Technical Overview of 3GPP LTE

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Cellular Wireless System Evolution

- 1G (Early 1980s)
  - Analog speech communications.
  - Analog FDMA.
  - Ex: AMPS
- 2G (Early 1990s)
  - Digital modulation of speech communications.
  - Advanced security and roaming.
  - TDMA and narrowband CDMA.
  - Ex: GSM, IS-95 (cdmaOne), and PDC
- 3G (Late 1990s)
  - Global harmonization and roaming.
  - Wideband CDMA
  - Ex: UMTS, cdma2000, and TD-SCDMA

Beyond 3G

- International Mobile Telecommunications (IMT)-2000 introduced global standard for 3G.
- Systems beyond IMT-2000 (IMT-Advanced) is set to introduce evolutionary path beyond 3G.
  - Mobile class targets 100 Mbps with high mobility and nomadic/ local area class targets 1 Gbps with low mobility.
- 3GPP and 3GPP2 are currently developing evolutionary/ revolutionary systems beyond 3G.
  - 3GPP Long Term Evolution (LTE)
  - 3GPP2 Ultra Mobile Broadband (UMB)
- IEEE 802.16-based WiMAX is also evolving towards 4G through 802.16m.

3GPP Evolution

- Release 99 (Mar. 2000): UMTS/WCDMA
- Rel-5 (Mar. 2002): HSDPA
- Rel-6 (Mar. 2005): HSUPA
- Rel-7 (2007): DL MIMO, IMS (IP Multimedia Subsystem), optimized real-time services (VoIP, gaming, push-to-talk).
- Long Term Evolution (LTE)
  - 3GPP work on the Evolution of the 3G Mobile System started in November 2004.
  - Standardized in the form of Rel-8.
  - Spec finalized and approved in January 2008.
  - Target deployment in 2010.
  - LTE-Advanced study phase in progress.

3GPP2 Evolution

- CDMA2000 1X (1999)
- CDMA2000 1xEV-DO (2000)
- EV-DO Rev. A (2004): VoIP
- EV-DO Rev. B (2006): Multi-carrier
- Ultra Mobile Broadband (UMB), f.k.a. EV-DO Rev. C
  - Based on EV-DO, IEEE 802.20, and FLASH-OFDM
  - Spec finalized in April 2007.
  - Commercially available in early 2009.

IEEE 802.16 Evolution

- 802.16 (2002): Line-of-sight fixed operation in 10 to 66 GHz
- 802.16a (2003): Air interface support for 2 to 11 GHz
- 802.16d (2004): Minor improvements to fixes to 16a
- 802.16e (2006): Support for vehicular mobility and asymmetrical link
- 802.16m (in progress): Higher data rate, reduced latency, and efficient security mechanism

Requirements of LTE

- Peak data rate
  - 100 Mbps DL/ 50 Mbps UL within 20 MHz bandwidth.
- Up to 200 active users in a cell (5 MHz)
- Less than 5 ms user-plane latency
- Mobility
  - Optimized for 0 ~ 15 km/h.
  - 15 ~ 120 km/h supported with high performance.
  - Supported up to 350 km/h or even up to 500 km/h.
- Enhanced multimedia broadcast multicast service (E-MBMS)
- Spectrum flexibility: 1.25 ~ 20 MHz
- Enhanced support for end-to-end QoS

LTE Enabling Technologies

- OFDM (Orthogonal Frequency Division Multiplexing)
- Frequency domain equalization
- SC-FDMA (Single Carrier FDMA)
- MIMO (Multi-Input Multi-Output)
- Multicarrier channel-dependent resource scheduling
- Fractional frequency reuse

LTE Enabling Technologies

– cont.

- Single Carrier FDMA (SC-FDMA)
  - SC-FDMA is a new single carrier multiple access technique which has similar structure and performance to OFDMA.
    - Utilizes ***single carrier modulation*** and ***orthogonal frequency multiplexing*** using ***DFT-spreading*** in the transmitter and ***frequency domain equalization*** in the receiver.
  - A salient advantage of SC-FDMA over OFDM/OFDMA is low PAPR.
    - Efficient transmitter and improved cell-edge performance.
  - H. G. Myung *et al.*, "Single Carrier FDMA for Uplink Wireless Transmission," *IEEE Vehic. Tech. Mag.*, vol. 1, no. 3, Sep. 2006
  - A comprehensive tutorial available at http://hgmyung.googlepages.com/scfdma.pdf.

Key Features of LTE

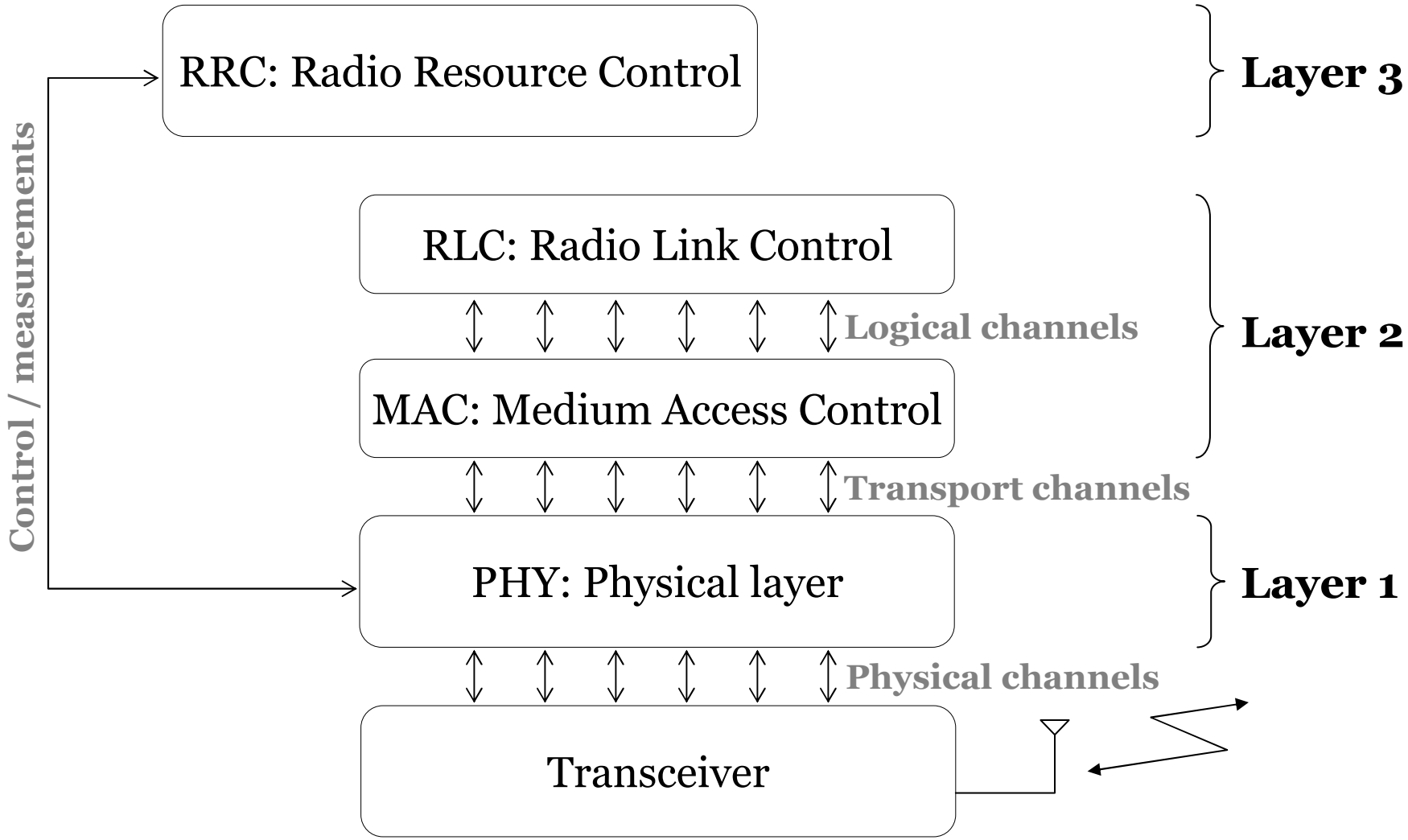
- Multiple access scheme
  - DL: OFDMA with CP.
  - UL: Single Carrier FDMA (SC-FDMA) with CP.
- Adaptive modulation and coding
  - DL/UL modulations: QPSK, 16QAM, and 64QAM
  - Convolutional code and Rel-6 turbo code
- Advanced MIMO spatial multiplexing techniques
  - (2 or 4)x(2 or 4) downlink and uplink supported.
  - Multi-user MIMO also supported.
- Support for both FDD and TDD
- H-ARQ, mobility support, rate control, security, and etc.

LTE Standard Specifications

- Freely downloadable from http://www.3gpp.org/ftp/Specs/html-info/36-series.htm

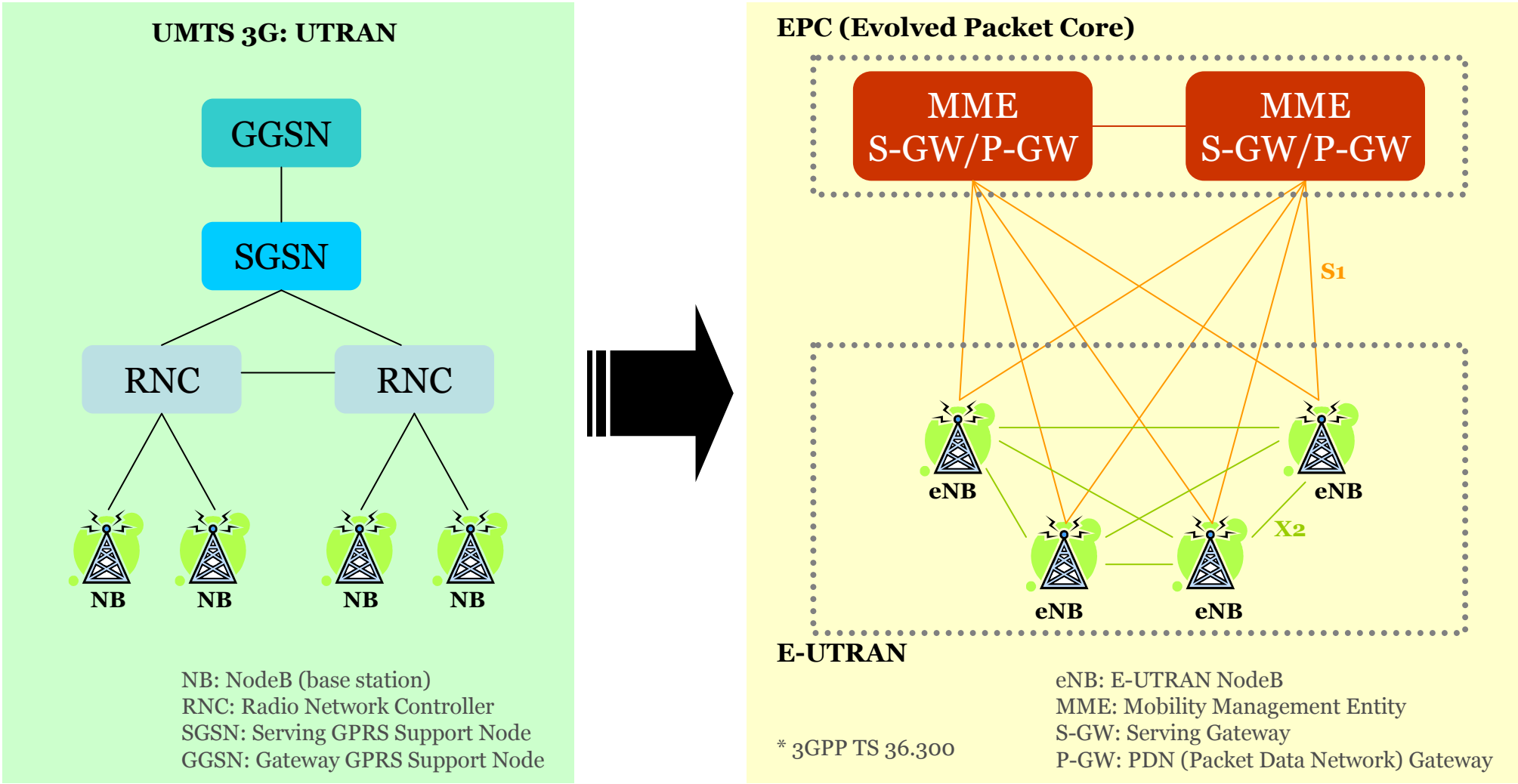
Specification index	Description of contents
TS 36.1xx	Equipment requirements: Terminals, base stations, and repeaters.
TS 36.2xx	Physical layer.
TS 36.3xx	Layers 2 and 3: Medium access control, radio link control, and radio resource control.
TS 36.4xx	Infrastructure communications (UTRAN = UTRA Network) including base stations and mobile management entities.
TS 36.5xx	Conformance testing.

Protocol Architecture



LTE Network Architecture

- E-UTRAN (Evolved Universal Terrestrial Radio Access Network)



LTE Network Architecture

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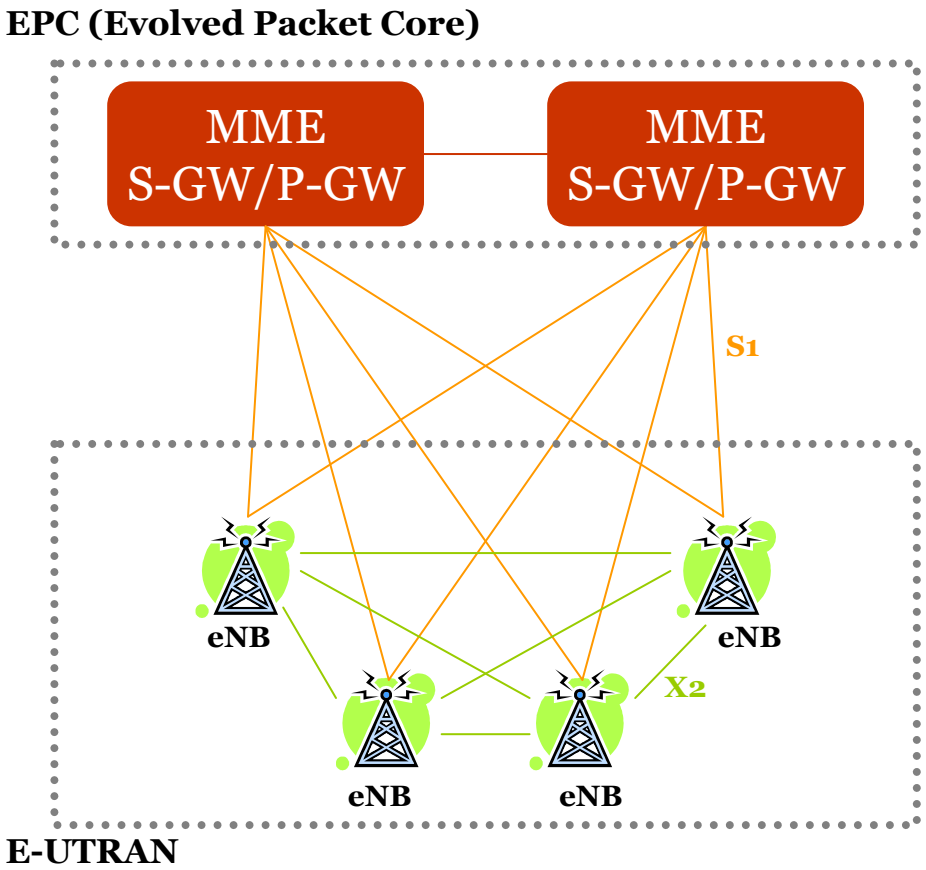
- eNB
  - All radio interface-related functions
- MME
  - Manages mobility, UE identity, and security parameters.
- S-GW
  - Node that terminates the interface towards E-UTRAN.
- P-GW
  - Node that terminates the interface towards PDN.



* 3GPP TS 36.300

eNB: E-UTRAN NodeB
MME: Mobility Management Entity
S-GW: Serving Gateway
P-GW: PDN (Packet Data Network) Gateway

LTE Network Architecture

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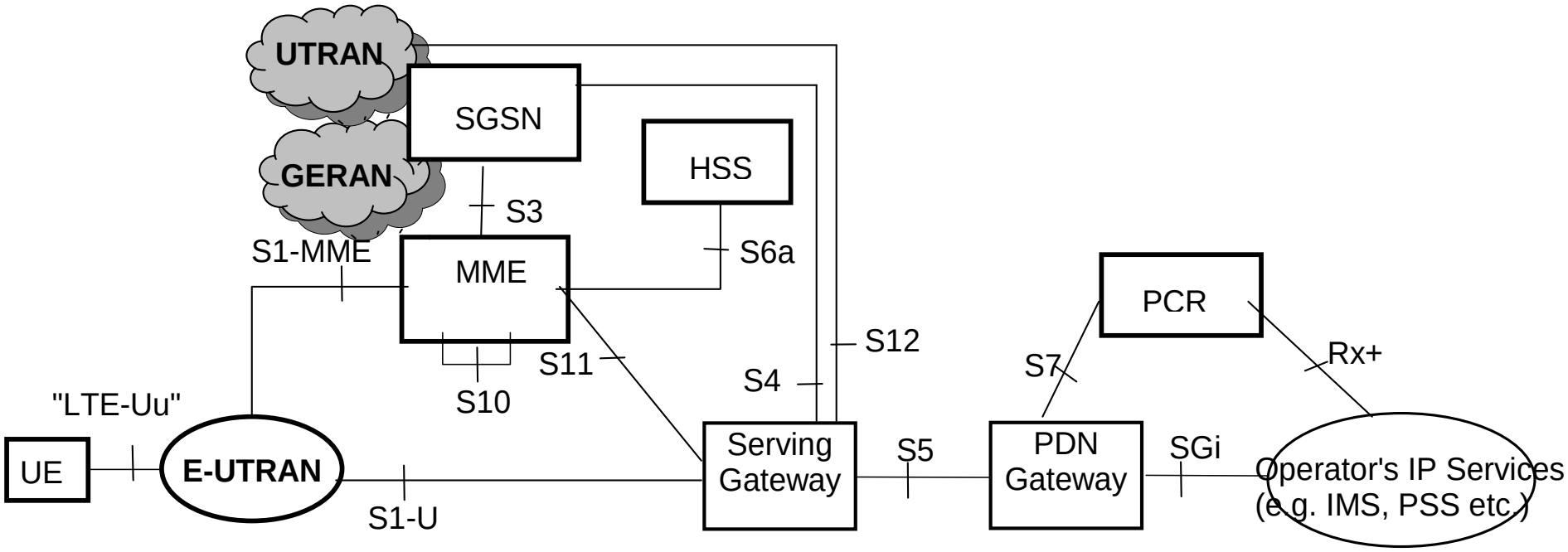
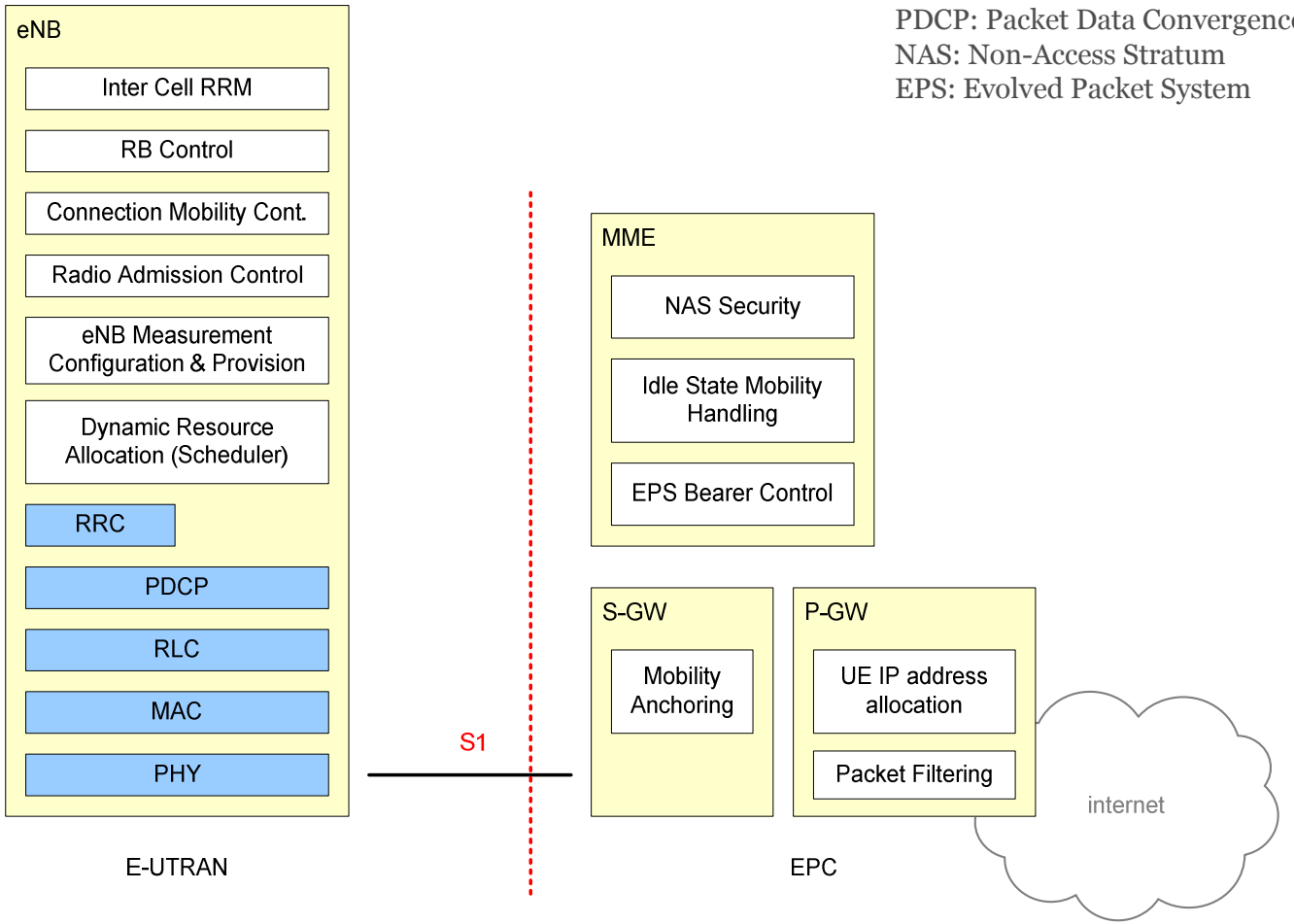


* Non-roaming architecture
* 3GPP TS 23.401

LTE Network Architecture

- cont.

RRM: Radio Resource Management
RB: Radio Bearer
RRC: Radio Resource Control
PDCP: Packet Data Convergence Protocol
NAS: Non-Access Stratum
EPS: Evolved Packet System



* 3GPP TS 36.300

LTE Network Architecture

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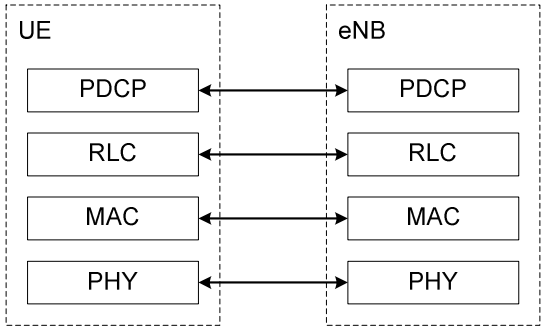
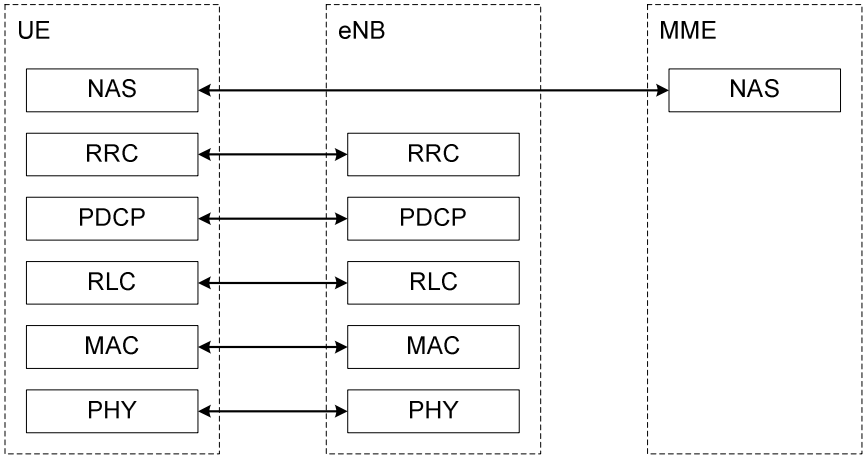
User-Plane Protocol Stack



Control-Plane Protocol Stack



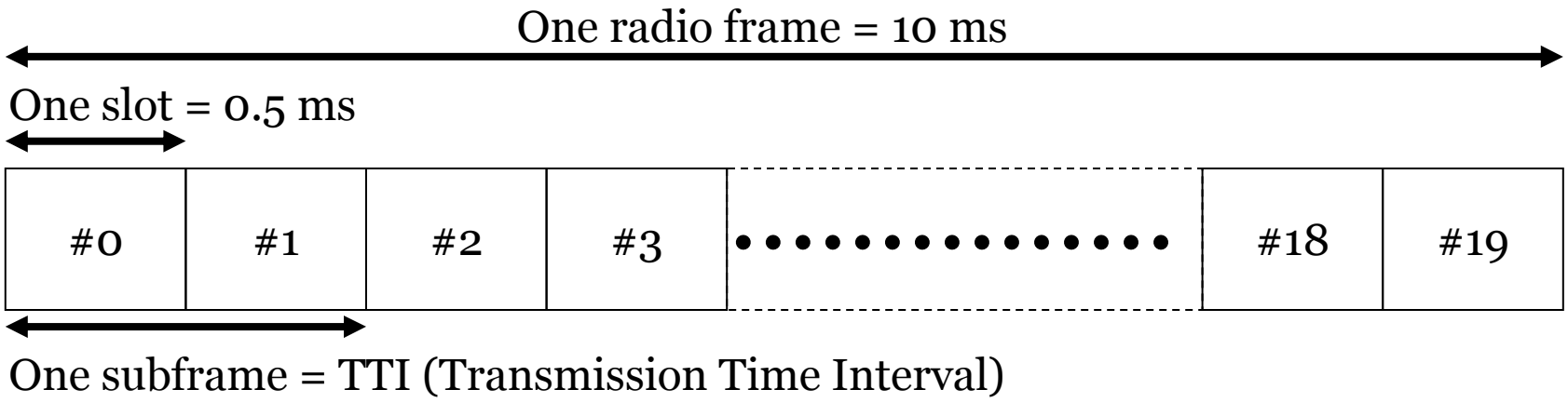
* 3GPP TS 36.300

Frame Structure

- Two radio frame structures defined.
  - Frame structure type 1 (FS1): FDD.
  - Frame structure type 2 (FS2): TDD.
- A radio frame has duration of 10 ms.
- A resource block (RB) spans 12 subcarriers over a slot duration of 0.5 ms. One subcarrier has bandwidth of 15 kHz, thus 180 kHz per RB.

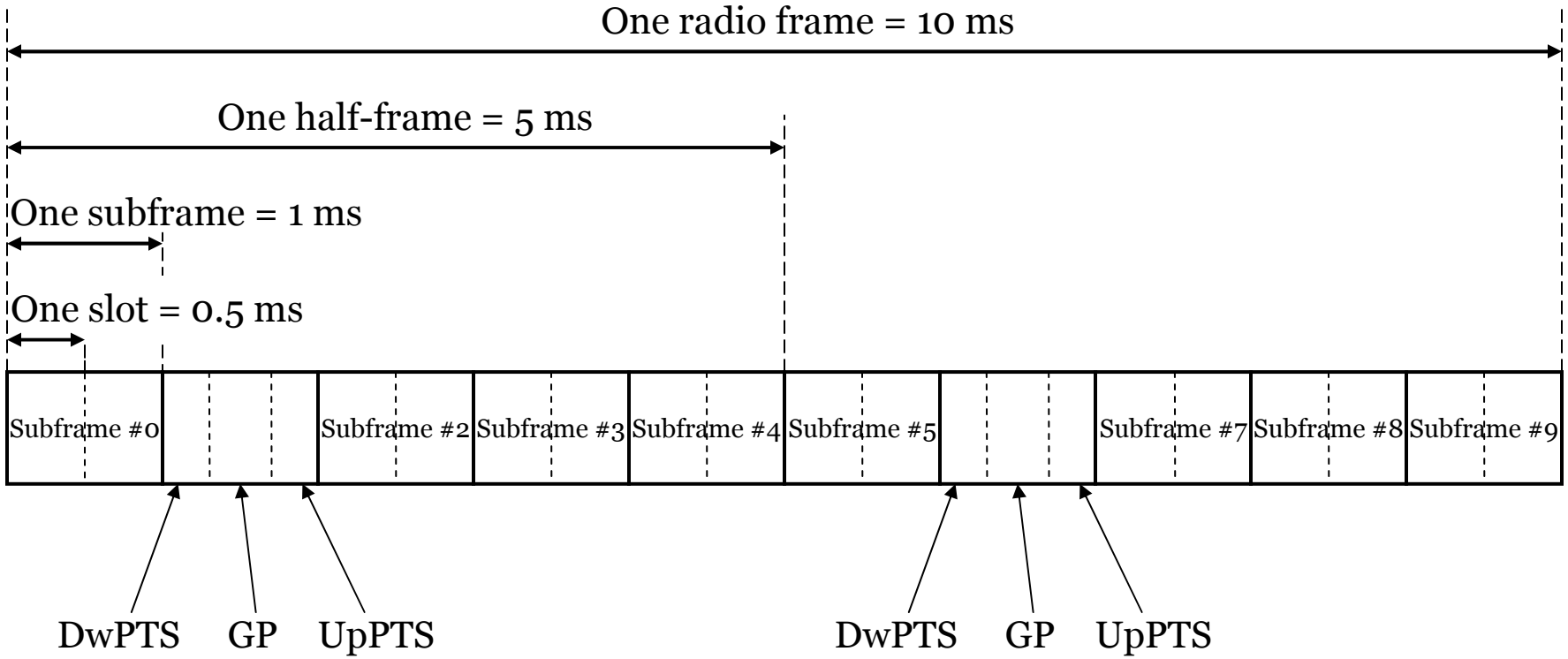
Frame Structure Type 1

- FDD frame structure

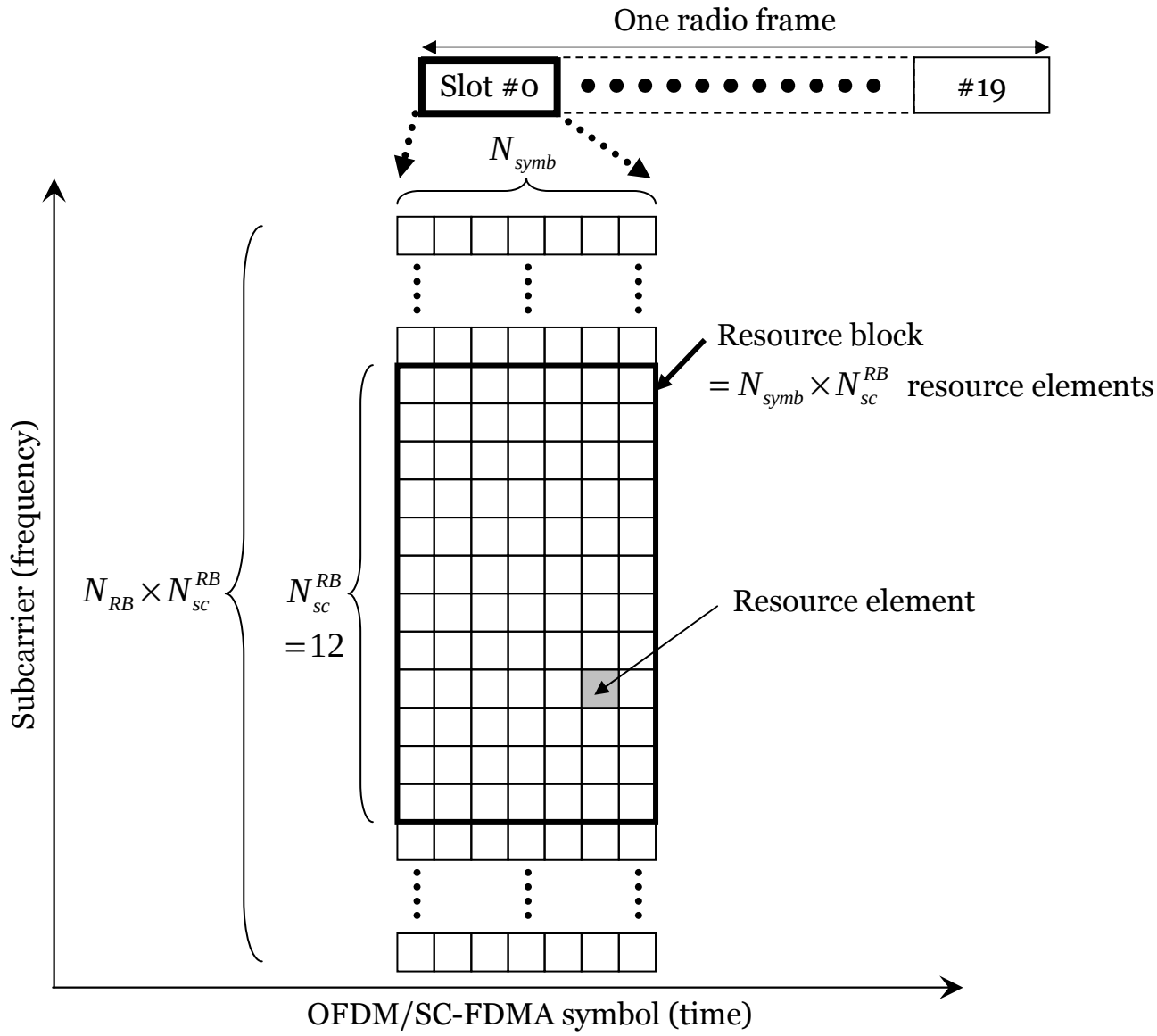


Frame Structure Type 2

- TDD frame structure



Resource Grid



Length of CP

Configuration	N_{symb}
Normal CP	7
Extended CP	6
Extended CP (Δf = 7.5 kHz)†	3

Configuration	CP length $N_{CP,l}$ [samples]
Normal CP	160 (≈ 5.21 μs) for l = 0 144 (≈ 4.69 μs) for l = 1, 2, …, 6
Extended CP	512 (≈ 16.67 μs) for l = 0, 1, …, 5
Extended CP (Δf = 7.5 kHz) †	1024 (≈ 33.33 μs) for l = 0, 1, 2

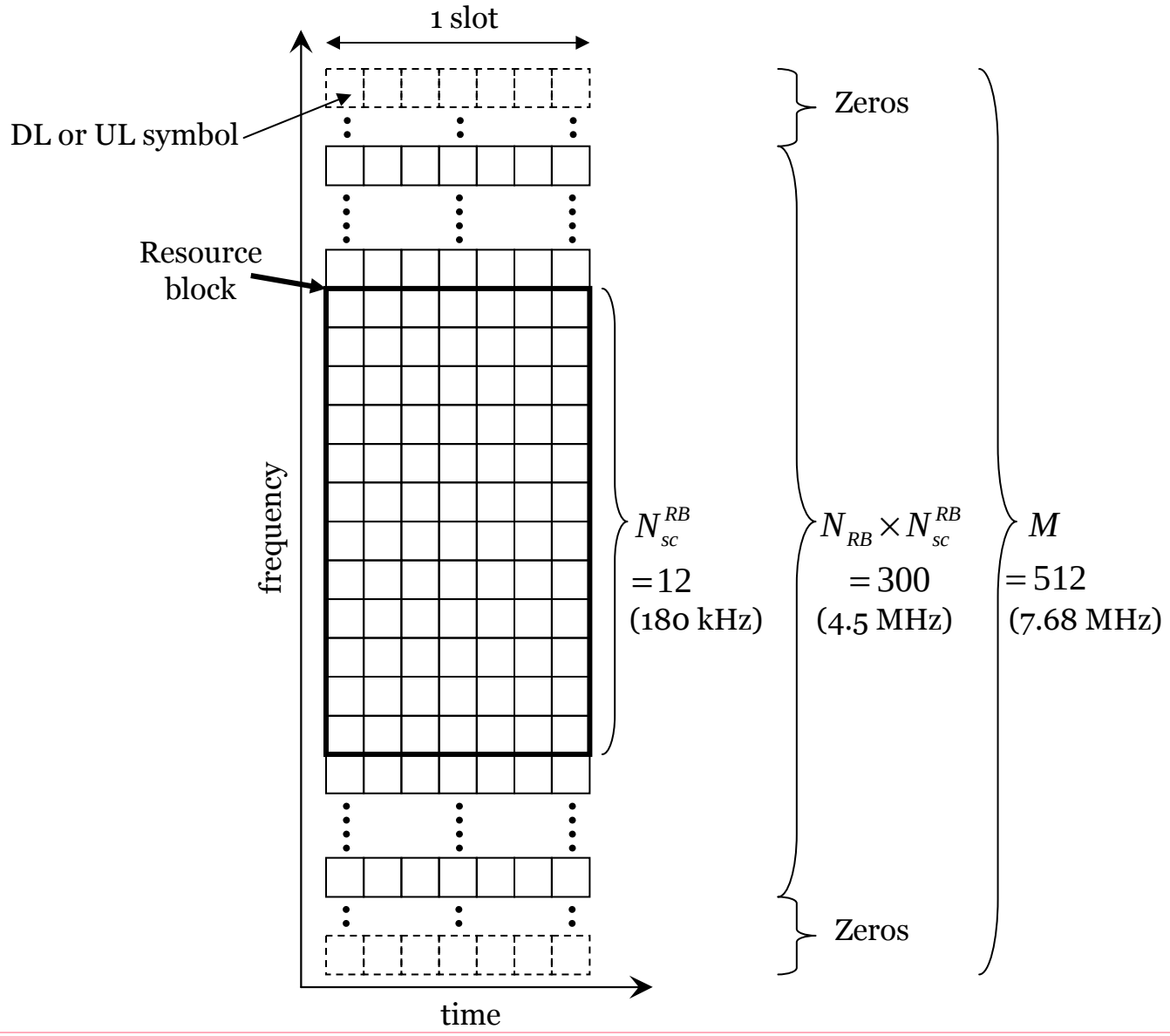
† Only in downlink

LTE Bandwidth/Resource Configuration

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

Bandwidth Configuration



* 5 MHz system with frame structure type 1

LTE Physical Channels

- DL
  - Physical Broadcast Channel (PBCH)
  - Physical Control Format Indicator Channel (PCFICH)
  - Physical Downlink Control Channel (PDCCH)
  - Physical Hybrid ARQ Indicator Channel (PHICH)
  - Physical Downlink Shared Channel (PDSCH)
  - Physical Multicast Channel (PMCH)
- UL
  - Physical Uplink Control Channel (PUCCH)
  - Physical Uplink Shared Channel (PUSCH)
  - Physical Random Access Channel (PRACH)

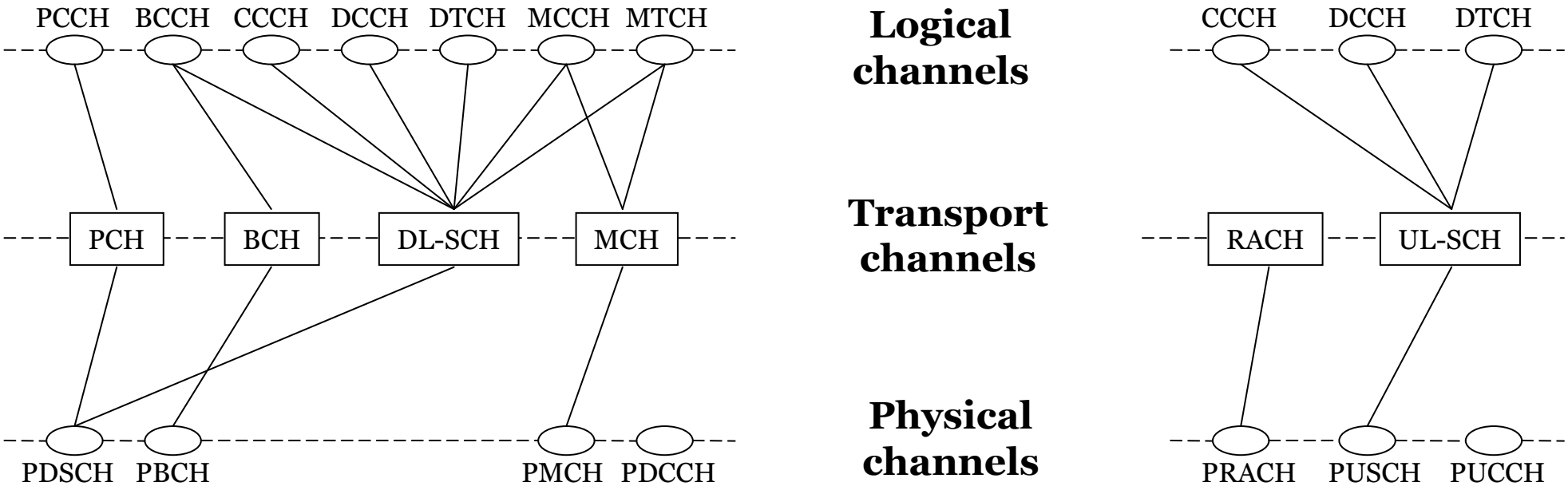
LTE Transport Channels

- Physical layer transport channels offer information transfer to medium access control (MAC) and higher layers.
- DL
  - Broadcast Channel (BCH)
  - Downlink Shared Channel (DL-SCH)
  - Paging Channel (PCH)
  - Multicast Channel (MCH)
- UL
  - Uplink Shared Channel (UL-SCH)
  - Random Access Channel (RACH)

LTE Logical Channels

- Logical channels are offered by the MAC layer.
- Control Channels: Control-plane information
  - Broadcast Control Channel (BCCH)
  - Paging Control Channel (PCCH)
  - Common Control Channel (CCCH)
  - Multicast Control Channel (MCCH)
  - Dedicated Control Channel (DCCH)
- Traffic Channels: User-plane information
  - Dedicated Traffic Channel (DTCH)
  - Multicast Traffic Channel (MTCH)

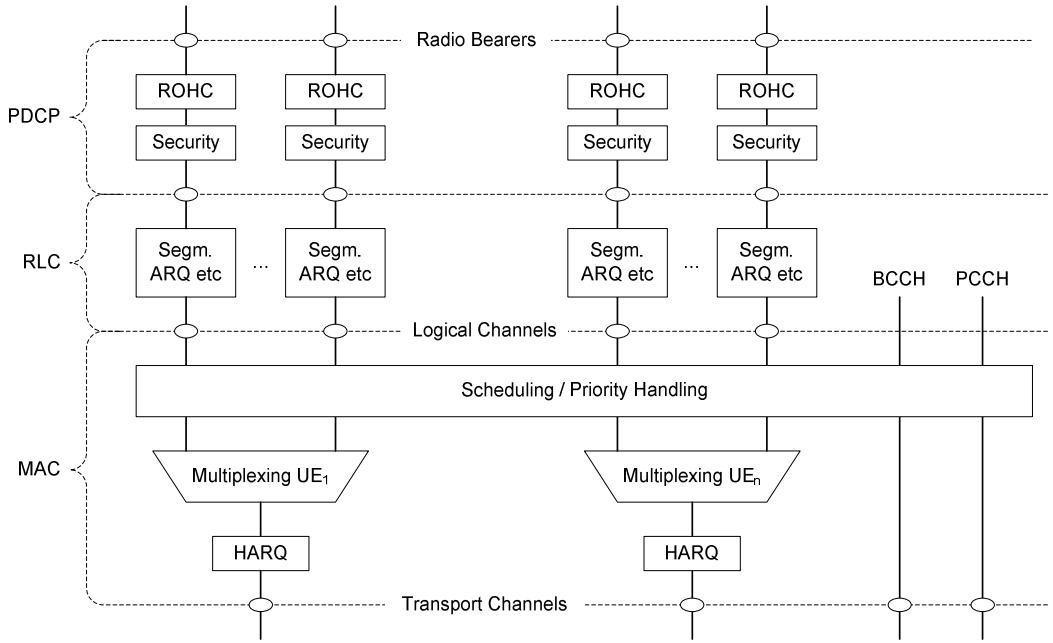
Channel Mappings



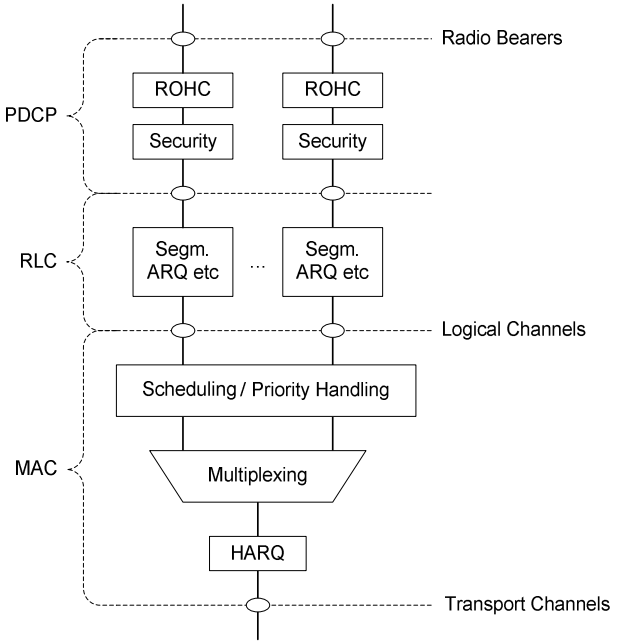
Downlink ***Uplink***

LTE Layer 2

- Layer 2 has three sublayers
  - MAC (Medium Access Control)
  - RLC (Radio Link Control)
  - PDCP (Packet Data Convergence Protocol)



DL



UL

ROHC: Robust Header Compression

* 3GPP TS 36.300

RRC Layer

- Terminated in eNB on the network side.
- Functions
  - Broadcast
  - Paging
  - RRC connection management
  - RB (Radio Bearer) management
  - Mobility functions
  - UE measurement reporting and control
- RRC states
  - RRC_IDLE
  - RRC_CONNECTED

Resource Scheduling of Shared Channels

- Dynamic resource scheduler resides in eNB on MAC layer.
- Radio resource assignment based on radio condition, traffic volume, and QoS requirements.
- Radio resource assignment consists of:
  - Physical Resource Block (PRB)
  - Modulation and Coding Scheme (MCS)

Radio Resource Management

- Radio bearer control (RBC)
- Radio admission control (RAC)
- Connection mobility control (CMC)
- Dynamic resource allocation (DRA) or packet scheduling (PS)
- Inter-cell interference coordination (ICIC)
- Load balancing (LB)

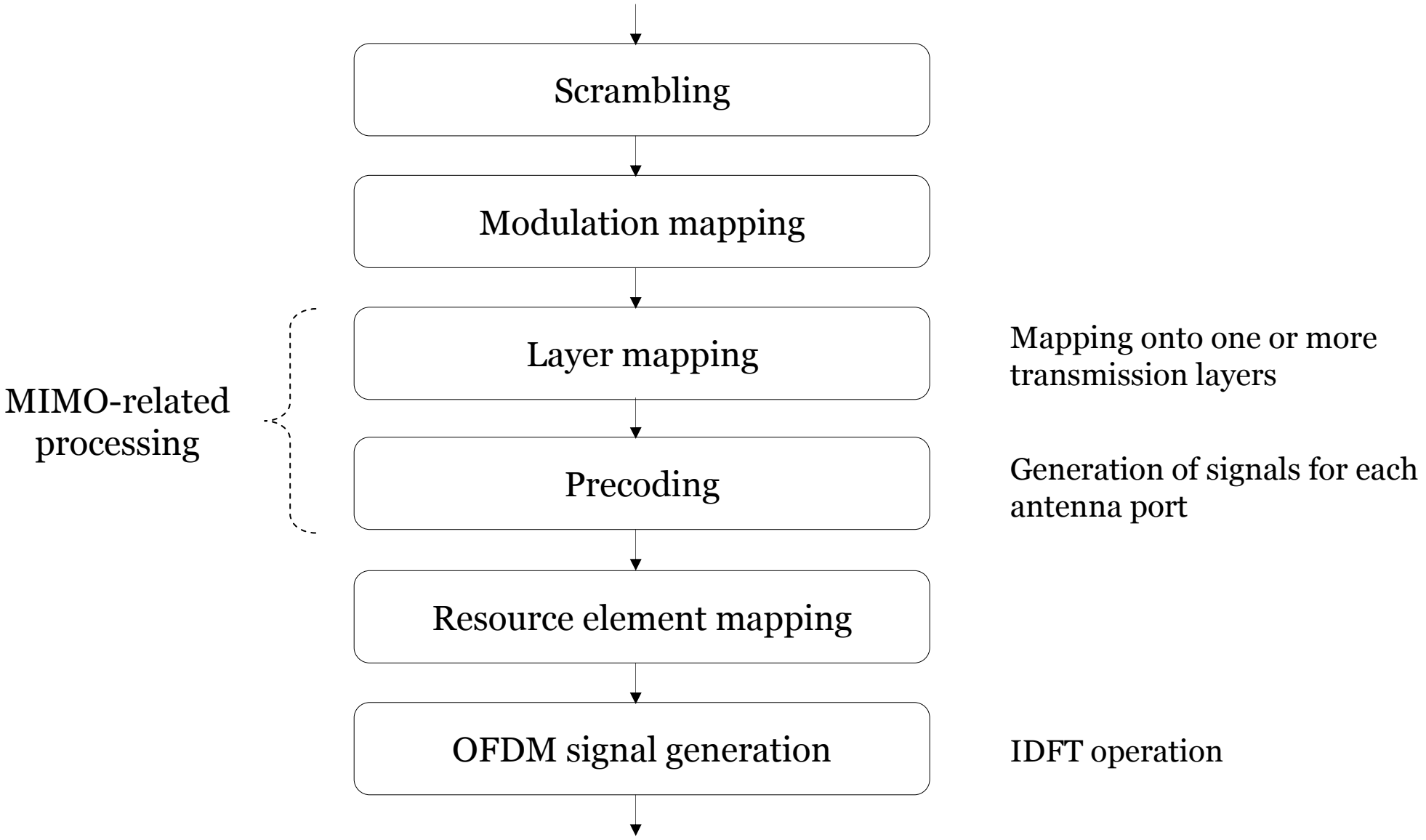
Other Features

- ARQ (RLC) and H-ARQ (MAC)
- Mobility
- Rate control
- DRX (Discontinuous Reception)
- MBMS
- QoS
- Security

DL Overview

- DL physical channels
  - Physical Broadcast Channel (PBCH)
  - Physical Control Format Indicator Channel (PCFICH)
  - Physical Downlink Control Channel (PDCCH)
  - Physical Hybrid ARQ Indicator Channel (PHICH)
  - Physical Downlink Shared Channel (PDSCH)
  - Physical Multicast Channel (PMCH)
- DL physical signals
  - Reference signal (RS)
  - Synchronization signal
- Available modulation for data channel
  - QPSK, 16-QAM, and 64-QAM

DL Physical Channel Processing



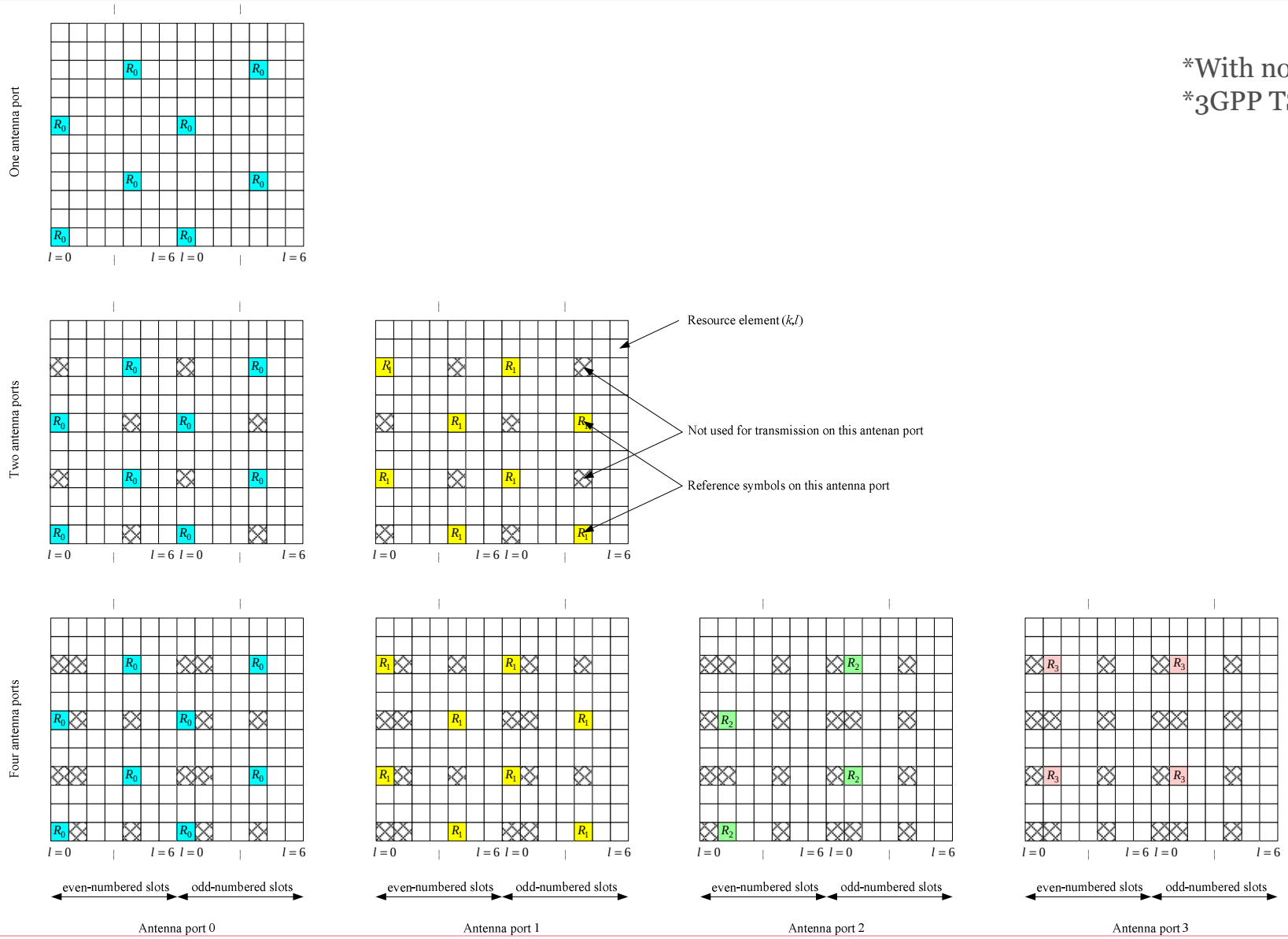
DL Reference Signal

- Cell-specific 2D RS sequence is generated as the symbol-by-symbol product of a 2D orthogonal sequence (OS) and a 2D pseudo-random sequence (PRS).
  - 3 different 2D OS and ~170 different PRS.
  - Each cell (sector) ID corresponds to a unique combination of one OS and one PRS ⇒ ~510 unique cell IDs.
- CDM of RS for cells (sectors)of the same eNodeB (BS)
  - Use complex orthogonal spreading codes.
- FDM of RS for each antenna in case of MIMO

DL Reference Signal

- cont.

*With normal CP
*3GPP TS 36.211



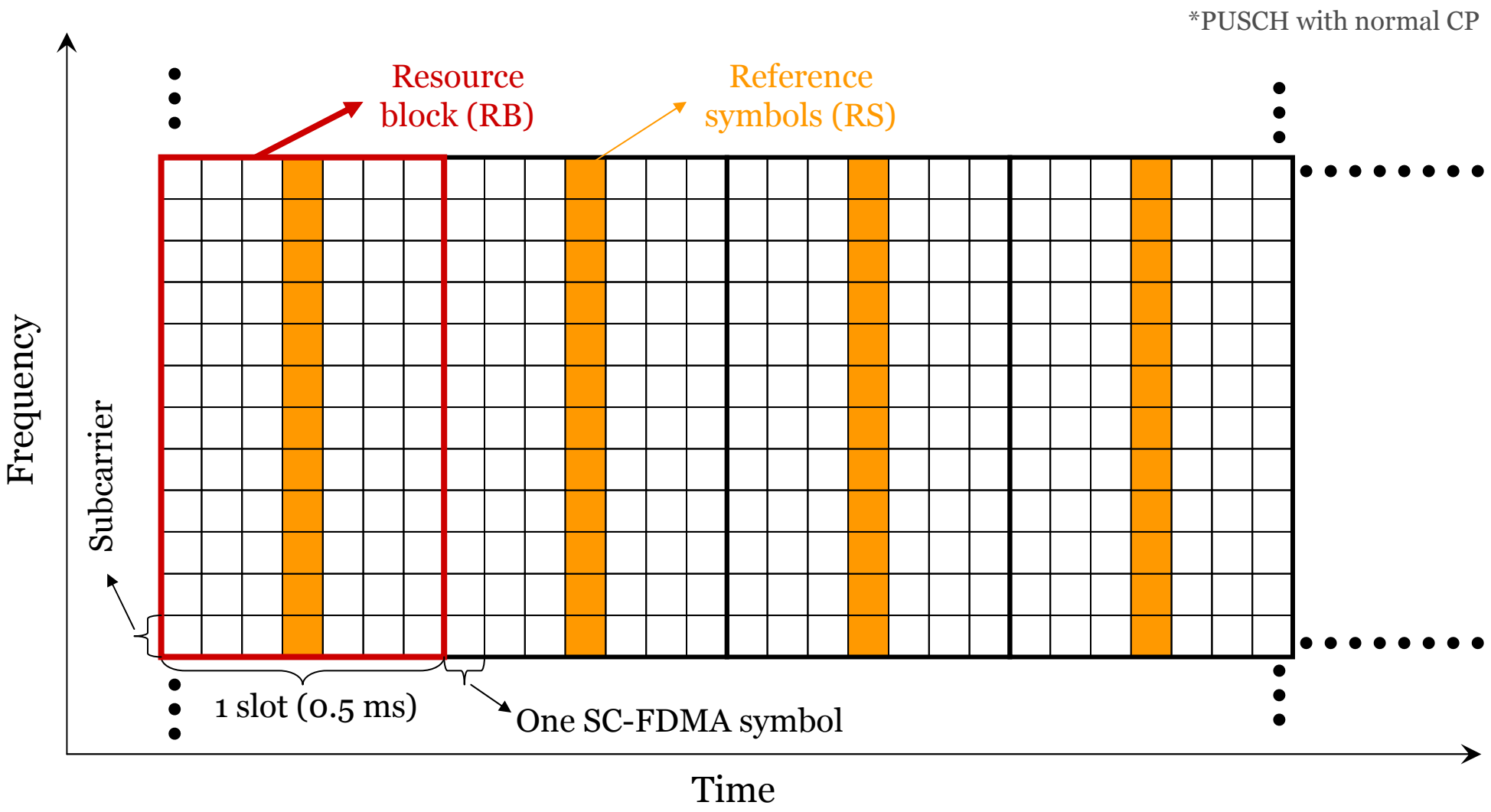
DL MIMO

- Supported up to 4x4 configuration.
- Support for both spatial multiplexing (SM) and Tx diversity (TxD)
  - SM
    - Unitary precoding based scheme with codebook based feedback from user.
    - Multiple codewords
  - TxD: SFBC/STBC, switched TxD, CDD (Cyclic Delay Diversity) considered.
- MU-MIMO supported.

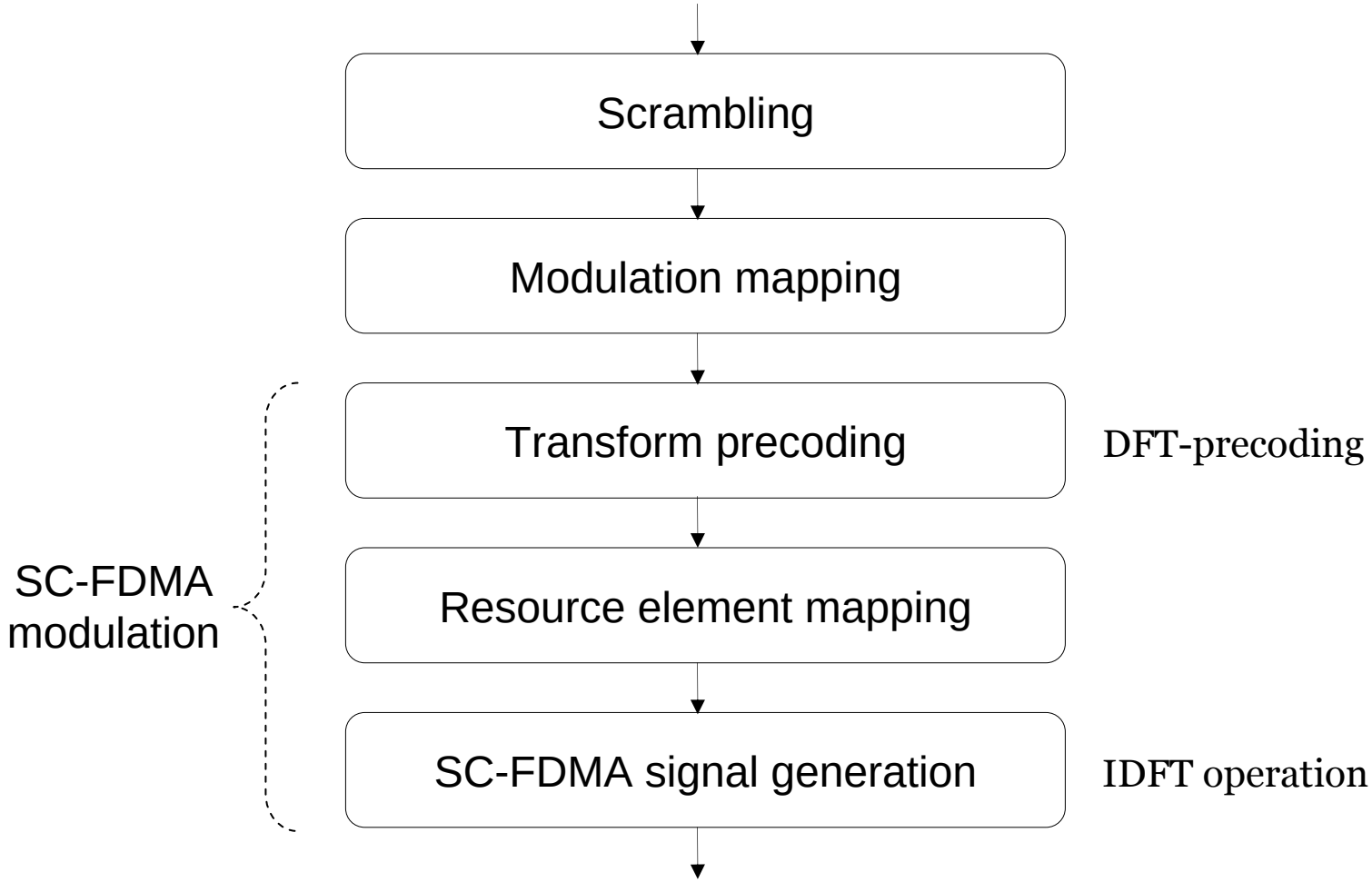
UL Overview

- UL physical channels
  - Physical Uplink Shared Channel (PUSCH)
  - Physical Uplink Control Channel (PUCCH)
  - Physical Random Access Channel (PRACH)
- UL physical signals
  - Reference signal (RS)
- Available modulation for data channel
  - QPSK, 16-QAM, and 64-QAM
- Single user MIMO not supported in current release.
  - But it will be addressed in the future release.
  - Multi-user collaborative MIMO supported.

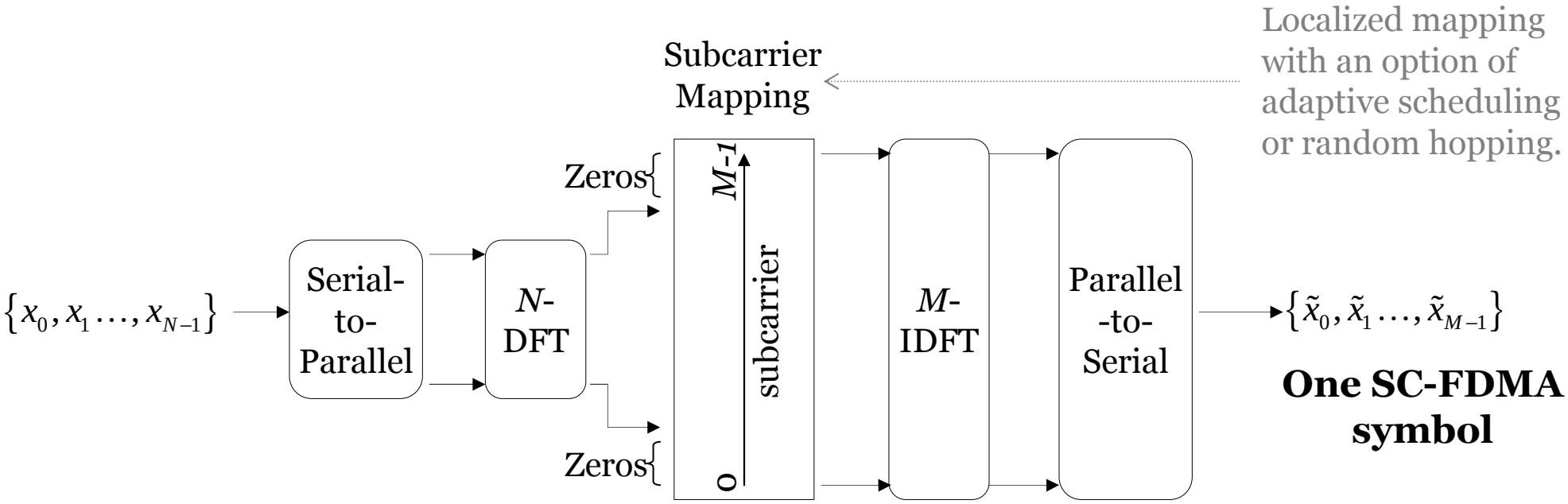
UL Resource Block



UL Physical Channel Processing



SC-FDMA Modulation in LTE UL



UL Reference Signal

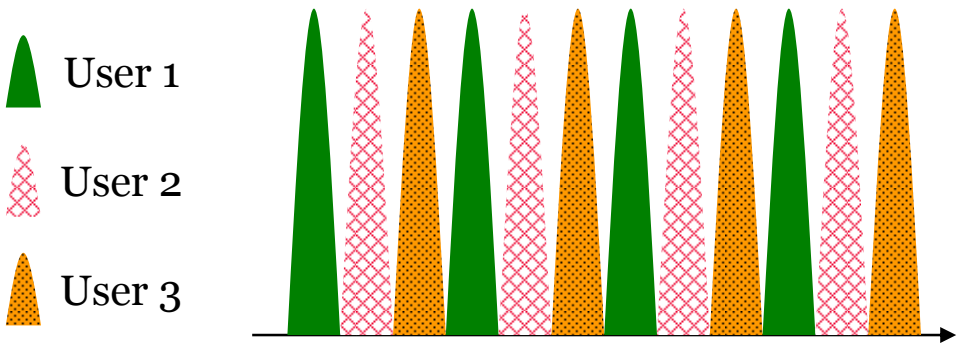
- Two types of UL RS
  - Demodulation (DM) RS ⇒ Narrowband.
  - Sounding RS: Used for UL resource scheduling ⇒ Broadband.
- RS based on Zadoff-Chu CAZAC (Constant Amplitude Zero Auto-Correlation) polyphase sequence
  - CAZAC sequence: Constant amplitude, zero circular auto-correlation, flat frequency response, and low circular cross-correlation between two different sequences.

$$a_k = \begin{cases} e^{-j2\pi\frac{r}{L}\left(\frac{k^2}{2}+qk\right)}, & k=0,1,2,\cdots,L-1; \text{ for } L \text{ even} \\ e^{-j2\pi\frac{r}{L}\left(\frac{k(k+1)}{2}+qk\right)}, & k=0,1,2,\cdots,L-1; \text{ for } L \text{ odd} \end{cases}$$

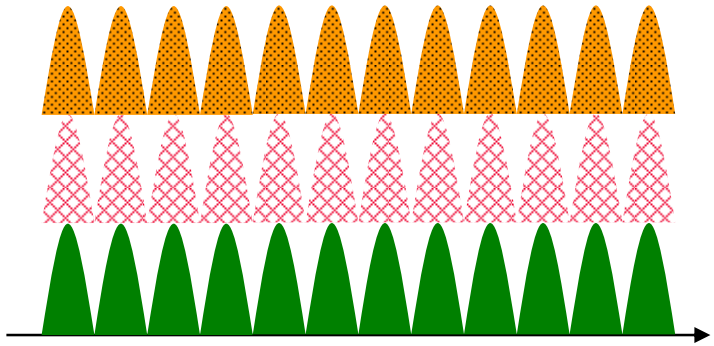
* r is any integer relatively prime with L and q is any integer.

B. M. Popovic, "Generalized Chirp-like Polyphase Sequences with Optimal Correlation Properties," *IEEE Trans. Info. Theory*, vol. 38, Jul. 1992, pp. 1406-1409.

UL RS Multiplexing



FDM Pilots



CDM Pilots

UL RS Multiplexing

- cont.

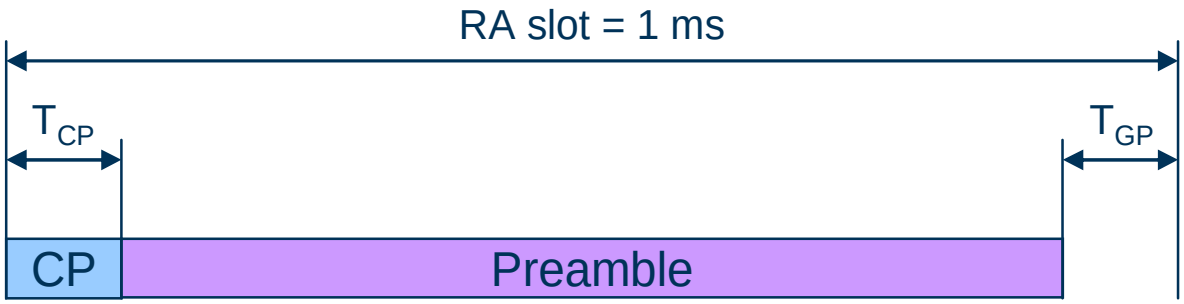
- DM RS
  - For SIMO: FDM between different users.
  - For SU-MIMO: CDM between RS from each antenna
  - For MU-MIMO: CDM between RS from each antenna
- Sounding RS
  - CDM when there is only one sounding bandwidth.
  - CDM/FDM when there are multiple sounding bandwidths.

Cell Search

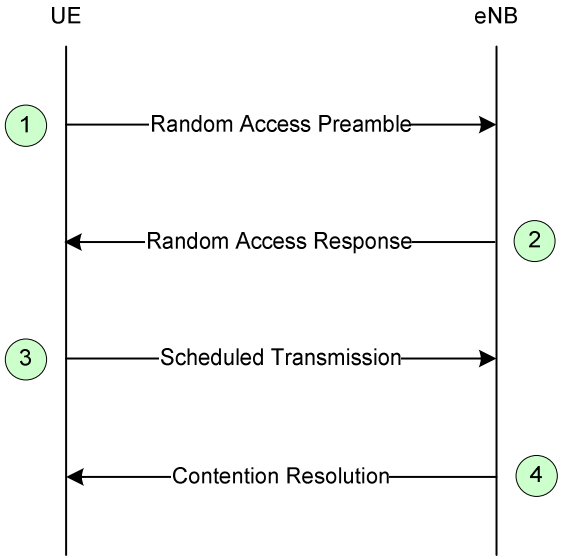
- Cell search: Mobile terminal or user equipment (UE) acquires time and frequency synchronization with a cell and detects the cell ID of that cell.
  - Based on BCH (Broadcast Channel) signal and hierarchical SCH (Synchronization Channel) signals.
- P-SCH (Primary-SCH) and S-SCH (Secondary-SCH) are transmitted twice per radio frame (10 ms) for FDD.
- Cell search procedure
  1. 5 ms timing identified using P-SCH.
  2. Radio timing and group ID found from S-SCH.
  3. Full cell ID found from DL RS.
  4. Decode BCH.

Random Access

- Non-synchronized random access.
- Open loop power controlled with power ramping similar to WCDMA.
- RACH signal bandwidth: 1.08 MHz (6 RBs)
- Preamble based on CAZAC sequence.



* T_{CP} = 0.1 ms, T_{GP} = 0.1 ms



*3GPP TR 25.814

Other Procedures

- Synchronization procedures
  - Radio link monitoring
  - Inter-Cell synchronization for MBMS
  - Transmission timing adjustments
- Power control for DL and UL
- UE procedure for CQI (Channel Quality Indication) reporting
- UE procedure for MIMO feedback reporting
- UE sounding procedure

Summary

- Key technologies of LTE system
  - Multicarrier-based radio air interface
    - OFDMA and SC-FDMA
  - IP-based flat network architecture
  - Multi-input multi-output (MIMO)
  - Active interference avoidance and coordination
    - Fractional frequency re-use (FFR)
  - Fast frequency-selective resource scheduling

Summary

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	3GPP LTE	3GPP2 UMB	Mobile WiMAX
Channel bandwidth	1.4, 3, 5, 10, 15, and 20 MHz	1.25, 2.5, 5, 10, and 20 MHz	5, 7, 8.75, and 10 MHz
DL multiple access	OFDMA	OFDMA	OFDMA
UL multiple access	SC-FDMA	OFDMA and CDMA	OFDMA
Duplexing	FDD and TDD	FDD and TDD	TDD
Subcarrier mapping	Localized	Localized and distributed	Localized and distributed
Subcarrier hopping	Yes	Yes	Yes
Data modulation	QPSK, 16QAM, and 64QAM	QPSK, 8PSK, 16QAM, and 64QAM	QPSK, 16QAM, and 64QAM
Subcarrier spacing	15 kHz	9.6 kHz	10.94 kHz
FFT size (5 MHz)	512	512	512
Channel coding	Convolutional coding and turbo coding.	Convolutional coding, turbo coding, and LDPC coding	Convolutional coding and convolutional turbo coding. Block turbo coding and LDPC coding optional.
MIMO	Multi-layer precoded spatial multiplexing space-time/frequency block coding, switched transmit diversity, and cyclic delay diversity	Multi-layer precoded spatial multiplexing, space-time transmit diversity, spatial division multiple access, and beamforming.	Beamforming, Space-time coding, and spatial multiplexing

References and Resources

- LTE enabling technologies
  - OFDM/OFDMA
    - R. van Nee and R. Prasad, *OFDM for Wireless Multimedia Communications*, Artech House, 2000.
  - SC-FDMA
    - H. G. Myung *et al.*, "Single Carrier FDMA for Uplink Wireless Transmission," *IEEE Vehicular Technology Mag.*, vol. 1, no. 3, Sep. 2006.
    - http://hgmyung.googlepages.com/scfdma
  - MIMO
    - A. Paulraj *et al.*, *Introduction to Space-Time Wireless Communications*, Cambridge University Press, May 2003.
    - G. L. Stüber *et al.*, "Broadband MIMO-OFDM Wireless Communications," *Proceedings of the IEEE*, Feb. 2004, vol. 92, no. 2, pp. 271-294.
  - Multicarrier scheduling
    - G. Song and Y. Li, "Utility-based Resource Allocation and Scheduling in OFDM-based Wireless Broadband Networks," *IEEE Commun. Mag.*, vol. 43, no. 12, Dec. 2005, pp. 127-134.

References and Resources

– cont.

- 3GPP LTE
  - Spec
    - http://www.3gpp.org/ftp/Specs/html-info/36-series.htm
    - http://www.3gpp.org/ftp/Specs/html-info/25814.htm (old)
  - E. Dahlman et al., *3G Evolution: HSPA and LTE for Mobile Broadband*, Academic Press, 2007
  - H. Ekström *et al.*, "Technical Solutions for the 3G Long-Term Evolution," *IEEE Commun. Mag.*, vol. 44, no. 3, March 2006, pp. 38-45
  - 3G Americas, "Mobile Broadband: The Global Evolution of UMTS/HSPA - 3GPP Release 7 and Beyond" *available at* http://www.3gamericas.org/pdfs/UMTS_Rel7_Beyond_Dec2006.pdf
  - http://www.LTEwatch.com

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