?

E-UTRAN architecture I

- Answer : flat architecture, smarter BS and frequent radio resource allocation (TTI = 1 ms vs 20 ms in UMTS and 2 ms in HSPA)
- The radio access network is called Evolved-UTRAN
- E-UTRAN = eNodes-B interconnected via X2 interface
- E-UTRAN is connected to the Evolved Packet Core (EPC) via S1 interface

E-UTRAN architecture II

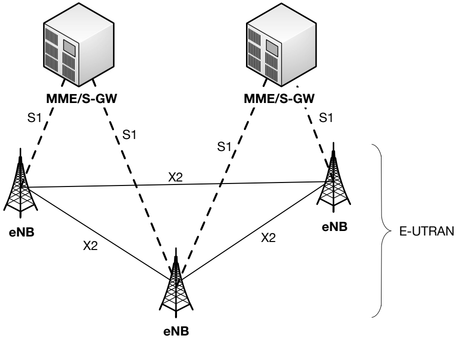

Figure : E-UTRAN architecture (from [2]).

E-UTRAN architecture III

- Mobility Management Entity (MME) = control plane
- Serving Gateway (S-GW) = user plane
- RNC disappears and the base station (eNB) gets augmented fonctionalities :
  - PHY and MAC layers (typical since GSM)
  - Fast scheduling and HARQ (like in HSPA)
  - New : RLC, PDCP, RRC
- Consequence : scheduling, retransmissions, link adaptation (i.e. of data rates as a function of the radio conditions) and reconfiguration decisions are taken closer to the radio link

Protocol stack I

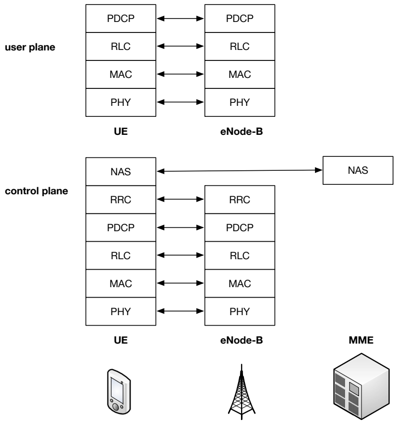

Figure : Protocol stack in user and control place of E-UTRAN. (from [2]).

Protocol stack II

- PHY :
  - RF processing
  - Error detection, correction
  - Transmission techniques (multi-carrier, modulation, MIMO)
  - Synchronization (time, frequency)
  - Measurements
- MAC :
  - Mapping of logical channels to transport channels
  - Multiplexing, demultiplexing of transport channels
  - Fats scheduling every 1 ms
  - HARQ retransmissions
  - Random access
  - Timing advance
  - Transport format selection
  - Priority management between logical channels

Protocol stack III

- RLC :
  - ARQ retransmissions (mode AM)
  - Concatenation, segmentation, reassembling of RLC SDUs
  - Resegmentation of RLC PDUs in case of retransmission
  - In sequence delivery of higher layers PDUs
  - Detection of duplicated RLC PDUs
- PDCP :
  - IP header compression, decompression (ROHC)
  - In sequence delivery (RLC AM)
  - Duplicatas detection
  - Retransmission of PDCP PDUs in case of handover (RLC AM)
  - Cyphering, decyphering of data
- RRC :
  - Radio resource management
  - Mobility management
  - Measurements feedbacks
  - Radio bearer control

Remember

Network latency : Keep this in mind !

- Flat architecture, no more RNC
- E-UTRAN = eNB, EPC = MME and SGW, X2 and S1 interfaces
- PHY layer, fast scheduling, retransmissions in the eNB
- TTI = 1 ms

Section 3

How to increase data rates ?

Context

- Remember the Shannon formula : $C \approx n_{ant} W \log_2(1 + SINR)$
- In practice however :
  - This is a not achieved upper bound
  - This function is bounded (by C_{max}) because we use finite modulations
  - Capacity should be shared by all active users in the cell
  - Some resources should be dedicated to signaling
- To increase data rates, we have few options :
  - Increase W... but issues with inter-symbol interference
  - Decrease interference with lower frequency spatial reuse... but less bandwidth per cell
  - Increase C_{max} by densifying the modulation... but the signal is more sensitive to noise and interference
  - Increase n_{ant}... but signal processing algorithm complexity increases and space is needed for antennas
  - Densify the network in order to decrease the number of users per cell... but more sites = more investments

General characteristics I

- Spread spectrum is withdrawn
- Multi-carrier transmission ⇒ a new organization of radio resources
- OFDMA (DL), SC-FDMA (UL)
- Possible signal bandwiths : 1,4, 3, 5, 10, 15 and 20 MHz (remember : 5 MHz in UMTS, 2×5 MHz in HSPA+ with double carrier)
- Modulations : BPSK, QPSK, 16-QAM, 64-QAM (remember : QPSK in UMTS, 16-QAM in HSPA)
- 64-QAM mandatory for the DL ; on the UL only cat. 5 terminals can use it
- Convolutional and turbo convolutional codes
- Duplexing : TDD and FDD

General characteristics II

- MIMO : 2 or 4 Tx, 2 or 4 Rx, up to 4 parallel flows can be used, MU-MIMO in DL and UL (remember : no MIMO in UMTS, 2×2 in HSPA+)
- MBMS : PHY layer is ready in R8, higher layers in the following releases
- FDD frequency bands : around 700, 800, 1400, 1700, 1800, 1900, 2100 et 2600 MHz (800, 1800, 2600 MHz in France)

OFDM/OFDMA I

- OFDM = a transmission technique
- Advantages : partly tackle the multi-path propagation issue, high spectral efficiency, simple implementation

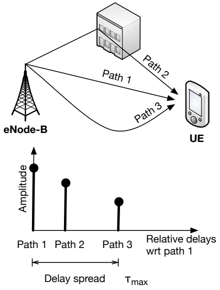

Figure : Multi-path propagation and maximum delay spread.

OFDM/OFDMA II

- If $\tau_{max} > T_{symb} \Rightarrow$ Inter-Symbol Interference (ISS)
- $1/\tau_{max} \approx$ channel coherence bandwidth
- $1/T_{symb} \approx$ signal bandwidth
- Wider is the signal bandwidth, higher is the ISS
- OFDM divides the global bandwidth in small frequency sub-channels or sub-carriers with bandwidth $\Delta f \ll 1/\tau_{max}$
- ISS is almost completely removed.

OFDM/OFDMA III

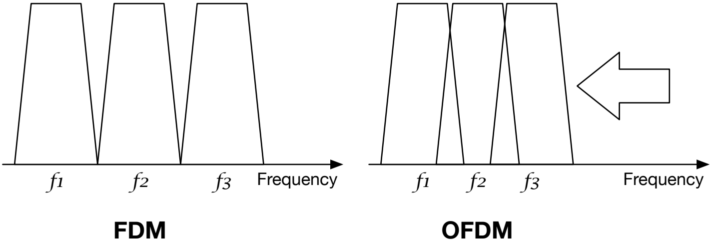

Figure : Comparison between OFDM and FDM in terms of spectral efficiency.

- Higher spectral efficiency than FDM
- Partial overlapping of the sub-channels thanks to the orthogonality between sub-carriers

OFDM/OFDMA IV

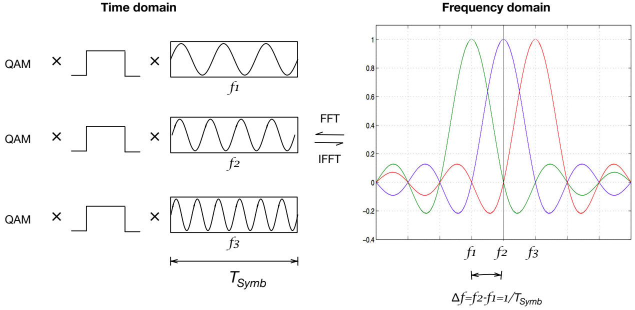

Figure : OFDM signal in time and frequency domains.

- Orthogonality : When the signal of sub-carrier n is maximum, the signal of all other sub-carriers is null.
- Orthogonality is obtained when $\Delta f = 1/T_{Symb}$
- Time domain : The OFDM symbol is the sum of modulated sub-carriers multiplied by a rectangle (gate) function

OFDM/OFDMA V

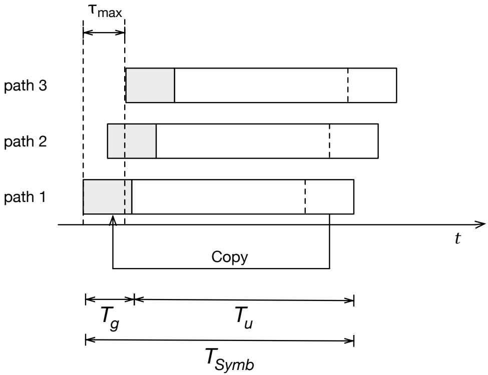

Figure : Guard interval/cyclic prefix of an OFDM symbol.

- To completely remove residual ISS, one adds a cyclic prefix.

OFDM/OFDMA VI

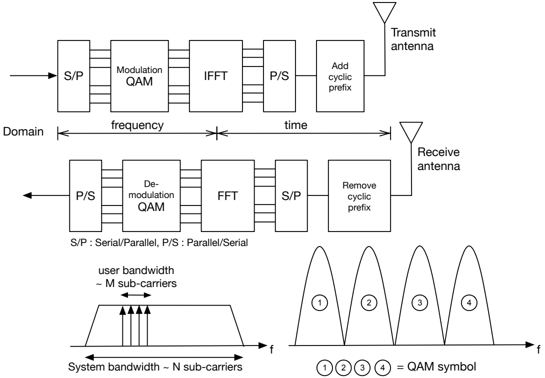

Figure : OFDM/OFDMA transmission and reception chains.

- The OFDM signal is easy to modulate and demodulate

OFDM/OFDMA VII

- OFDM has two drawbacks : (1) Inter-carrier interference (due to imperfect synchronization or strong Doppler effect) and (2) High Peak to Average Ratio (PAPR)

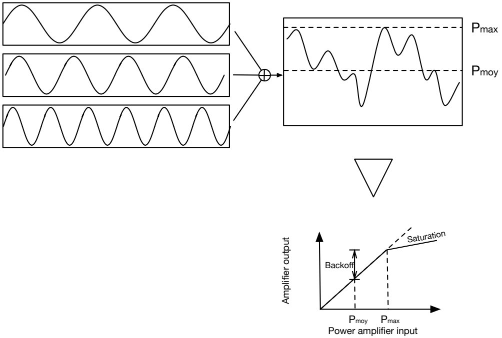

Figure : Peak to Average Ratio of the OFDM signal.

OFDM/OFDMA VIII

- OFDM = transmission technique
- OFDMA = multiple access method based on OFDM
- Groups of sub-carriers can be allocated to different users
- $\Rightarrow$ no intra-cell interference ($\neq$ CDMA)
- Radio resource allocation in the time/frequency domain.

SC-FDMA I

- High PAPR $\Rightarrow$ an issue for the UL
- SC-FDMA = Transmission technique with low PAPR for the UL

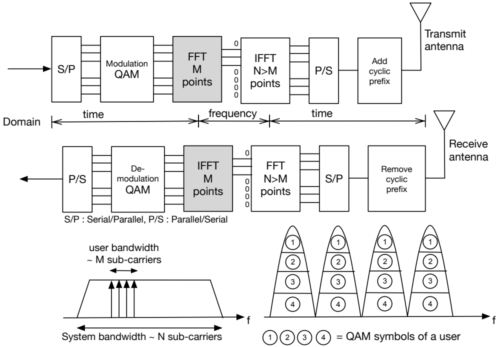

Figure : SC-FDMA transmission and reception chains.

SC-FDMA II

- The FFT spreads every QAM symbol over M sub-carriers
- Every sub-carrier successively carriers all QAM symbols
- At a given instant, a unique QAM symbol is transmitted
- The resulting PAPR is thus the same as for a QAM modulation
- The remaining $N - M$ sub-carriers are available and can be allocated to other users

LTE configurations I

Configuration	Δf (kHz)	Cyclic prefix (μs)	T_u (μs)
Normal prefix	15	5,2 (first symbol) 4,7 (other symbols)	66,6
Extended prefix	15	16,7	66,6

Table : OFDM parameters on the downlink of LTE.

- Normal configuration : 7 OFDM symbols per slot, small prefix duration $\Rightarrow$ relatively small cells (cell radius $<$ 2 Km)
- Extended configuration : higher prefix duration, 6 OFDM symbols per slot $\Rightarrow$ larger cells (up to 10 Km) and single frequency networks (MBSFN)

LTE configurations II

Transmission techniques : Keep this in mind !

- OFDM advantages : combat and take advantage of multi-path propagation, high spectral efficiency, easy and cheap implementation
- OFDM drawbacks : Inter-carrier interference (ICI), PAPR
- OFDMA/SC-FDMA are multiple access schemes
- SC-FDMA advantage : A solution for a low PAPR UL
- SC-FDMA drawback : A user can be allocated only a set of contiguous sub-carriers
- Spectral separation between sub-carriers is constant equal to 15 KHz whatever the total signal bandwidth

Single Frequency Networks (SFN)

- Single Frequency Network = All cells use the same carrier frequency (=CDMA, $\neq$ GSM)
- Frequency reuse ($K > 1$) or SFN ($K = 1$) ?
  - $K > 1$: less interference but cell capacity divided by K
  - $K = 1$: maximum cell capacity but cell border is highly interfered $\Rightarrow$ *outage*

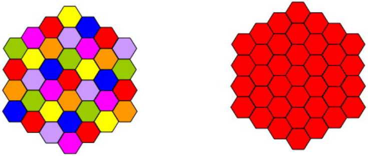

Figure : Frequency reuse $K = 7$ and SFN ($K = 1$).

MIMO gains

- Diversity gain : several independent copies of the signal are available at the receiver, improve the robustness of the signal
- Array gain : transmission side : energy is focused in one or several directions *(beamforming)*, reception side : more energy is captured by several antennas, improve the SNR, may reduce interferences
- Multiplexing gain : several parallel flows are simultaneously transmitted, the SISO channel capacity is multiplied by $\min(M, N)$, where M and N are the number of transmit and receive antennas resp.
- Typical configurations : 2×2 and 4×2, then : 4×4

Transmit diversity (TM2)

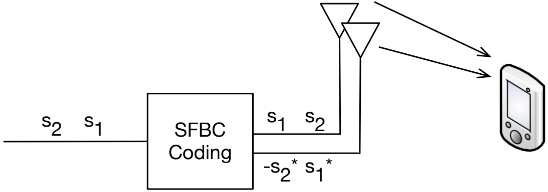

Figure : Transmit diversity.

- 2 or 4 transmit antennas
- Space-Time Block Code (SFBC) : Alamouti code [4] in the frequency domain
- Improves the robustness of the signal without increasing the data rate
- Open loop
- Backup transmission mode for other modes

Spatial multiplexing (TM3 : open loop, TM4 : closed loop)

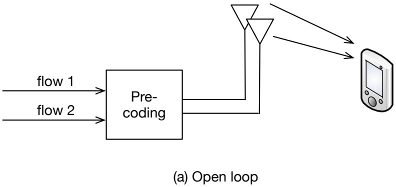

Figure : Spatial multiplexing.

- Several flows are simultaneously transmitted (2 or 4 antennas)
- Open loop : precoding matrices are known at the receiver and change in a cyclic manner at the transmitter
- Closed loop : the UE feedbacks its preferred precoding matrix, this solution is well adapted to UEs in low mobility

TM5 : Multi-user MIMO

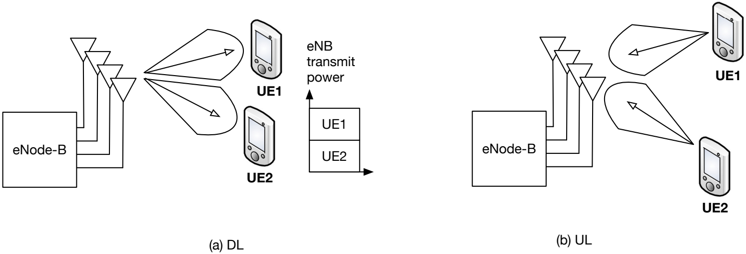

Figure : MU-MIMO transmission (a) on the downlink and (b) on the uplink.

- Two simultaneous flows on a single time/frequency resource
- Technique similar to the spatial multiplexing scheme with closed loop

TM6 and TM7 : Beamforming

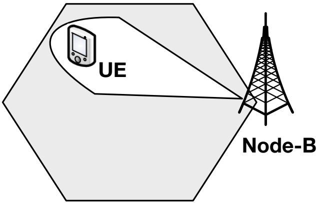

Figure : Beamforming.

- An antenna array is used to create an antenna beam in the direction of the UE $\Rightarrow$ increase useful signal power at the receiver
- Pilot signals specific to the UE are required

Remember

MIMO : Keep this in mind !

- Transmit diversity : improves the signal robustness
- Spatial multiplexing : increases data rates in good radio conditions
- Beamforming : increases the useful signal power
- Open loop : no feedback from UEs (for fast UEs)
- Closed loop : feedback from UEs (more efficient but for slow UEs)

Frame structure (type 1 for FDD)

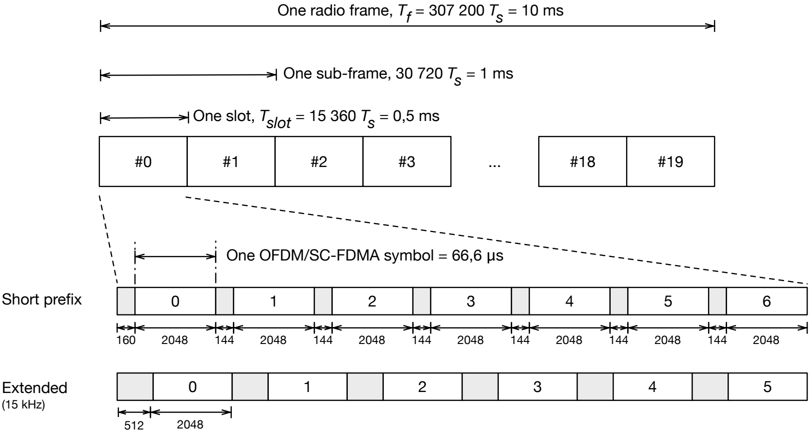

Figure : Frame structure type 1 in LTE FDD for 20 MHz (from [1]).

Reference signals

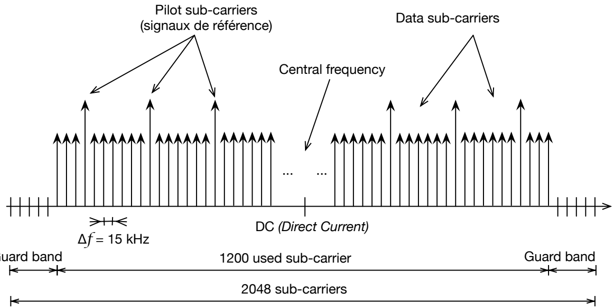

Figure : Data, pilot (reference signals) and null (carrier frequency and guard bands) sub-carriers on the DL of LTE.

- Reference signals are required for the channel estimation and the decoding of user data

Resource elements (RE) and blocks (RB) I

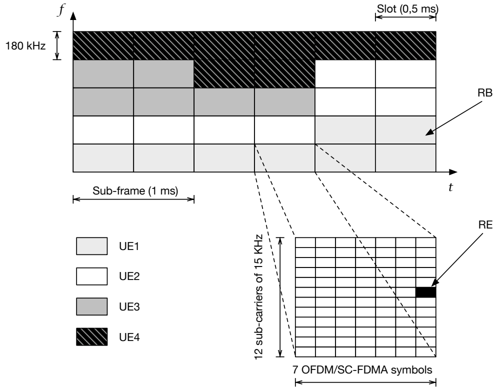

Figure : Resource Elements and Resource Blocks in LTE in normal configuration.

Resource elements (RE) and blocks (RB) II

- 1 RE = 1 sub-carrier $\times$ 1 OFDM/SC-FDMA symbol
- 1 RB = 12 sub-carriers $\times$ 7 OFDM/SC-FDMA symbols
- Minimum amount of resource allocated to a UE : 2 successive RBs

Parameter	**Bandwidth (MHz)**					
	1,4	**3**	**5**	**10**	**15**	**20**
FFT size	128	256	512	1024	1536	2048
Used sub-carriers	72	180	300	600	900	1200
RB	6	15	25	50	75	100

Table : Available radio resources vs. signal bandwidth (from [3]).

Remember

Radio resource organization : Keep this in mind !

- Radio resources are organized in the time-frequency domain (or slot-sub-carrier)
- 1 radio frame (10 ms) $=$ 10 sub-frames (1 ms) $=$ 20 slots $(0,5$ ms$)$
- 1 RE $=$ 1 sub-carriers $\times$ 1 symbol
- 1 RB $=$ 12 sub-carriers $\times$ 7 symbols
- Minimum allocation : 2 successive RBs (every 1 ms)
- 20 MHz $\triangleq$ 100 RB

Section 4

How to synchronize ?

Objectives

- **Objectives** : time and frequency, PCI (Physical Cell Identifier) and System Informations acquisition
- PCI : 504 identities classified in 168 groups of 3
- System Informations : network identity, common channels configuration, selection/reselection/handover parameters, informations on neighbor cells. They are organized in one MIB (Master Information Block) and several SIBs (System Information Block)

Downlink physical channels

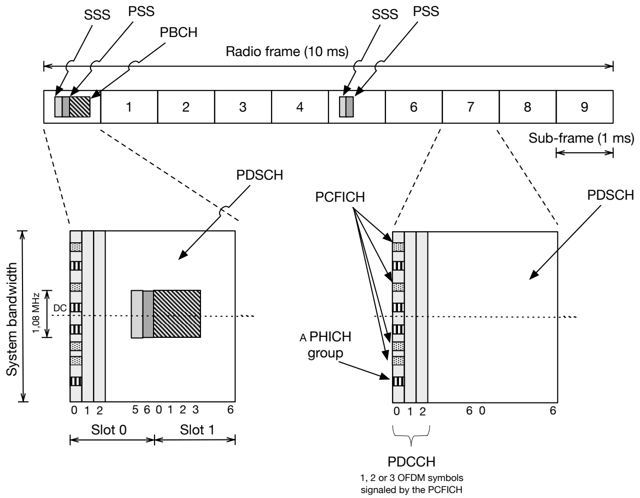

Figure : Mapping of downlink physical channels on the radio frame.

Transport and logical channels

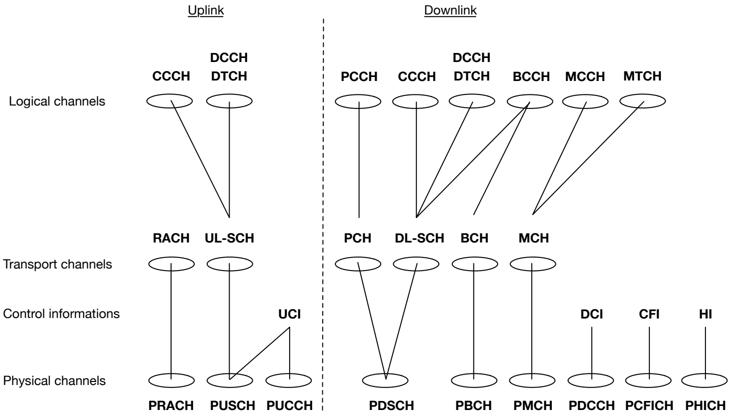

Figure : Mapping of physical, transport and logical channels.

Cell search I

1. **Find the most powerful carrier** in the operator spectrum
2. **PSS decoding** (62 sub-carrier in the middle of the band whatever the bandwidth) $\Rightarrow$ the PSS broadcasts a sequence among 3
3. **SSS decoding** $\Rightarrow$ the SSS broadcasts 2 pseudo-random sequences of 62 bits on slots 0 and 10, there are 168 possible pairs
4. **Radio quality evaluation** using RSs $\Rightarrow$ the UE is synchronized if the quality is sufficient ; the transmitted sequence and the position of the RSs in the frame depend on the PCI so that RSs from neighboring cells do not interfere

Cell search II

5 **PBCH decoding** $\Rightarrow$ MIB (Master Information Block), antenna configuration : the position of the PBCH does not depend on the bandwidth, it is scrambled by a sequence that depends on the PCI
The MIB includes :
   - the bandwidth (in # of RBs)
   - PHICH parameters
   - the frame number

6 **PCFICH decoding** $\Rightarrow$ Number of OFDM symbols dedicated to PDCCHs

7 **PDCCH decoding** $\Rightarrow$ DCI message (with SI-RNTI address) giving the location of the SIB1 in the PDSCH

8 **SIB1 decoding** $\Rightarrow$ scheduling of other SIBs

9 SIBs (System Information Block) are received on the PDSCH

Cell search III

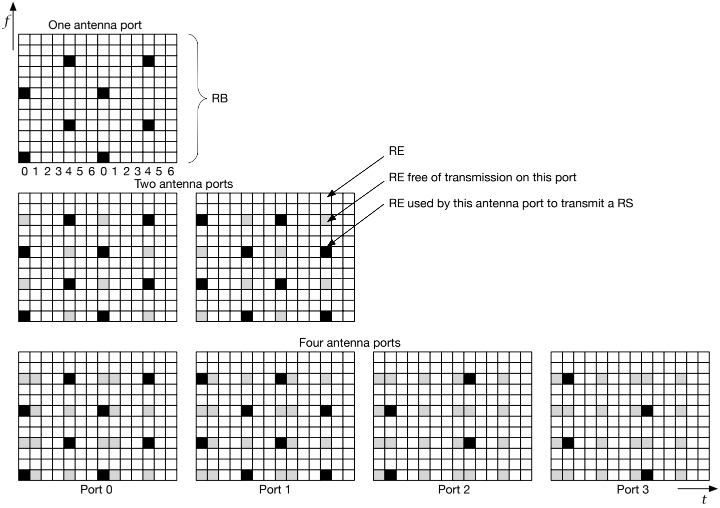

Figure : Reference signals (from [1]).

Section 5

How to access the network ?

Objectives

- Objectives :
  - Establishment or re-establishment of the RRC connection
  - Intra-system handovers
  - Upon arrival of DL or UL data whereas the UE has lost its synchronization with the network
- 2 random access types : contention-based / conflict-free
  - Contention-based access : can be used in all cases
  - Conflict-free access : for handovers or upon arrival of DL data
- PRACH transmission on the uplink then transmission of a CCCH message signaling the reason of the access

Uplink physical channels I

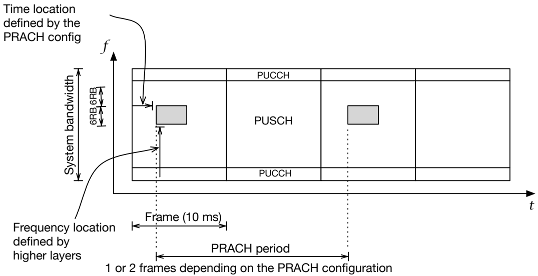

Figure : Position of the PRACH, PUSCH and PUCCH in the LTE frame.

Uplink physical channels II

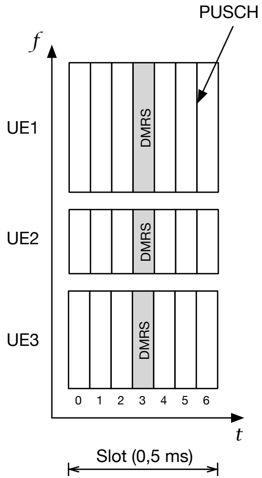

Figure : DMRS during a PUSCH transmission (from [1]).

Transport and logical channels

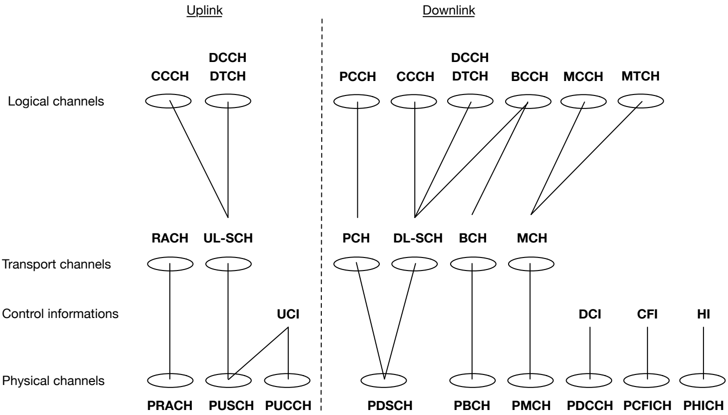

Figure : Mapping between physical, transport and logical channels.

Contention-based access I

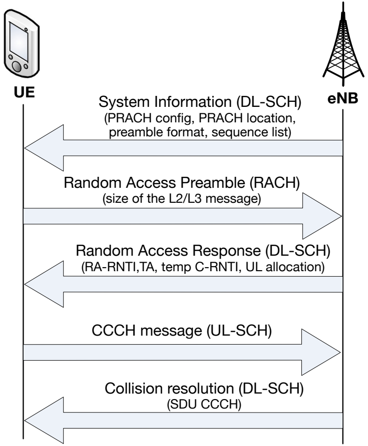

Figure : Contention-based access in LTE.

Contention-based access II

1) The UE obtains from SIB the PRACH configuration, the PRACH frequency location, the preamble format, the target received power and the list of sequences to be used (64 Zadoff-Chu sequences including those reserved to the conflict-free access)
3) The UE chooses at random one sequence among those available
4) It sends the preamble on the PRACH with an open loop power control : the UE tries to compensate the path-loss by using measurements made on DL RSs $\Rightarrow$ power control makes sequence detection easier at the BS
   - *Collision* : several UEs have used the same sequence on the same radio resource
   - *Capture* : the eNB manages to decode one of the messages in collision

Contention-based access III

5) If there is no answer from the network : *power ramping* (like in CDMA), i.e., the UE stepwise increases its transmit power
6) The RAR identifies the decoded preamble + provides the timing advance (TA) + gives an UL allocation + a temporary identity (temporary C-RNTI address)
7) CCCH message on the PUSCH = e.g. a RRC connection request + temporary C-RNTI
8) Collision resolution : the eNB sends a copy of the CCCH message on the DL. The UE that recognizes its message adopts the temporary C-RNTI (now its address), other UEs leave the procedure

Conflict-free access

- The UE has a valid identity (C-RNTI)
- The eNB sends a (DCI) message on the PDCCH including the Zadoff-Chu sequence to be used
- Collisions are no more possible, no collision resolution phase

Timing advance I

- **Objective** : synchronize UL signals, maintain orthogonality between UEs of a given cell

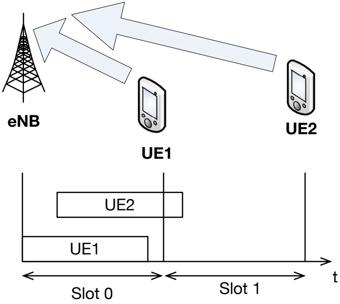

Figure : Timing advance issue.

Timing advance II

- First measurement during the access phase :
  - The eNB estimates the timing advance with the PRACH preamble
  - It sends an (absolute) command of 11 bits in the RAR (Random Access Response)
  - 11 bits allows an adjustment in the interval 0 to $0,67$ ms
  - The maximum value corresponds to a distance of 100 Km
- Regular updates (mobility, handover, inactivity period)
  - The eNB estimates the TA thanks to Sounding Reference Signals (SRS) and Channel Quality Indicators (CQI)
  - The eNB sends commands on the PDSCH 1 or 2 times per s
  - If an UE hasn't receive any command after some delay, it is considered as desynchronized and have to do a new random access

Section 6

How to send and receive data ?

Objectives

- **Objectives** :
  - Resource allocation : tell UEs on which radio resources they will receive data on the DL-SCH or on which resource they are allowed to transmit on the UL-SCH
  - UE scheduling : allocate RBs to UEs as a function of their demand and their radio conditions
  - Error control : ARQ and HARQ retransmissions
  - Measurement feedbacks : the UE tells the network the downlink channel radio quality or its preferred MIMO precoding matrix

Resource allocation I

- Location of resources in the sub-frame, modulation and coding scheme are signaled in Downlink Control Information (DCI) messages transmitted on the PDCCHs

Format	Description
0	Resource allocation on the PUSCH
1	PDSCH resource allocation in TM1, TM2, TM7
1A	PDSCH compact allocation and PRACH signature
1B	PDSCH resource allocation in TM6
1C	PDSCH very compact allocation
1D	PDSCH compact allocation in TM5
2	PDSCH compact allocation in TM4
2A	PDSCH compact allocation in TM3
3	Power control on PUCCH/PUSCH (2 bits)
3A	Power control on PUCCH/PUSCH (1 bit)

Table : DCI formats.

Resource allocation II

- DCI 0 = resource allocation on the PUSCH
- DCI 1 to 2A = resource allocation on the PDSCH
- TM1 (SIMO), TM2 (TxDiv) and TM7 (beamforming) do not require specific information from the transmitter $\Rightarrow$ DCI 1
- $\neq$ TM6 (rank 1 precoding, 1B), TM5 (MU-MIMO, 1D), TM3 et TM4 (spatial multiplexing, 2 et 2A)
- DCI 1A = allocation + PRACH sequence for conflict-free access
- DCI 1C = compact allocation (no MIMO, no HARQ info, QPSK modulation) $\Rightarrow$ random access response, SIB broadcasting or paging
- DCI 3 and 3A = power control commands for the UL

Resource allocation III

- DCI 0 example :
  - A flag to differentiate 1 and 1A
  - A flag for frequency hopping on the PUSCH
  - Resource block allocation
  - Modulation and coding scheme, redundancy version for HARQ
  - HARQ new transmission indicator
  - A power control command for the UL
  - Cyclic shift to be applied to ZC sequence for DMRS
  - A CQI request
- Every DCI includes a CRC scrambled with a RNTI identity
  - C-RNTI = to address a unique UE
  - P-RNTI = paging message
  - SI-RNTI = SIB
  - RA-RNTI = random access response

Scheduling I

- Fast (every 1 ms) and adaptive (modulation and coding are adapted to radio conditions) scheduling
- DL : scheduling decisions are based on CQI feedbacks, buffer status and priorities between logical channels
- UL : the UE has to feedback its buffer status and radio resource needs by using either the PUCCH (scheduling request) or the UL-SCH (MAC control messages)

Scheduling II

- Algorithm : LTE offers a new degree of freedom wrt HSPA : the possibility to schedule users on different radio blocks

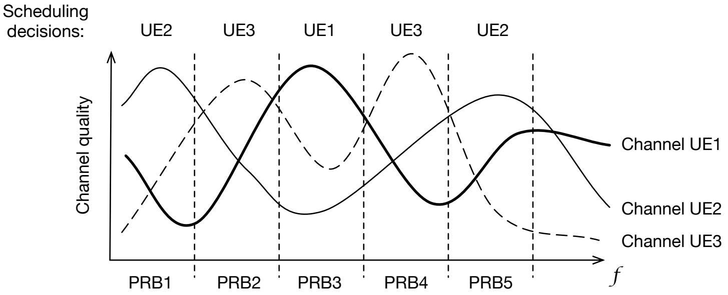

Figure : Frequency Dependent Packet Scheduling (FDPS) in LTE.

Scheduling III

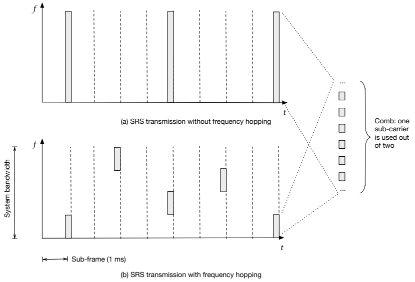

Figure : Sounding Reference Signals (SRS) transmissions.

- The eNB estimates the channel quality on the UL thanks to SRS
- SRS is transmitted on a bandwidth much larger than the one allocated to UE transmissions
- SRS from different UEs are multiplexed in time (different sub-frames and periods), frequency (different sets of RBs, odd/even sub-carriers) or code (different sequences)

ARQ and HARQ

- Like in HSPA, HARQ is in the MAC layer and ARQ in the RLC
- HARQ DL : sequence number is signaled in the PDCCH, ACK/NACK are fed back in the PUSCH (with data) or in the PUCCH
- HARQ UL : ACK/NACK transmitted in the PHICH
- ARQ : Transparent Mode (TM) (no header, no segmentation or concatenation), Unacknowledged (UM) (header with sequence number), Acknowledged (AM) (ARQ)

Measurements

- Radio quality measurements :
  - **CQI** (Channel Quality Indicator) : modulation (QPSK, 16-QAM or 64-QAM) and transport block maximum size that a UE can receive with a BLER<10% (Block Error Rate)
  - **RI** (Rank Indicator) : rank of the DL transmission = number of independent spatial layers that can be used
  - **PMI** (Precoding Matrix Indicator) : UE preferred precoding matrix W for transmission modes with closed loop
- Physical channels :
  - PUSCH : for aperiodic feedbacks with data transmission
  - PUCCH : for periodic feedbacks
- Periods :
  - **Aperiodic feedbacks** : measurement is requested by the network
  - **Periodic feedbacks** : the period is configured by higher layers

Section 7

Terminals categories

Terminals categories

Caracteristics	Cat. 1	Cat. 2	Cat. 3	Cat. 4	Cat. 5
Max. number of bits per TTI (DL)	10296	51024	102048	150752	299552
Max. number of bits per TTI (UL)	5160	25456	51024	51024	75376
Max data rate (DL)	10 Mbps	50 Mbps	100 Mbps	150 Mbps	300 Mbps
Max data rate (UL)	5 Mbps	25 Mbps	50 Mbps	50 Mbps	75 Mbps
64 QAM (UL)	No	No	No	No	Yes
MIMO (DL)	Option.	2×2	2×2	2×2	4×4

Table : Terminal categories in LTE.

- For example the Semsong S5 is cat. 4., the Semsong S6 is cat. 6 (Release 10, 300/50 Mbps)

Section 8

Summary on channels

Physical channels : DL I

- **PDSCH** (Physical Downlink Shared Ch.) : physical shared channel for data
- **RS** (Reference Signals) : pilots required to estimate radio quality and to allow decoding on the DL
- **SS** (Synchronization Signals) = PSS (Primary)+SSS (Secondary) : for time and frequency synchronization
- **PBCH** (Physical Broadcast Ch.) : beacon, MIB transmission
- **PCFICH** (Physical Control Format Indicator Ch.) : tell the UEs how many OFDM symbols are dedicated to the control part of the sub-frame (CFI)
- **PDCCH** (Physical Downlink Control Ch.) : control informations (DCI : resource allocation, UE identity, HARQ information, MIMO, etc)
- **PHICH** (Physical Hybrid ARQ Indicator Ch.) : ACK/NACK responses to HARQ transmissions from a UE (HI)

Physical channels : UL I

- In UL, a UE is not able to multiplex different physical channels in the frequency domain because of SC-FDMA limitation ⇒ time multiplexing is required
- **DMRS** (Demodulation Reference Signal) : used by the eNB to estimate the channel and make radio quality measurements on the signal transmitted by the UE. DMRS are sent in conjunction with PUCCH and PUSCH
- **SRS** (Sounding Reference Signal) : pilots used by the scheduler for the radio quality estimation on a bandwidth larger than the one allocated to the UE
- **PUCCH** (Physical Uplink Control Ch.) : control informations UCI including channel quality (CQI), MIMO (closed loop) or HARQ (ACK/NACK) informations
- **PUSCH** (Physical Uplink Shared Ch.) : shared physical channels for data and control
- If a UE has data to transmit, it uses the PUSCH for data and control. Otherwise, it uses the PUCCH for the control.

Transport channels : DL

- **DL-SCH** (DL Shared Ch.) : shared channel for data associated to PDSCH
- **PCH** (Paging Ch.) : broadcast of paging messages on the PDSCH
- **BCH** (Broadcast Ch.) : broadcast of system informations (SIBs) on the PBCH and on the PDSCH
- **DCI** (DL Control Indicator) : control information transmitted on the PDCCHs (transport format, resource allocation, HARQ and MIMO informations, power control commands)
- **CFI** (Control Format Indicator) : number of OFDM symbols (1,2 or 3) used by PDCCHs at the beginning of every sub-frame. CFI is sent on the PCFICH
- **HI** (HARQ Indicator) : ACK or NACK in response to a transmission on the UL-SCH. HI is transmitted on the PHICH

transport channels : UL

- **RACH** (Random Access Ch.) : random access
- **UL-SCH** (UL Share Ch.) : shared channel for data and control associated to PUSCH. User data and control informations are multiplexed in time and frequency on the PUSCH
- **UCI** (UL Control Indicator) : control information transmitted by the PUCCH (channel quality CQI, closed loop MIMO informations PMI/RI, ACK/NACK of HARQ, scheduling request)

Logical channels

Logical channel	Type	Description	Link
BCCH	Control	System information	DL
PCCH	Control	*Paging*	DL
CCCH	Control	Control without RRC conn.	UL/DL
DCCH	Contrôle	Dedicated control	UL/DL
DTCH	Traffic	user plane	UL/DL

Table : Logical channels in LTE DL and UL.

- **BCCH** (Broadcast COntrol Ch.) : system information, associated to BCH for the MIB and DL-SCH for the SIBs
- **PCCH** (Paging Control Ch.) : paging, associated to PCH
- **CCCH** (Common Control Ch.) : control messages between the network and UEs **without** RRC connection, associated to DL-SCH and UL-SCH
- **DCCH** (Dedicated Control Ch.) : control messages between the network and UEs **with** RRC connection, associated to DL-SCH and UL-SCH

Section 9

Conclusion

Conclusion

LTE :

- A brand new standard
- A certain simplicity that is reminiscent of GSM
- Similarities with 3G (channels, HARQ, MAC, RLC, etc)
- New features (MIMO, MU-MIMO, multi-carrier transmissions)

After LTE, LTE-A :

- R12 frozen in March 2015, R13 on going
- Peak rates of the order of 1Gbps
- Carrier aggregation, discontinuous resource allocation on the UL, MIMO 8$\times$8, relays, HetNets, CoMP, Self-Organized Networks, MBMS, M2M, etc.

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