Cellular networks
LTE

EP2950

KTH Technology
and Health

4G TECHNOLOGY

- High-speed, universally accessible wireless service capability
- LTE and LTE-Advanced
  - Goals and requirements, complete system architecture, core network (Evolved Packet System), LTE channel and physical layer
  - LTE Release 8, then enhancements from Releases 9-12

PURPOSE AND MOTIVATION

- International Telecommunication Union (ITU) 4G directives for IMT-Advanced
  - All-IP packet switched network.
  - Peak data rates
    - Up to 100 Mbps for high-mobility mobile access
    - Up to 1 Gbps for low-mobility access
  - Dynamically share and use network resources
  - Smooth handovers across heterogeneous networks, including 2G and 3G networks, small cells such as picocells, femtocells, and relays, and WLANs
  - High quality of service for multimedia applications

PURPOSE AND MOTIVATION

- No support for circuit-switched voice
  - Instead providing Voice over LTE (VoLTE)
- Replace spread spectrum with OFDM

Table 14.1 Wireless Network Generations

Technology	1G	2G	2.5G	3G	4G
Design began	1970	1980	1985	1990	2000
Implementation	1984	1991	1999	2002	2012
Services	Analog voice	Digital voice	Higher capacity packetized data	Higher capacity, broadband	Completely IP based
Data rate	1.9. kbps	14.4 kbps	384 kbps	2 Mbps	200 Mbps
Multiplexing	FDMA	TDMA, CDMA	TDMA, CDMA	CDMA	OFDMA, SC-FDMA
Core network	PSTN	PSTN	PSTN, packet network	Packet network	IP backbone

LTE ARCHITECTURE

- Two candidates for 4G
  - IEEE 802.16 WiMax (described in Chapter 16)
    - Enhancement of previous fixed wireless standard for mobility
  - Long Term Evolution
    - Third Generation Partnership Project (3GPP)
    - Consortium of Asian, European, and North American telecommunications standards organizations
- Both are similar in use of OFDM and OFDMA
- LTE has become the universal standard for 4G

LTE ARCHITECTURE

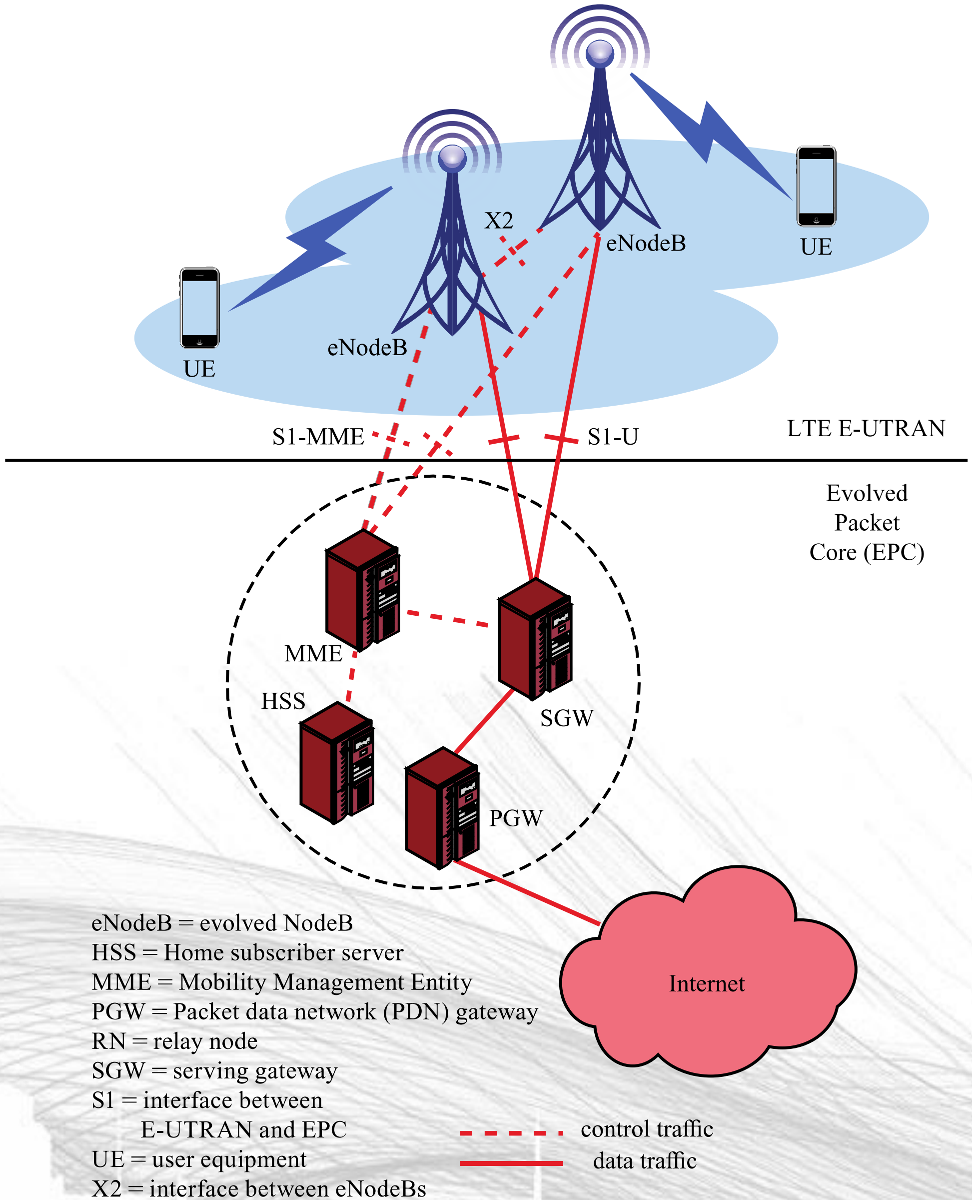
- 3GPP Release 8
  - *Clean slate* approach
  - Completely new air interface
    - OFDM, OFDMA, MIMO
- 3GPP Release 10 *LTE-Advanced*
  - Further enhanced by Releases 11 and 12

Table 14.2 Comparison of Performance Requirements for LTE and LTE-Advanced

System Performance		LTE	LTE-Advanced
Peak rate	Downlink	100 Mbps @20 MHz	1 Gbps @100 MHz
	Uplink	50 Mbps @20 MHz	500 Mbps @100 MHz
Control plane delay	Idle to connected	<100 ms	< 50 ms
	Dormant to active	<50 ms	< 10 ms
User plane delay		< 5ms	Lower than LTE
Spectral efficiency (peak)	Downlink	5 bps/Hz @2×2	30 bps/Hz @8×8
	Uplink	2.5 bps/Hz @1×2	15 bps/Hz @4×4
Mobility		Up to 350 km/h	Up to 350—500 km/h

LTE ARCHITECTURE

- evolved NodeB (eNodeB)
  - Most devices connect into the network through the eNodeB
- Evolution of the previous 3GPP NodeB
  - Now based on OFDMA instead of CDMA
  - Has its own control functionality, rather than using the Radio Network Controller (RNC)
    - eNodeB supports radio resource control, admission control, and mobility management
    - Originally the responsibility of the RNC



14.2 OVERVIEW OF THE EPC/LTE ARCHITECTURE

EVOLVED PACKET SYSTEM

- Overall architecture is called the Evolved Packet System (EPS)
- 3GPP standards divide the network into
  - Radio access network (RAN)
  - Core network (CN)
- Long Term Evolution (LTE) is the RAN
  - Called Evolved UMTS Terrestrial Radio Access (E-UTRA)
  - Enhancement of 3GPP's 3G RAN
    - Called the Evolved UMTS Terrestrial Radio Access Network (E-UTRAN)
  - eNodeB is the only logical node in the E-UTRAN
  - No RNC

EVOLVED PACKET SYSTEM

- Evolved Packet Core (EPC)
  - Operator or carrier core network
- Design principles of the EPS
  - Clean slate design
  - Packet-switched transport for traffic belonging to all QoS classes including conversational, streaming, real-time, non-real-time, and background
  - Radio resource management for the following: end-to-end QoS, transport for higher layers, load sharing/balancing, policy management/enforcement across different radio access technologies
  - Integration with existing 3GPP 2G and 3G networks
  - Scalable bandwidth from 1.4 MHz to 20 MHz
  - Carrier aggregation for overall bandwidths up to 100 MHz

FUNCTIONS OF THE EPS

- Network access control
  - Network selection, authentication, authorization, admission control, policy and charging enforcement, and lawful interception
- Packet routing and transfer
- Security
  - Ciphering, integrity protection, and network interface physical link protection
- Mobility management
  - Keep track of the current location of the UE
- Radio resource management
  - Assign, reassign, and release radio resources taking into account single and multi-cell aspects
- Network management
- IP networking functions
  - Connections of eNodeBs, E-UTRAN sharing, emergency session support

EVOLVED PACKET CORE

- Traditionally circuit switched but now entirely packet switched
  - Based on IP
  - Voice supported using voice over IP (VoIP)
- Core network was first called the System Architecture Evolution (SAE)

EPC COMPONENTS

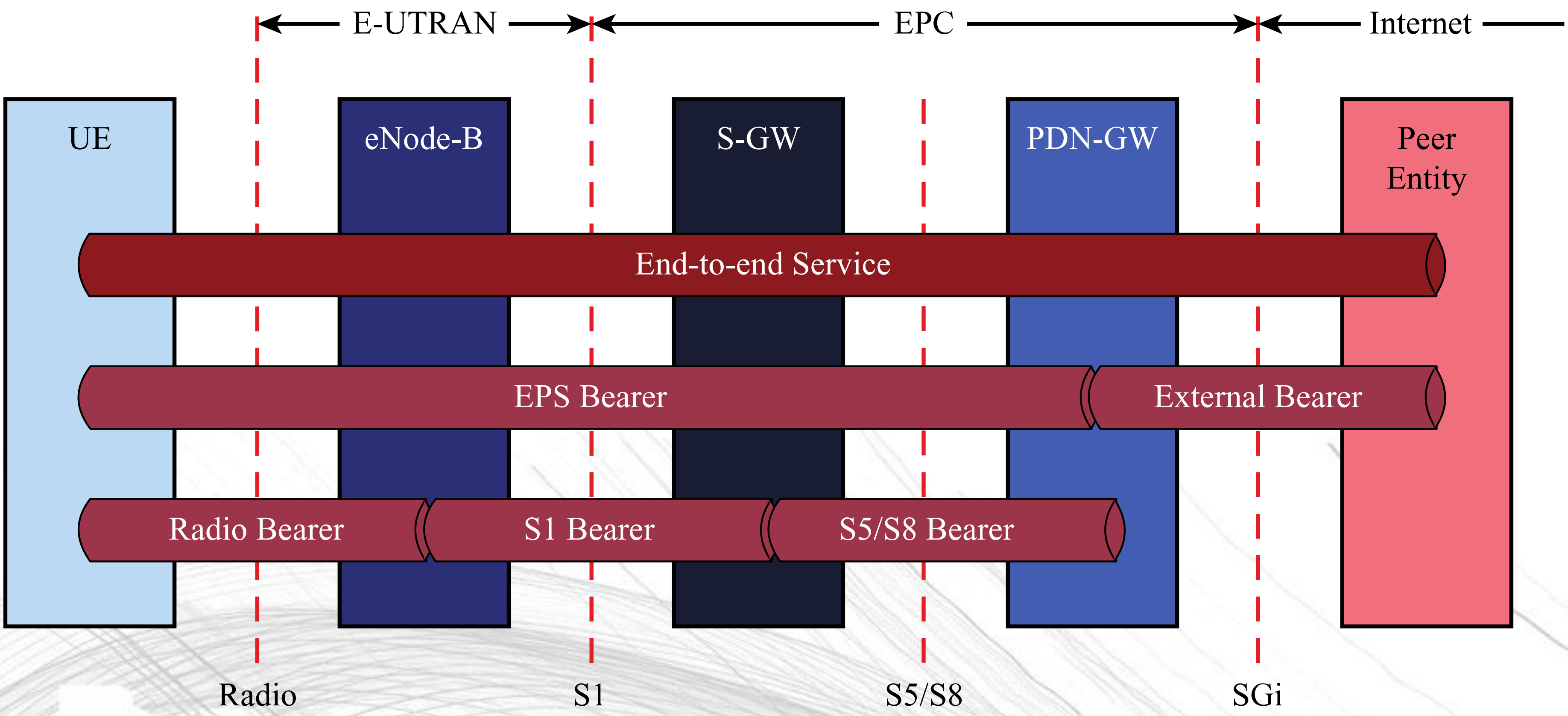
- Mobility Management Entity (MME)
  - Supports user equipment context, identity, authentication, and authorization
- Serving Gateway (SGW)
  - Receives and sends packets between the eNodeB and the core network
- Packet Data Network Gateway (PGW)
  - Connects the EPC with external networks
- Home Subscriber Server (HSS)
  - Database of user-related and subscriber-related information
- Interfaces
  - S1 interface between the E-UTRAN and the EPC
    - For both control purposes and for user plane data traffic
  - X2 interface for eNodeBs to interact with each other
    - Again for both control purposes and for user plane data traffic

NON-ACCESS STRATUM PROTOCOLS

- Non-access stratum (NAS)
  - The highest stratum of the control plane between UE and EPC (MME) at the radio interface
  - EPS Mobility Management (EMM)
    - Manage the mobility of the UE
  - EPS Session Management (ESM)
    - Activate, authenticate, modify, and de-activate user-plane channels for connections between the UE, SGW, and PGW

LTE RESOURCE MANAGEMENT

- LTE uses *bearers* for quality of service (QoS) control instead of circuits
  - QoS is discussed in Chapter 3
- EPS bearers
  - Between PGW and UE
  - Maps to specific QoS parameters such as data rate, delay, and packet error rate
- Service Data Flows (SDFs) differentiate traffic flowing between applications on a client and a service
- End-to-end service is not completely controlled by LTE



14.3 LTE QOS BEARERS

CLASSES OF BEARERS

- Guaranteed Bit Rate (GBR) bearers
  - Guaranteed a minimum bit rate
    - And possibly higher bit rates if system resources are available
  - Useful for voice, interactive video, or real-time gaming
- Non-GBR (GBR) bearers
  - Not guaranteed a minimum bit rate
  - Performance is more dependent on the number of UEs served by the eNodeB and the system load
  - Useful for e-mail, file transfer, Web browsing, and P2P file sharing.

BEARER MANAGEMENT

- Each bearer is given a QoS class identifier (QCI)

Table 14.3 Standardized QCI characteristics

QCI	Resource Type	Priority	Packet Delay Budget	Packet Error Loss Rate	Example Services
1	GBR	2	100 ms	10^{-2}	Conversational Voice
2		4	150 ms	10^{-3}	Conversational Video (live streaming)
3		3	50 ms	10^{-3}	Real Time Gaming
4		5	300 ms	10^{-6}	Non-Conversational Video (buffered streaming)
5	Non-GBR	1	100 ms	10^{-6}	IMS Signalling
6		6	300 ms	10^{-6}	Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		7	100 ms	10^{-3}	Voice, Video (live streaming) Interactive Gaming
8		8	300 ms	10^{-6}	Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
9*		9			

* QCI value typicaly used for the default bearer

EPC FUNCTIONS

- Mobility management
  - X2 interface used when moving within a RAN coordinated under the same MME
  - S1 interface used to move to another MME
  - Hard handovers are used: A UE is connected to only one eNodeB at a time

EPC FUNCTIONS

- Inter-cell interference coordination (ICIC)
  - Reduces interference when the same frequency is used in a neighboring cell
  - Goal is universal frequency reuse ($N = 1$ Chapter 13)
    - Must avoid interference at cell edges
    - Interference randomization (scrambling), coordination of time, frequency and transmit power
  - eNodeBs send indicators
    - Information about frequencies, power etc
  - Later releases of LTE have improved interference control

NO DETAILS IN CHAPTER 14.5
LTE CHANNEL STRUCTURE AND PROTOCOLS

- Hierarchical channel structure between the layers of the protocol stack
  - Provides efficient support for QoS
- LTE radio interface is divided
  - Control Plane
  - User Plane
- User plane protocols
  - Part of the *Access Stratum*
  - Transport packets between UE and PGW
  - PDCP transports packets between UE and eNodeB on the radio interface (Fig. 14.4)
  - GTP sends packets through the other interfaces (Fig. 14.5)

LTE RADIO ACCESS NETWORK

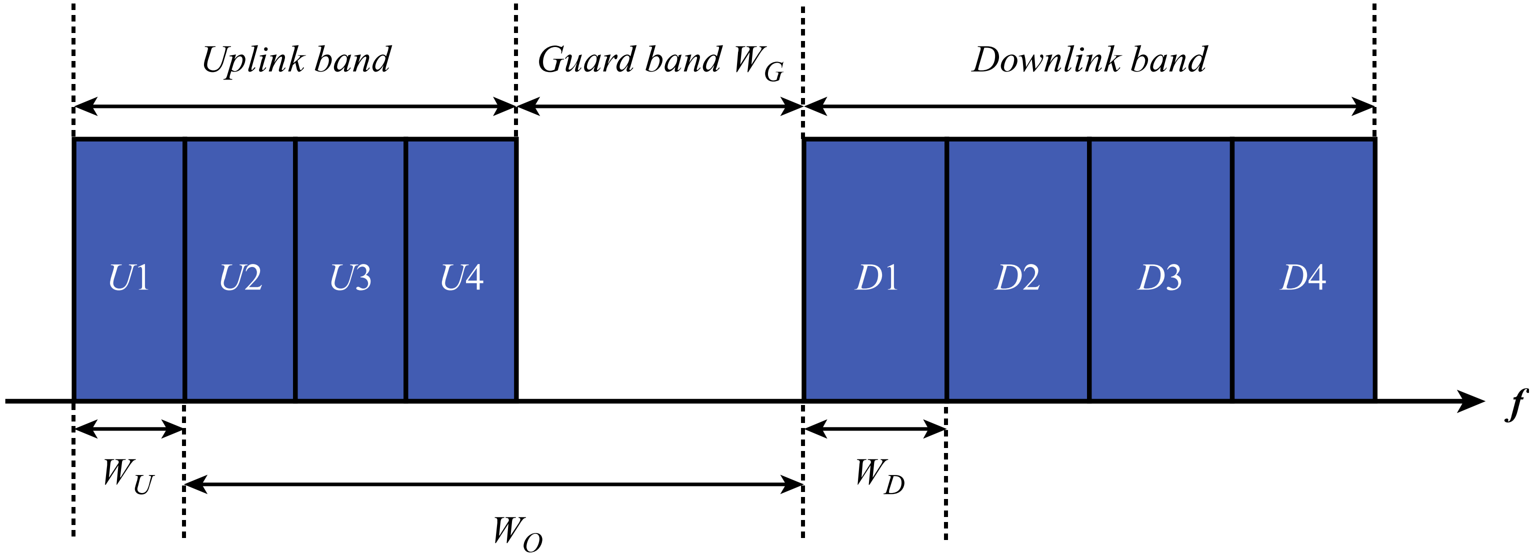
- LTE uses MIMO and OFDM
  - OFDMA on the downlink
  - SC-OFDM on the uplink, which provides better energy and cost efficiency for battery-operated mobiles
- LTE uses subcarriers 15 kHz apart
  - Maximum FFT size is 2048
  - Basic time unit is

$$T_s = 1/(15000 \quad 2048) = 1/30{,}720{,}000 \text{ seconds.}$$

  - Downlink and uplink are organized into radio frames
    - Duration 10 ms., which corresponds to $307200T_s$.
    - Consisting of 20 time slots of 0.5 ms (Fig. 14.11)

LTE RADIO ACCESS NETWORK

- LTE uses both TDD and FDD
  - Both have been widely deployed
  - See Table 14.4 for comparison
  - Time Division Duplexing (TDD)
    - Uplink and downlink transmit in the same frequency band alternating in the time domain
  - Frequency Division Duplexing (FDD)
    - Different frequency bands for uplink and downlink
- LTE uses two cyclic prefixes (CPs)
  - Normal CP = 144 T_s = 4.7 μs (multi-path difference 1.41 km)
  - Extended CP = 512 T_s = 16.7 μs (multi-path difference 5.0 km)
    - For worse environments



(a) FDD

(b) TDD

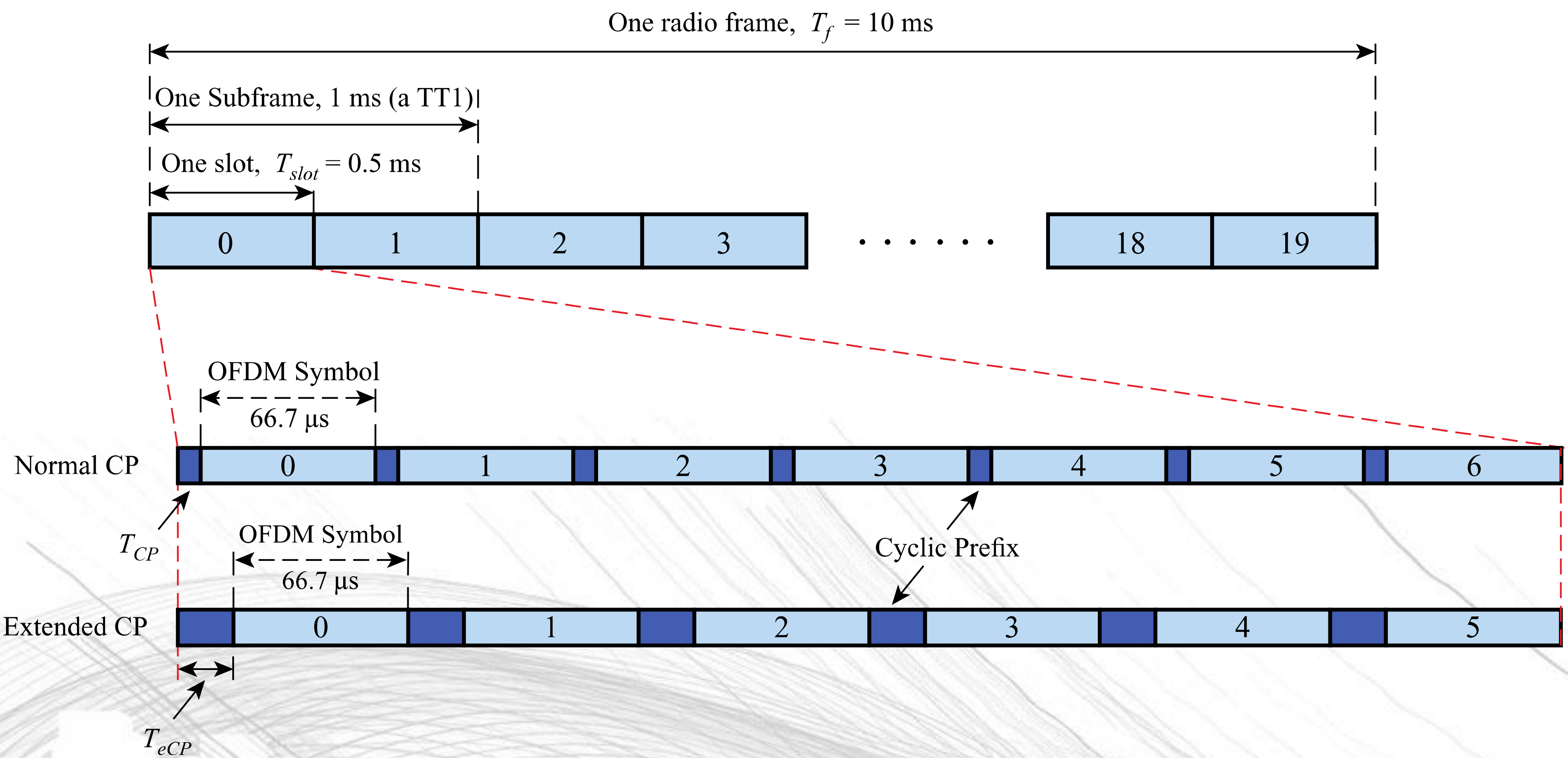
14.10 SPECTRUM ALLOCATION FOR FDD AND TDD

FDD FRAME STRUCTURE

- Three different time units
  - The *slot* equals T_{slot} = 15360 T_s = 0.5 ms
  - Two consecutive slots comprise a *subframe* of length 1 ms
    - Channel dependent scheduling and link adaptation (otherwise known as adaptive modulation and coding) occur on the time scale of a subframe (1000 times/sec.).
  - 20 slots (10 subframes) equal a *radio frame* of 10 ms
    - Radio frames schedule distribution of more slowly changing information, such as system information and reference signals.

FDD FRAME STRUCTURE

- Normal CP allows 7 OFDM symbols per slot
- Extended CP only allows time for 6 OFDM symbols
  - Use of extended CP results in a 1/7 = 14.3 % reduction in throughput
  - But provides better compensation for multipath



14.11 FDD FRAME STRUCTURE, TYPE 1

- Parameters in downlink transmission

TABLE 1 LTE DOWNLINK PHYSICAL LAYER PARAMETERS.

Channel Bandwidth (MHz)	1.25	2.5	5	10	15	20
Frame Duration (ms)	10					
Subframe Duration (ms)	1					
Sub-carrier Spacing (kHz)	15					
Sampling Frequency (MHz)	1.92	3.84	7.68	15.36	23.04	30.72
FFT Size	128	256	512	1024	1536	2048
Occupied Sub-carriers (inc. DC sub-carrier)	76	151	301	601	901	1201
Guard Sub-carriers	52	105	211	423	635	847
Number of Resource Blocks	6	12	25	50	75	100
Occupied Channel Bandwidth (MHz)	1.140	2.265	4.515	9.015	13.515	18.015
DL Bandwidth Efficiency	77.1%	90%	90%	90%	90%	90%
OFDM Symbols/Subframe	7/6 (short/long CP)					
CP Length (Short CP) (μs)	5.2 (first symbol) / 4.69 (six following symbols)					
CP Length (Long CP) (μs)	16.67					

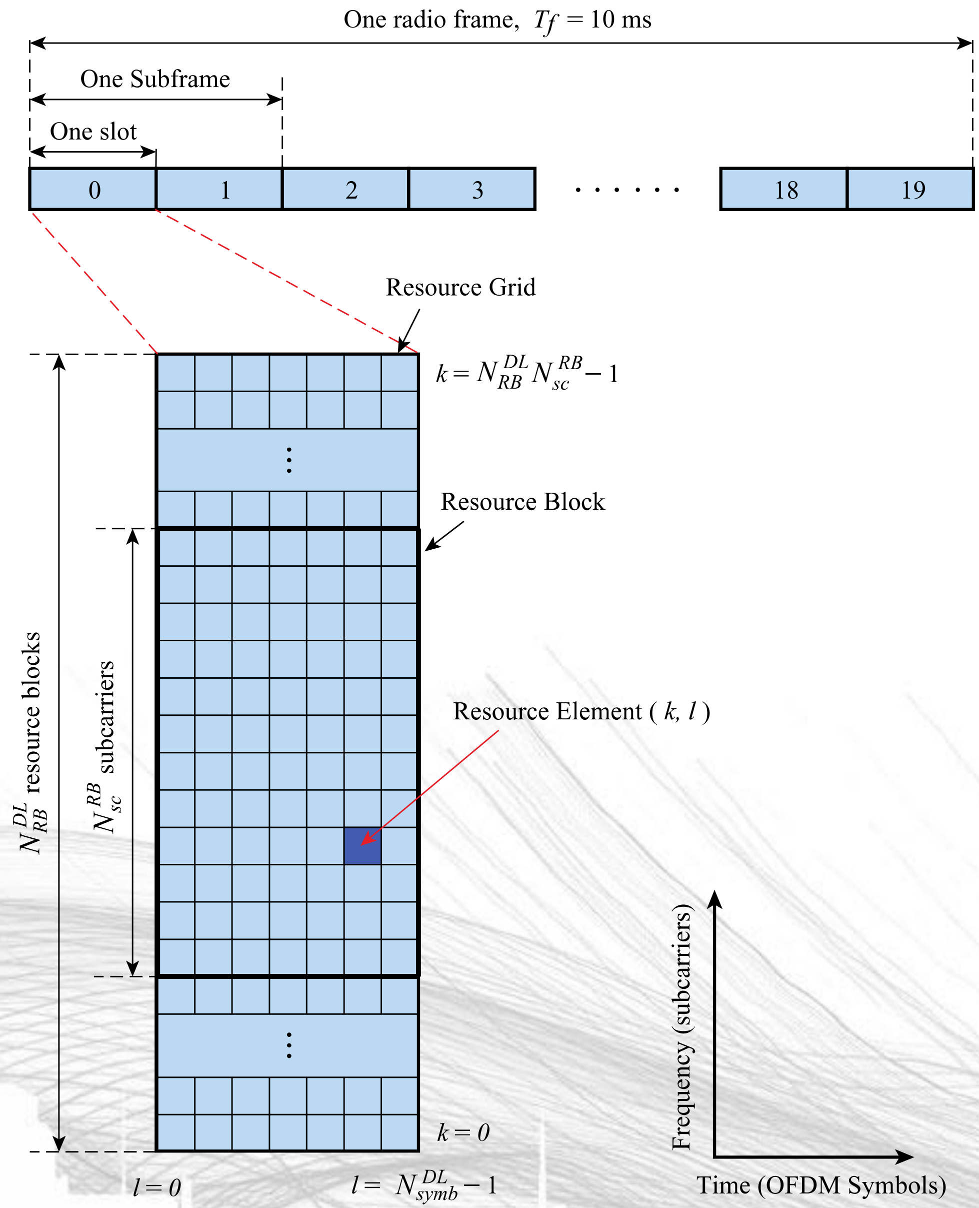
READ BRIEFLY

TDD FRAME STRUCTURE

- Radio frame is again 10 ms.
- Includes special subframes for switching downlink-to-uplink
  - Downlink Pilot TimeSlot (DwPTS): Ordinary but shorter downlink subframe of 3 to 12 OFDM symbols
  - Uplink Pilot TimeSlot (UpPTS): Short duration of one or two OFDM symbols for sounding reference signals or random access preambles
  - Guard Period (GP): Remaining symbols in the special subframe in between to provide time to switch between downlink and uplink

RESOURCE BLOCKS

- A time-frequency grid is used to illustrate allocation of physical resources
- Each column is 6 or 7 OFDM symbols per slot
- Each row corresponds to a subcarrier of 15 kHz
  - Some subcarriers are used for guard bands
  - 10 % of bandwidth is used for guard bands for channel bandwidths of 3 MHz and above



14.13 LTE RESOURCE GRID

RESOURCE BLOCKS

- Resource Block
  - 12 subcarriers
  - 6 or 7 OFDM symbols
  - Results in 72 or 84 *resource elements* in a *resource block* (*RB*)
- For the uplink, contiguous frequencies must be used for the 12 subcarriers
  - Called a *physical resource block*
- For the downlink, frequencies need not be contiguous
  - Called a *virtual resource block*

PHYSICAL TRANSMISSION

- Release 8 supports up to 4   4 MIMO
- ⅓ rate convolutional codes
- QPSK, 16-QAM, and 64-QAM based on channel conditions
- UE determines a CQI index that will provide the highest throughput while maintaining at most a 10 % block error rate

Table 14.7 4-Bit CQI Table

CQI Index	Modulation	Code Rate × 1024	Efficiency
0	Out of Range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

POWER-ON PROCEDURES

1. Power on the UE
2. Select a network
3. Select a suitable cell
4. Use contention-based random access to contact an eNodeB
5. Establish an RRC connection
6. Attach: Register location with the MME and the network configures control and default EPS bearers.
7. Transmit a packet
8. Mobile can then request improved quality of service. If so, it is given a dedicated bearer

LTE-ADVANCED

- Release 10 meets the ITU 4G guidelines
  - Took on the name LTE-Advanced
- Key improvements
  - Carrier aggregation
  - Support higher dimensional MIMO
  - Relay nodes
  - Heterogeneous networks involving small cells such as femtocells, picocells, and relays
  - Cooperative multipoint transmission and enhanced intercell interference coordination
  - Voice over LTE