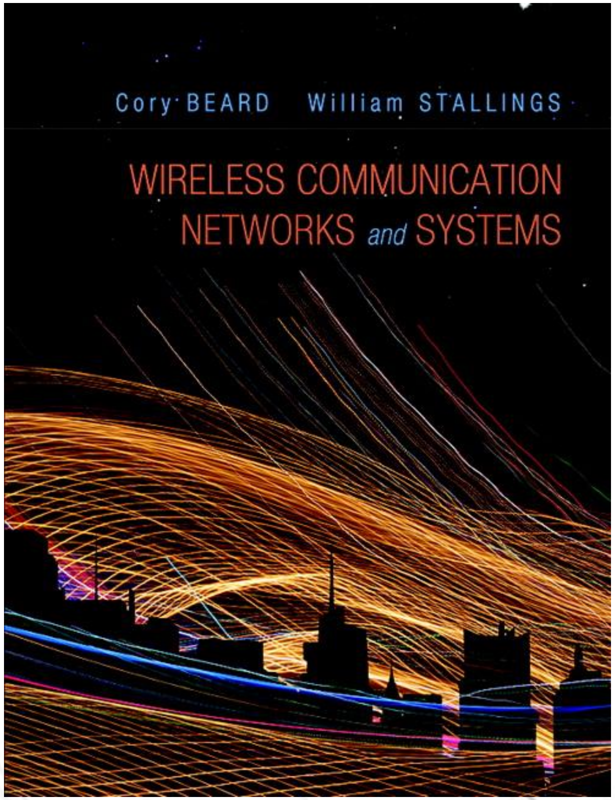
CHAPTER 14
4^{TH} GENERATION SYSTEMS AND LONG TERM EVOLUTION



Wireless Communication Networks and Systems

1^{st} edition

Cory Beard, William Stallings

4G TECHNOLOGY

- High-speed, universally accessible wireless service capability
- Creating a revolution
  - Networking at all locations for tablets, smartphones, computers, and devices.
  - Similar to the revolution caused by Wi-Fi
- LTE and LTE-Advanced will be studied here
  - Goals and requirements, complete system architecture, core network (Evolved Packet System), LTE channel and physical layer
  - Will first study LTE Release 8, then enhancements from Releases 9-12

PURPOSE, MOTIVATION, AND APPROACH TO 4G

- Ultra-mobile broadband access
  - For a variety of mobile devices
- 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, MOTIVATION, AND APPROACH TO 4G

- 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

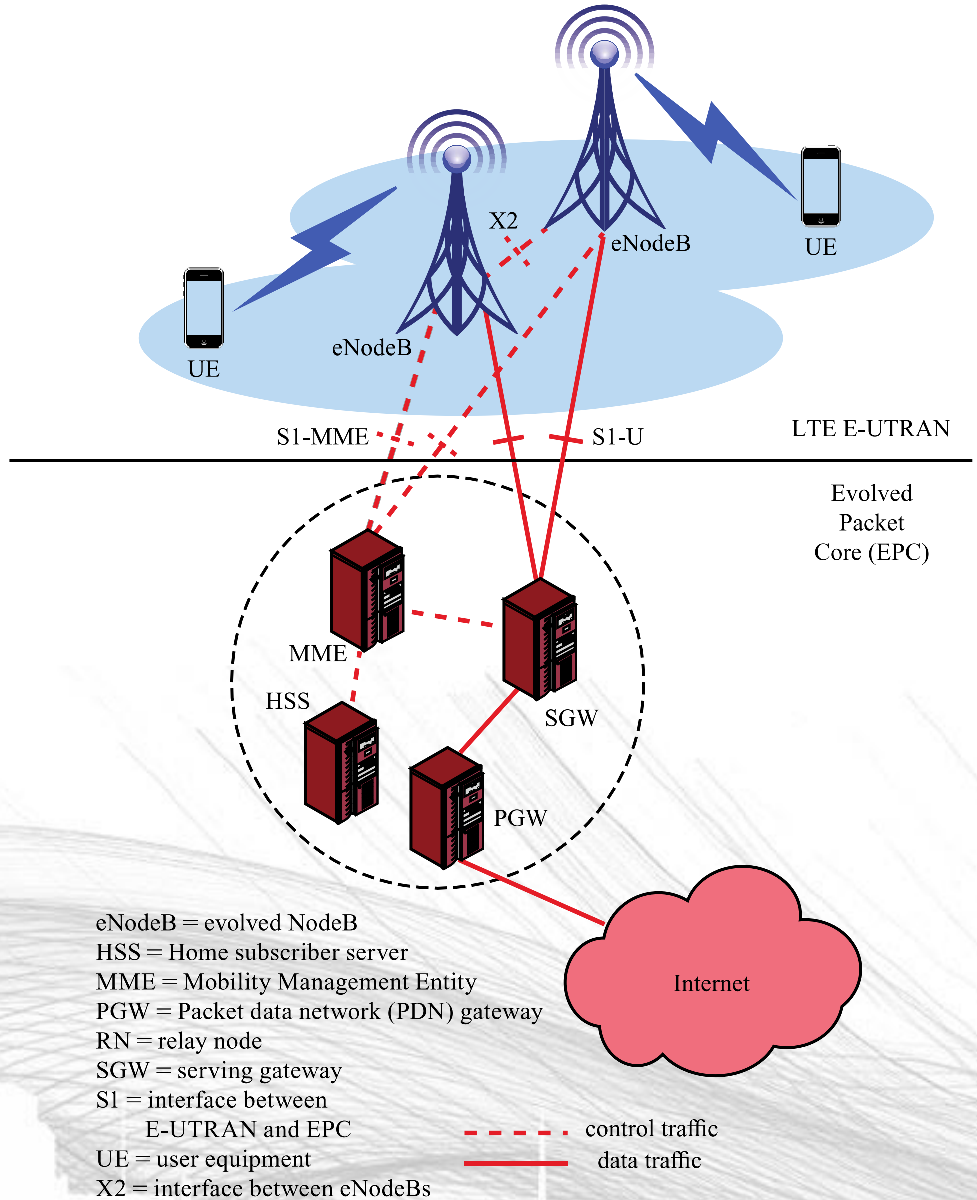
- Some features started in the 3G era for 3GPP
- Initial LTE data rates were similar to 3G
- 3GPP Release 8
  - *Clean slate* approach
  - Completely new air interface
    - OFDM, OFDMA, MIMO
- 3GPP Release 10
  - Known as *LTE-Advanced*
  - Further enhanced by Releases 11 and 12

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)
- Each evolve independently.
- 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
  - It is important to understand the EPC to know the full functionality of the architecture
- Some of the 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, including network selection, authentication, authorization, admission control, policy and charging enforcement, and lawful interception
- Packet routing and transfer
- Security, including ciphering, integrity protection, and network interface physical link protection
- Mobility management to keep track of the current location of the UE
- Radio resource management to assign, reassign, and release radio resources taking into account single and multi-cell aspects
- Network management to support operation and maintenance
- IP networking functions, connections of eNodeBs, E-UTRAN sharing, emergency session support, among others

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

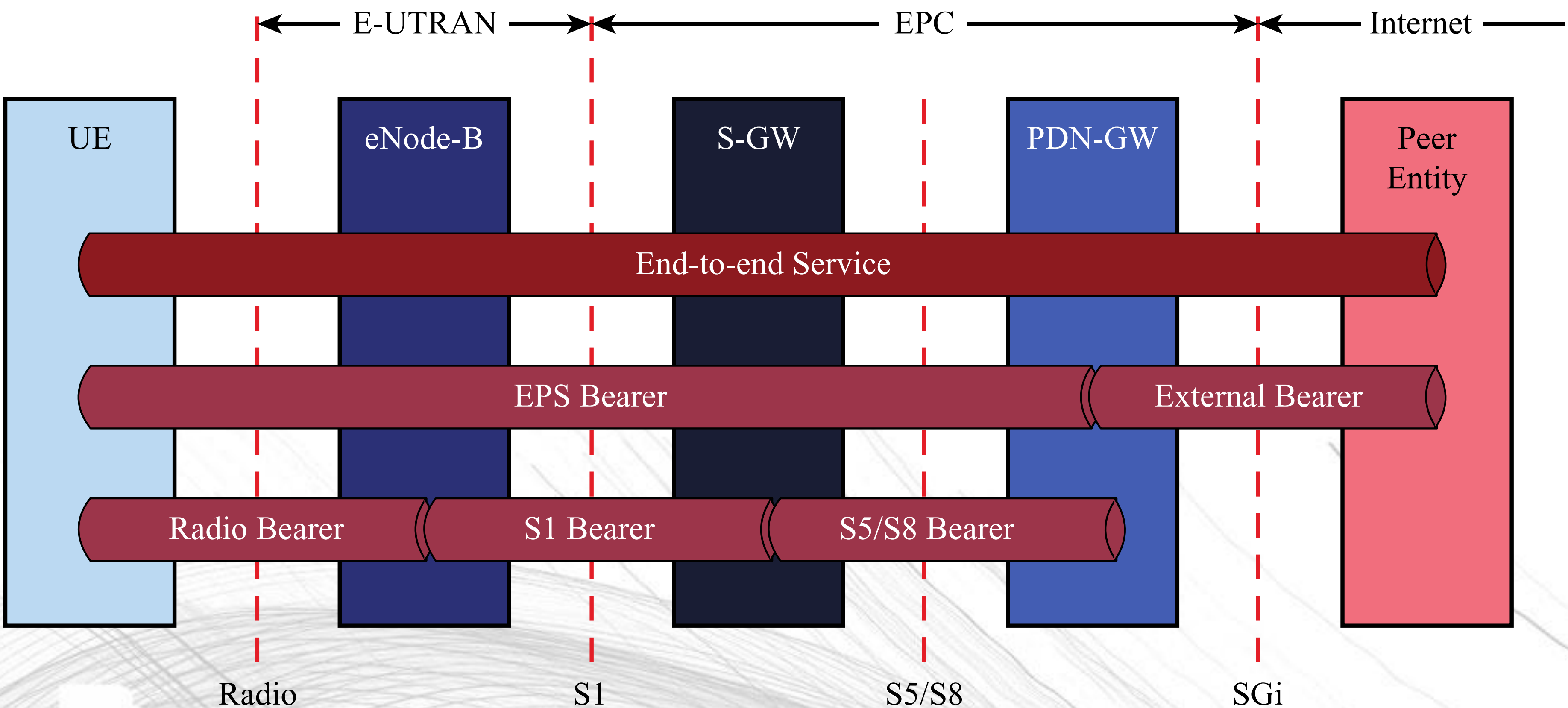
- Mobility Management Entity (MME)
  - Supports user equipment context, identity, authentication, and authorization
- Serving Gateway (SGW)
  - Receives and sends packets between the eNodeB and the core network
- Packet Data Network Gateway (PGW)
  - Connects the EPC with external networks
- Home Subscriber 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

- For interaction between the EPC and the UE
  - Not part of the *Access Stratum* that carries data
- 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
- 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
  - SDFs must be mapped to EPS bearers for QoS treatment
  - SDFs allow traffic types to be given different treatment
- 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

BEARER MANAGEMENT

- Each QCI is given standard forwarding treatments
  - Scheduling policy, admission thresholds, rate-shaping policy, queue management thresholds, and link layer protocol configuration
- For each bearer the following information is associated
  - QoS class identifier (QCI) value
  - Allocation and Retention Priority (ARP): Used to decide if a bearer request should be accepted or rejected
- Additionally for GBR bearers
  - Guaranteed Bit Rate (GBR): minimum rate expected from the network
  - Maximum Bit Rate (MBR): bit rate not to be exceeded from the UE into the bearer

EPC FUNCTIONS

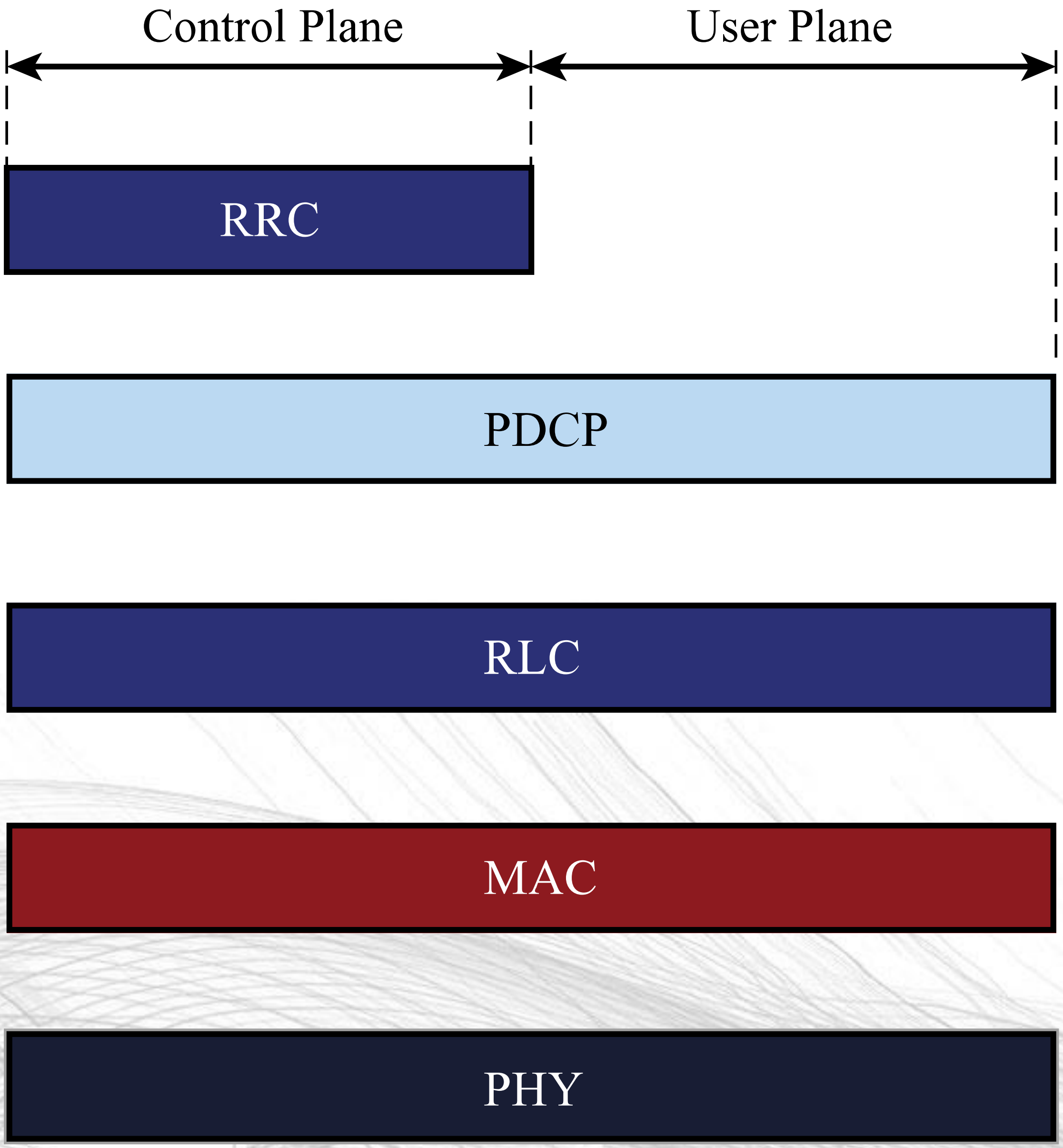
- Mobility management
  - X2 interface used when moving within a RAN coordinated under the same MME
  - S1 interface used to move to another MME
  - *Hard handovers* are used: A UE is connected to only one eNodeB at a time

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 from Chapter 13)
    - Must avoid interference when UEs are near each other at cell edges
    - Interference randomization, cancellation, coordination, and avoidance are used
  - eNodeBs send *indicators*
    - Relative Narrowband Transmit Power, High Interference, and Overload indicators
  - Later releases of LTE have improved interference control

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)



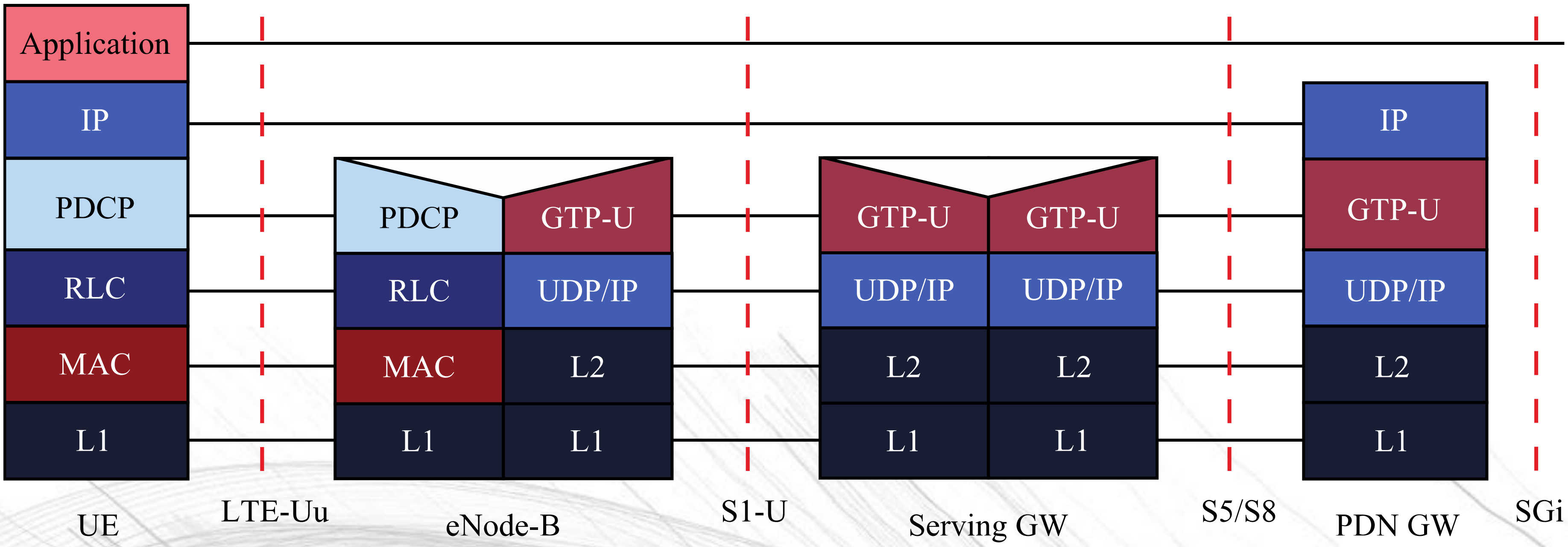
14.4 LTE RADIO INTERFACE PROTOCOLS

PROTOCOL LAYERS

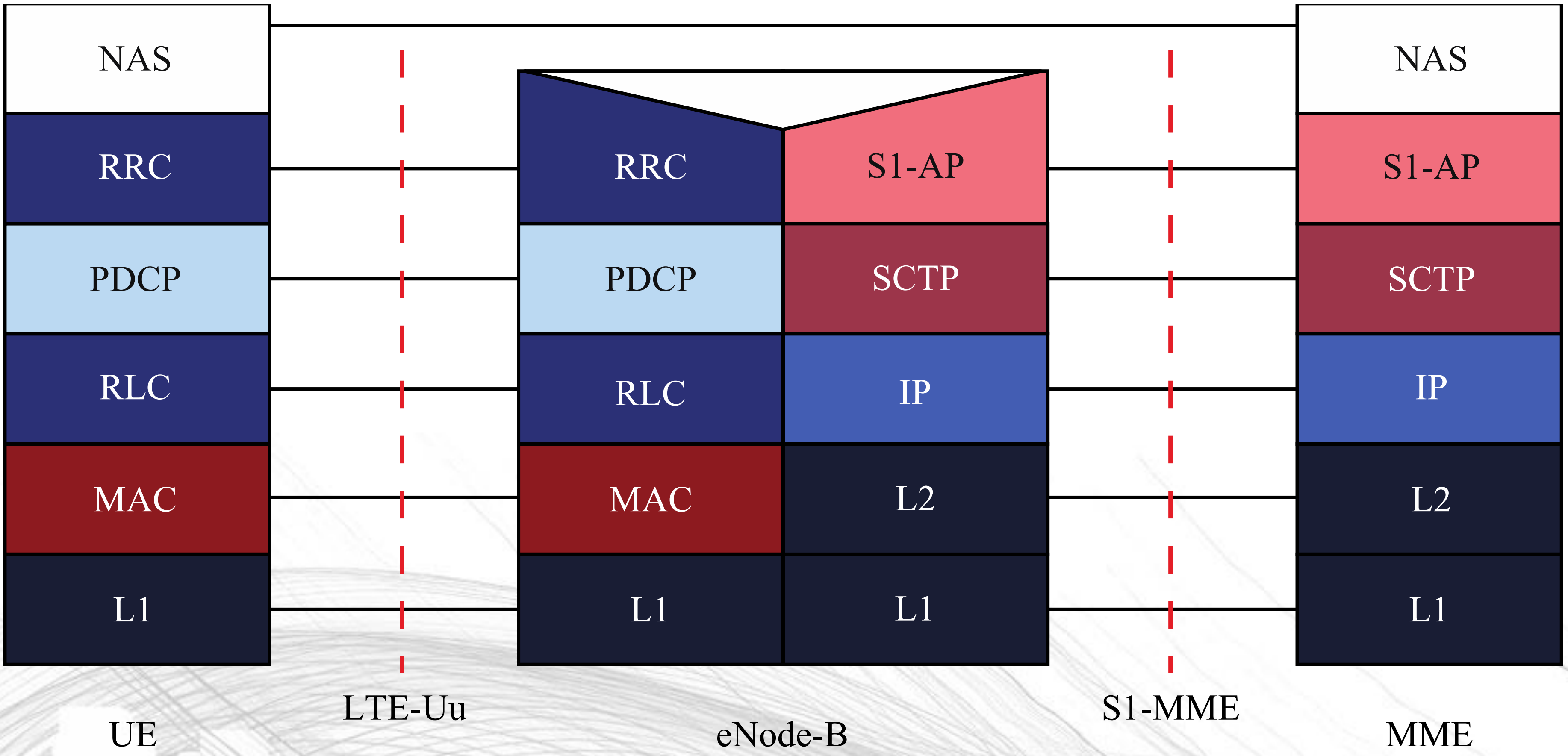
- Radio Resource Control (RRC)
  - Performs control plane functions to control radio resources
  - Through RRC_IDLE and RRC_CONNECTED connection states
- Packet Data Convergence Protocol (PDCP)
  - Delivers packets from UE to eNodeB
  - Involves header compression, ciphering, integrity protection, in-sequence delivery, buffering and forwarding of packets during handover

PROTOCOL LAYERS

- Radio Link Control (RLC)
  - Segments or concatenates data units
  - Performs ARQ when MAC layer H-ARQ fails
- Medium Access Control (MAC)
  - Performs H-ARQ
  - Prioritizes and decides which UEs and radio bearers will send or receive data on which shared physical resources
  - Decides the transmission format, i.e., the modulation format, code rate, MIMO rank, and power level
- Physical layer actually transmits the data



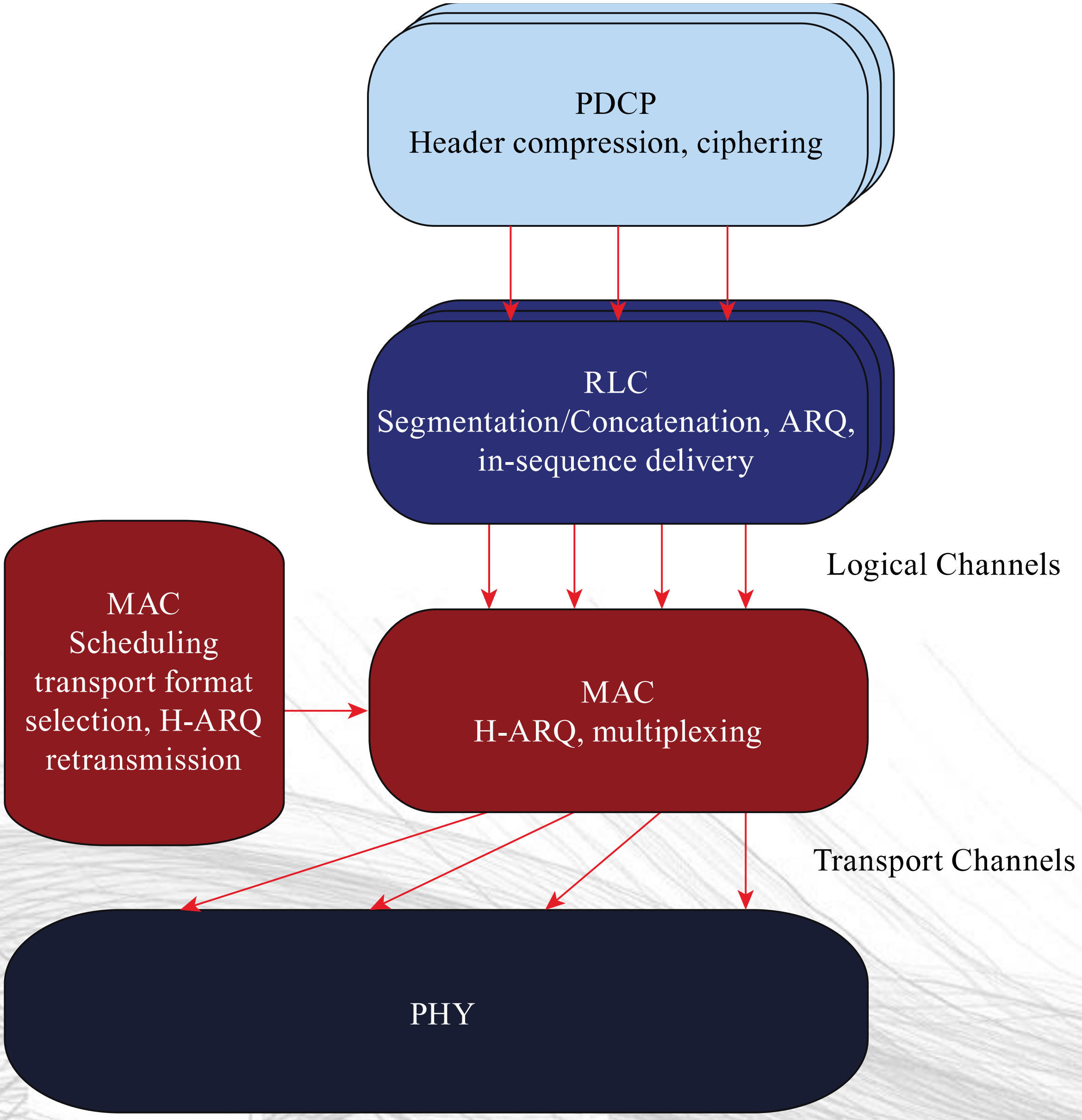
14.5 USER PLANE PROTOCOL STACK



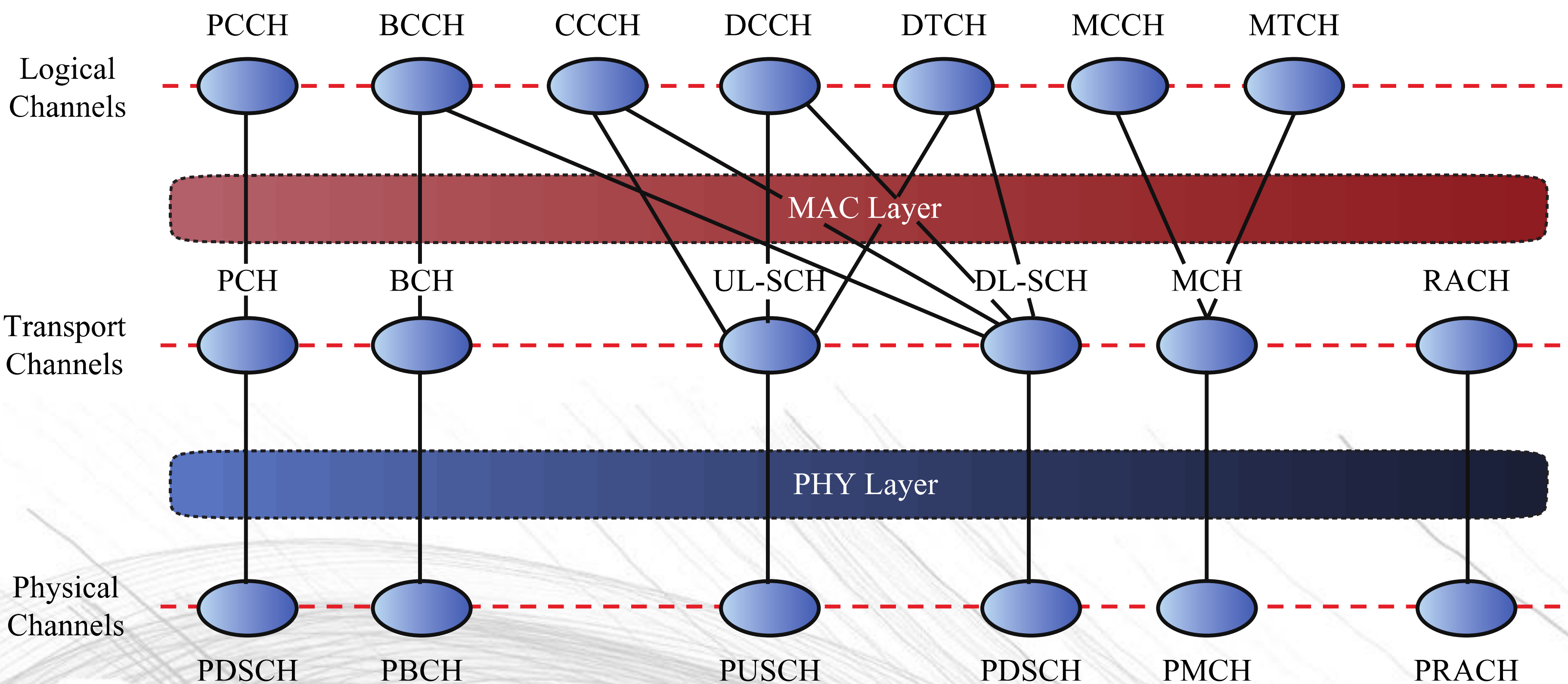
14.6 CONTROL PLANE PROTOCOL STACK

LTE CHANNEL STRUCTURE

- Three types of channels
  - Channels provide services to the layers above
  - Logical channels
    - Provide services from the MAC layer to the RLC
    - Provide a logical connection for control and traffic
  - Transport channels
    - Provide PHY layer services to the MAC layer
    - Define modulation, coding, and antenna configurations
  - Physical channels
    - Define time and frequency resources use to carry information to the upper layers
- Different types of broadcast, multicast, paging, and shared channels



14.8 RADIO INTERFACE ARCHITECTURE AND SAPS



14.9 MAPPING OF LOGICAL, TRANSPORT, AND PHYSICAL CHANNELS

LTE RADIO ACCESS NETWORK

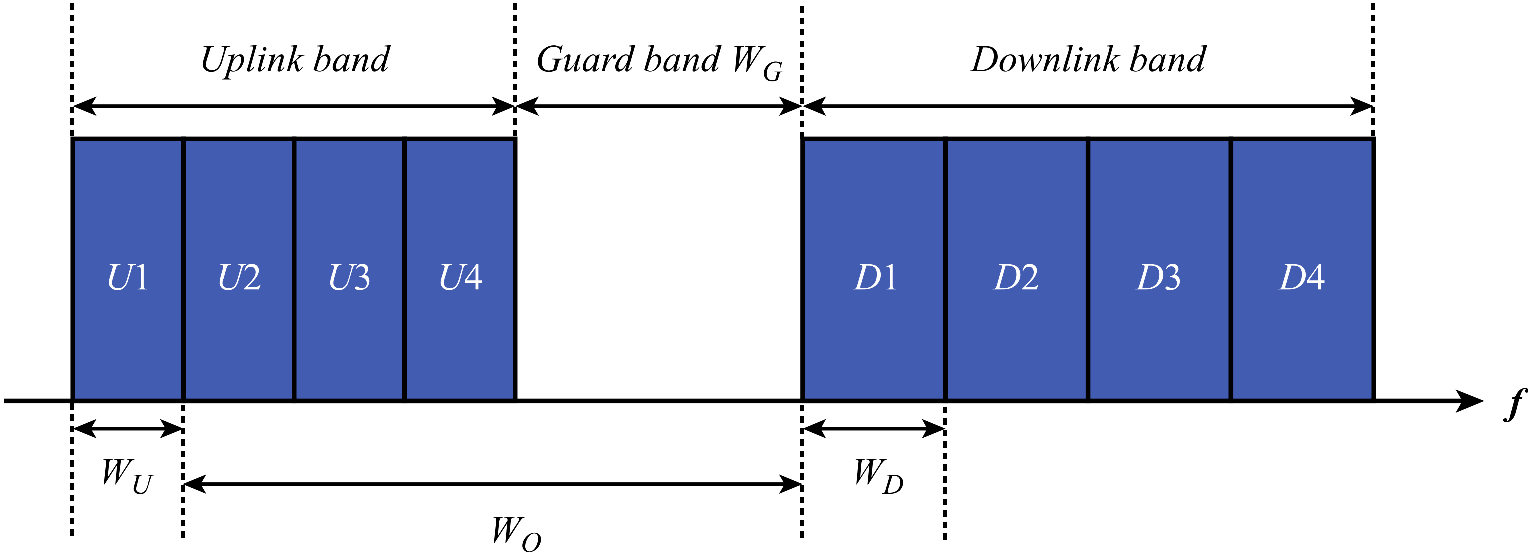
- LTE uses MIMO and OFDM
  - OFDMA on the downlink
  - SC-OFDM on the uplink, which provides better energy and cost efficiency for battery-operated mobiles
- LTE uses subcarriers 15 kHz apart
  - Maximum FFT size is 2048
  - Basic time unit is

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

  - Downlink and uplink are organized into *radio frames*
    - Duration 10 ms., which corresponds to $307200T_s$.

LTE RADIO ACCESS NETWORK

- LTE uses both TDD and FDD
  - Both have been widely deployed
  - Time Division Duplexing (TDD)
    - Uplink and downlink transmit in the same frequency band, but alternating in the time domain
  - Frequency Division Duplexing (FDD)
    - Different frequency bands for uplink and downlink
- LTE uses two cyclic prefixes (CPs)
  - Normal CP = $144 \times T_s = 4.7\ \mu s$.
  - Extended CP = $512 \times T_s = 16.7\ \mu s$.
    - For worse environments



(a) FDD

(b) TDD

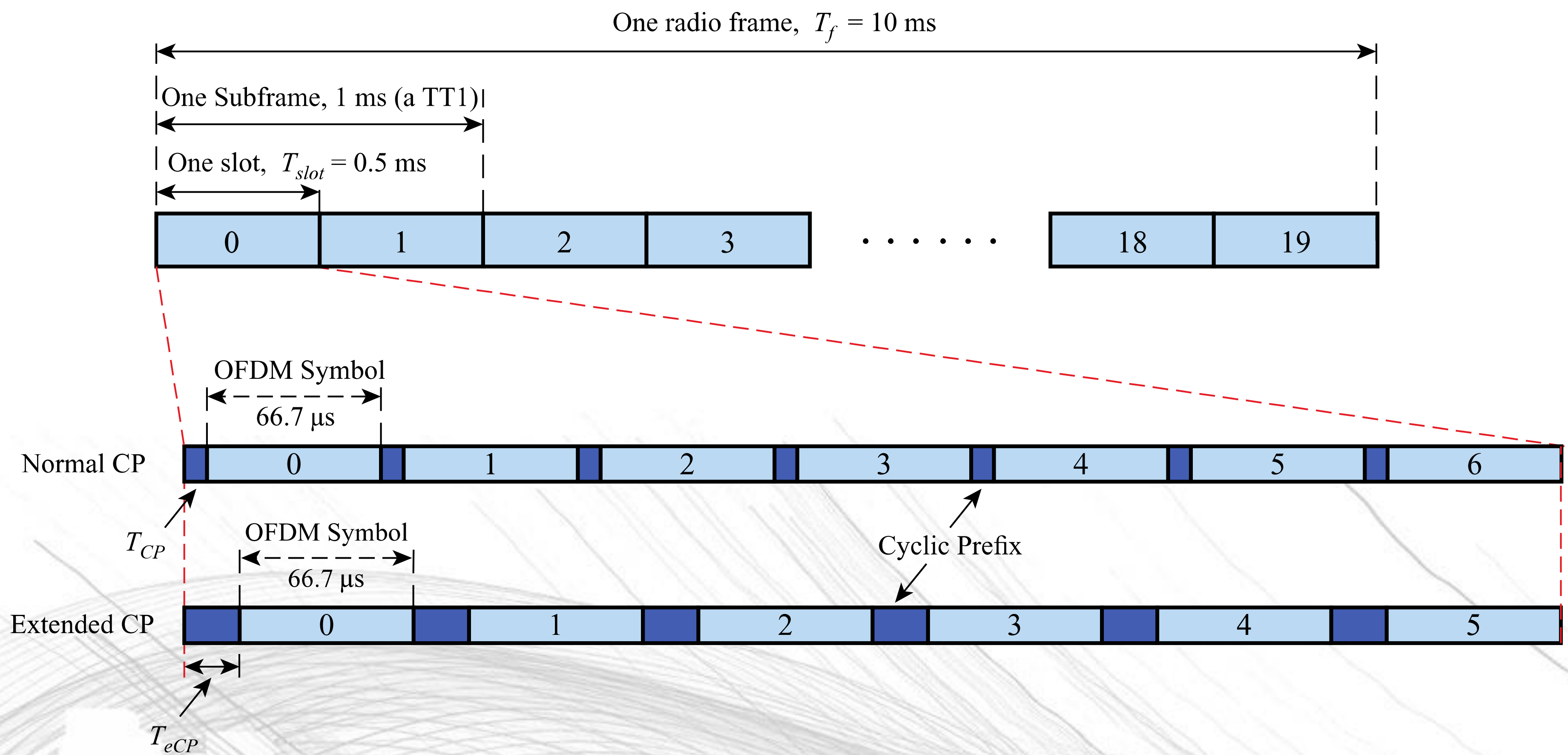
14.10 SPECTRUM ALLOCATION FOR FDD AND TDD

FDD FRAME STRUCTURE TYPE 1

- Three different time units
  - The *slot* equals $T_{slot} = 15360 \times T_s = 0.5$ 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 TYPE 1

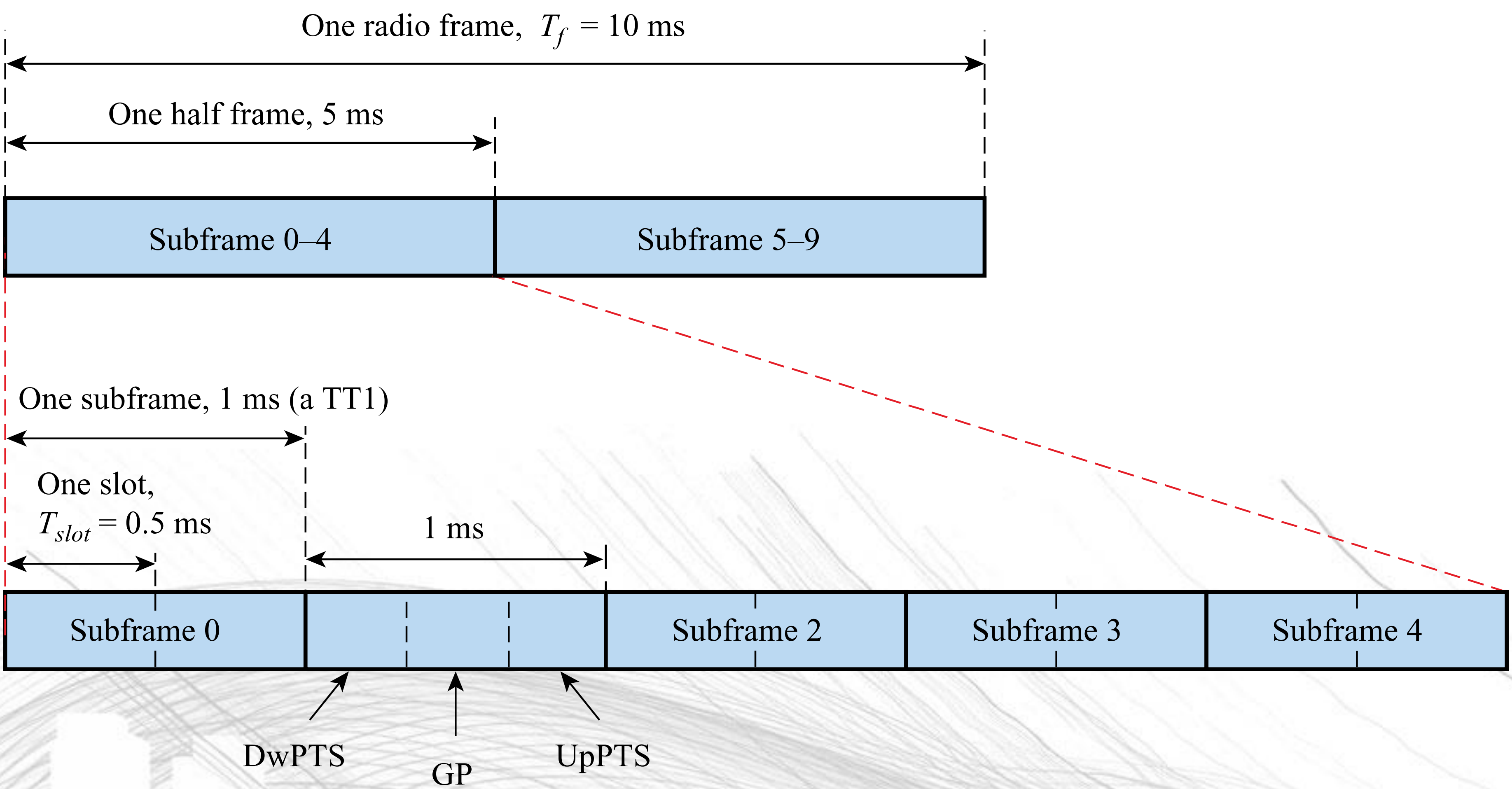
- Normal CP allows 7 OFDM symbols per slot
- Extended CP only allows time for 6 OFDM symbols
  - Use of extended CP results in a 1/7 = 14.3% reduction in throughput
  - But provides better compensation for multipath



14.11 FDD FRAME STRUCTURE, TYPE 1

TDD FRAME STRUCTURE TYPE 2

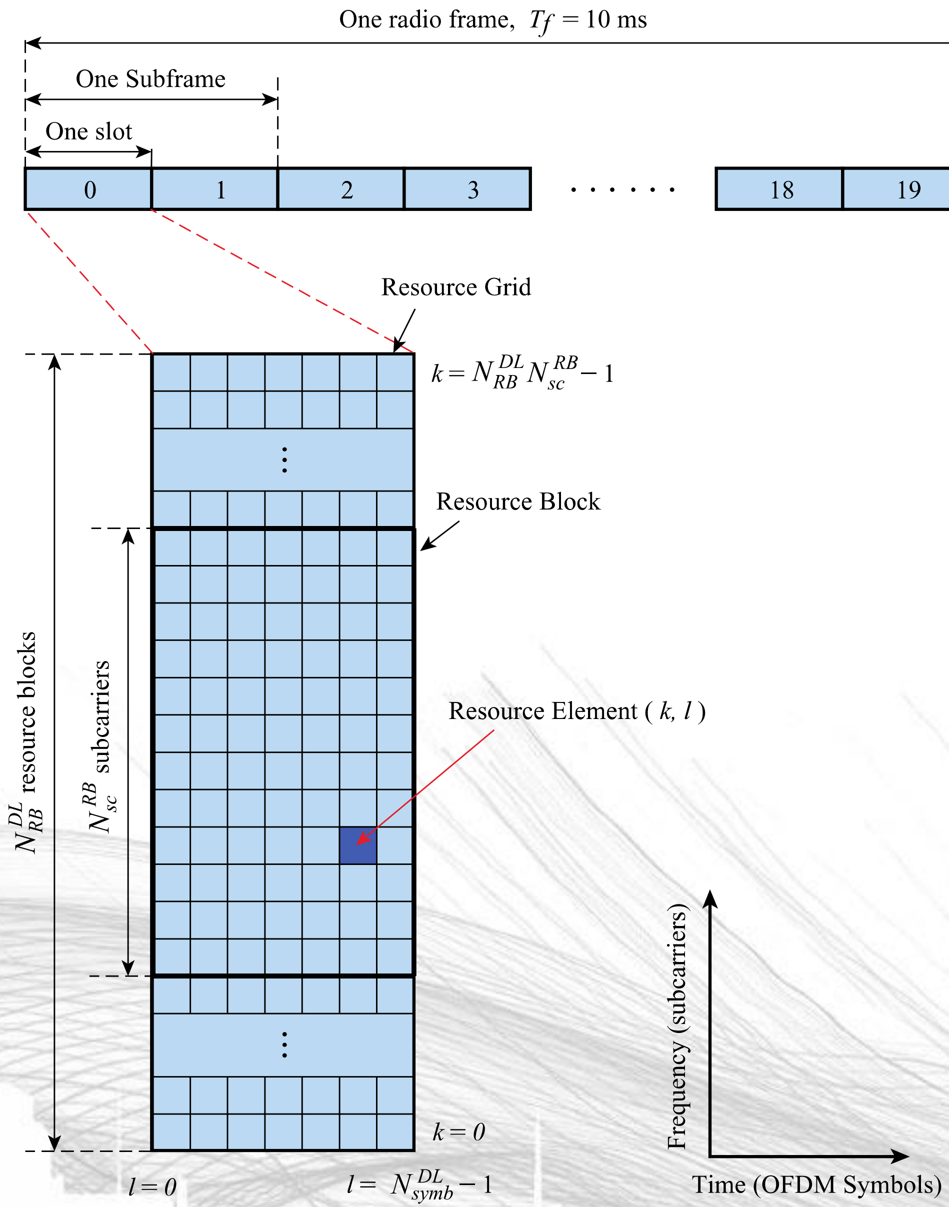
- Radio frame is again 10 ms.
- Includes special subframes for switching downlink-to-uplink
  - Downlink Pilot TimeSlot (DwPTS): Ordinary but shorter downlink subframe of 3 to 12 OFDM symbols
  - Uplink Pilot TimeSlot (UpPTS): Short duration of one or two OFDM symbols for sounding reference signals or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



14.12 TDD FRAME STRUCTURE, TYPE 2

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*

RESOURCE BLOCKS

- MIMO
  - 4×4 in LTE, 8×8 in LTE-Advanced
  - Separate resource grids per antenna port
- eNodeB assigns RBs with channel-dependent scheduling
- *Multiuser diversity* can be exploited
  - To increase bandwidth usage efficiency
  - Assign resource blocks for UEs with favorable qualities on certain time slots and subcarriers
  - Can also include
    - Fairness considerations
    - Understanding of UE locations
    - Typical channel conditions versus fading
    - QoS priorities.

PHYSICAL TRANSMISSION

- Release 8 supports up to 4 × 4 MIMO
- The eNodeB uses the Physical Downlink Control Channel (PDCCH) to communicate
  - Resource block allocations
  - Timing advances for synchronization
- Two types of ⅓ rate convolutional codes
- QPSK, 16QAM, and 64QAM modulation based on channel conditions

PHYSICAL TRANSMISSION

- UE determines a CQI index that will provide the highest throughput while maintaining at most a 10% block error rate

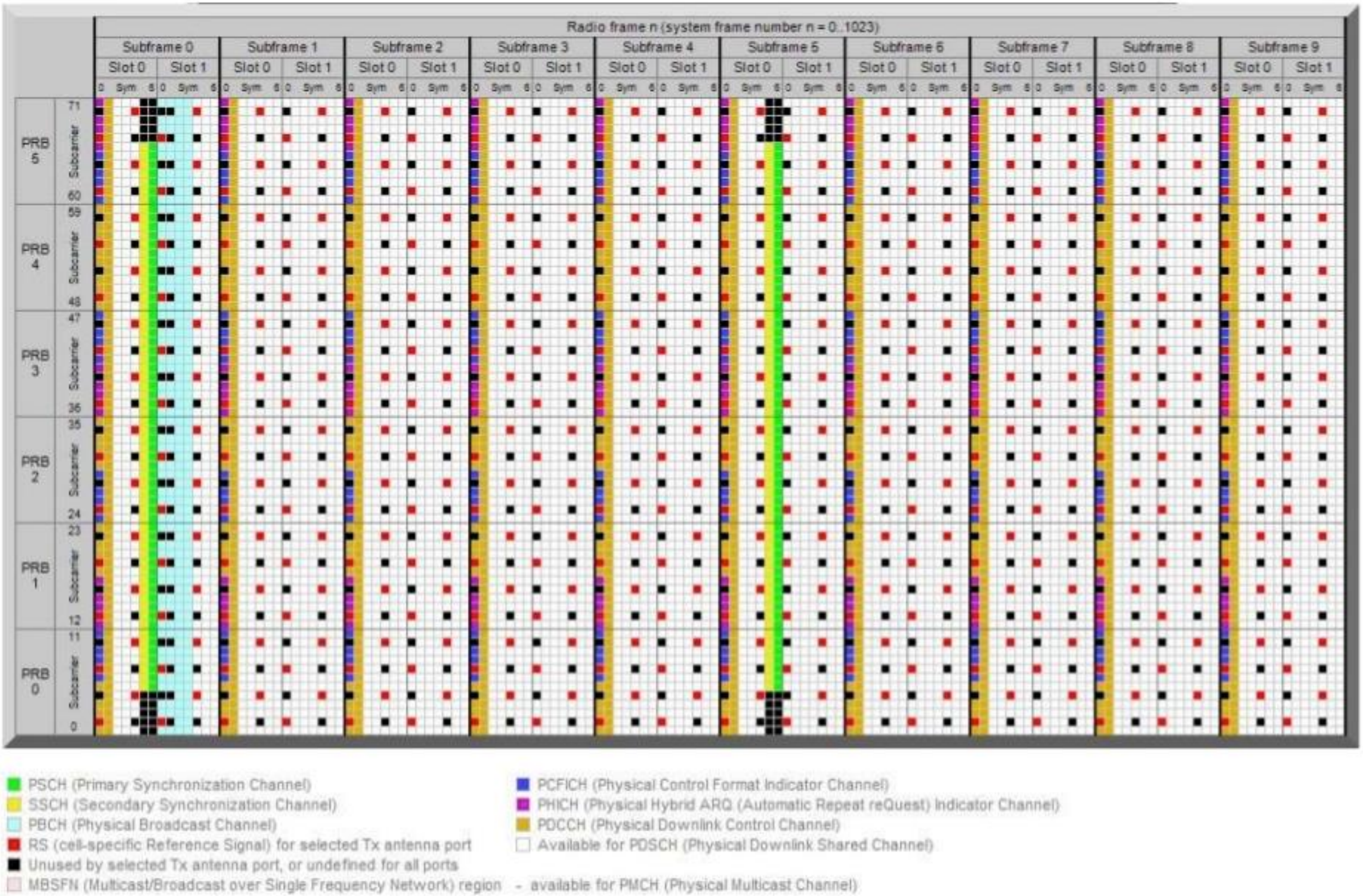
Table 14.7 4-Bit CQI Table

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

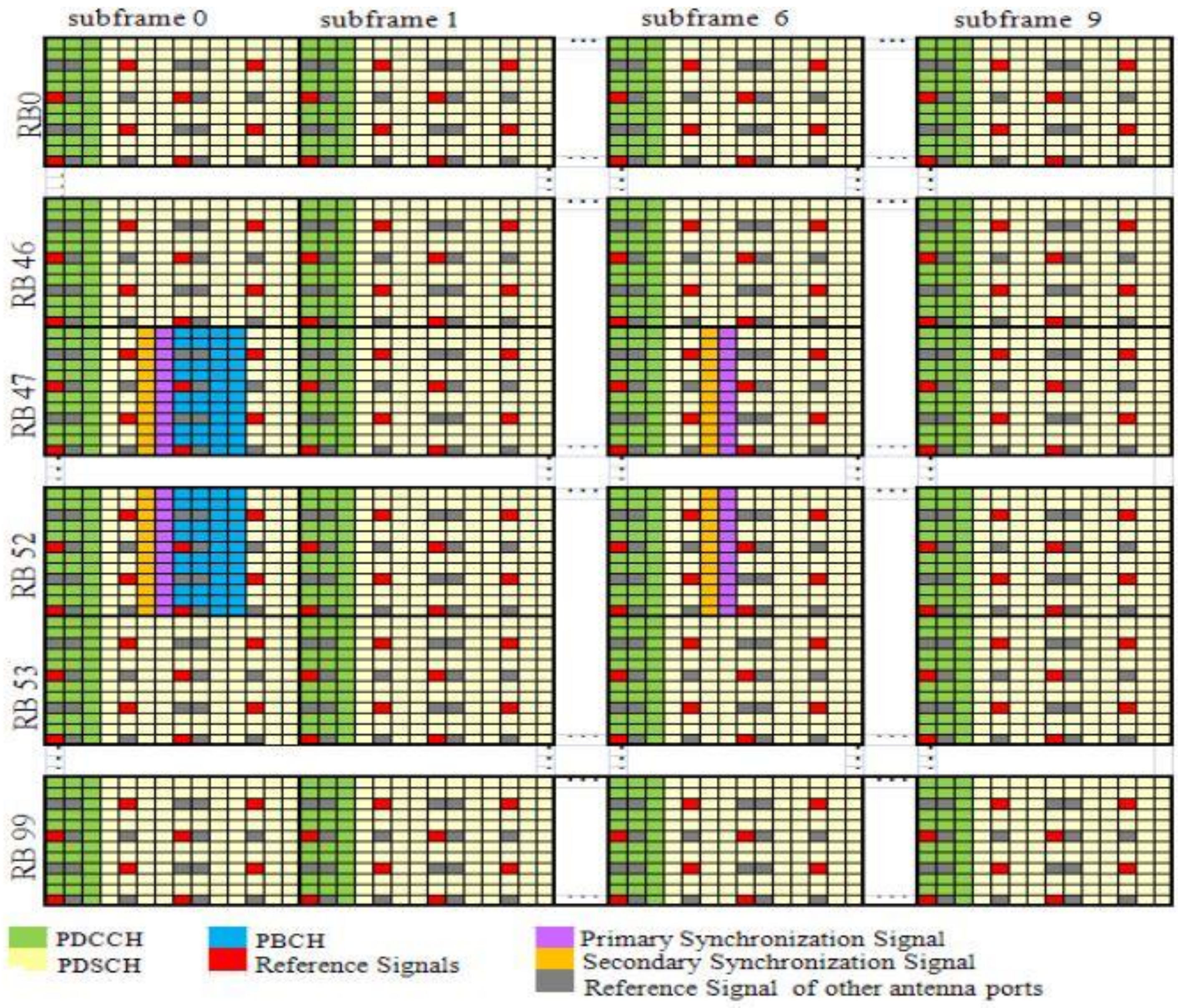
POWER-ON PROCEDURES

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

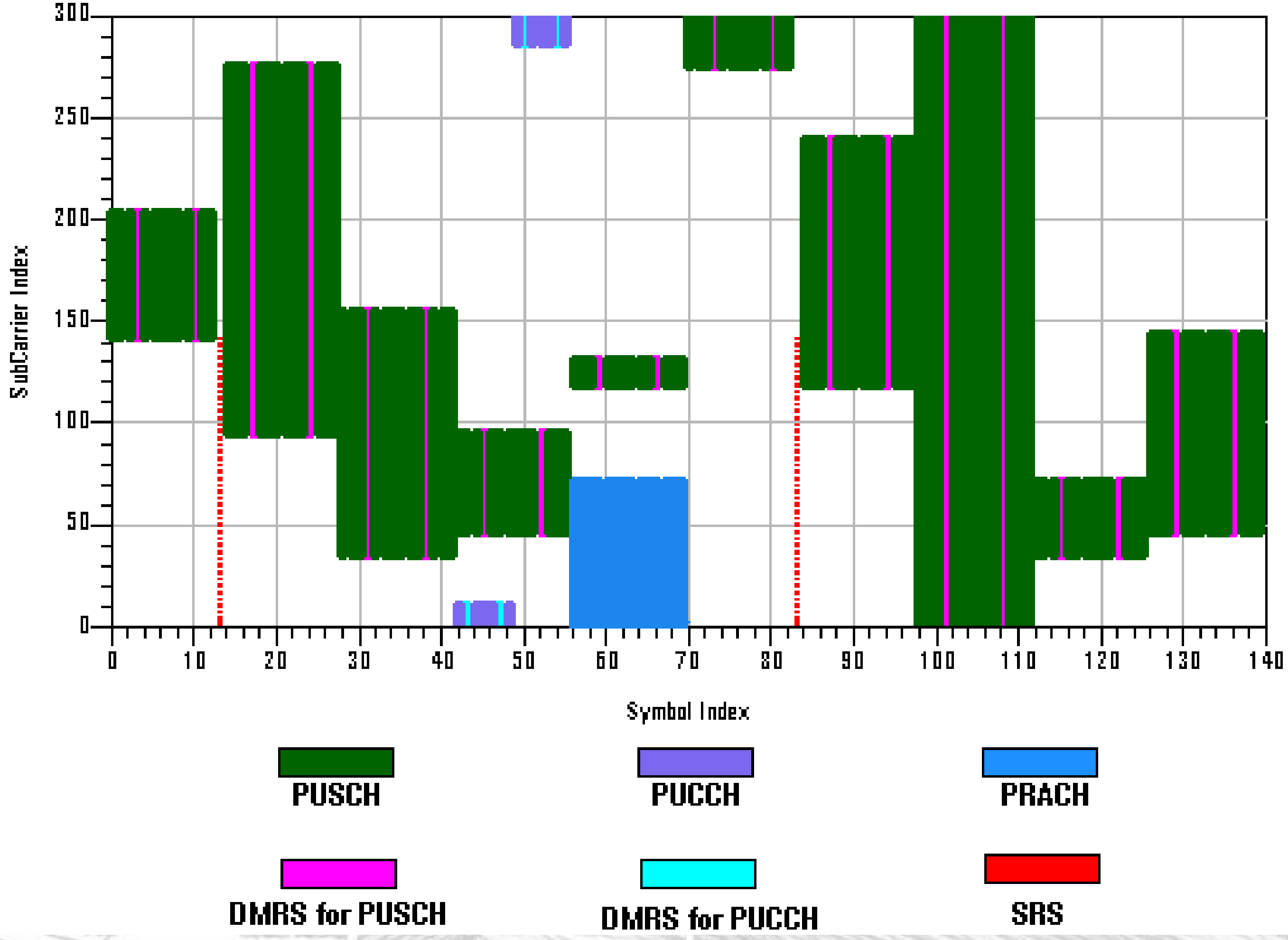
PHY CHANNEL MULTIPLEXING (DL)



PHY CHANNEL MULTIPLEXING (DL)



PHY CHANNEL MULTIPLEXING (UL)

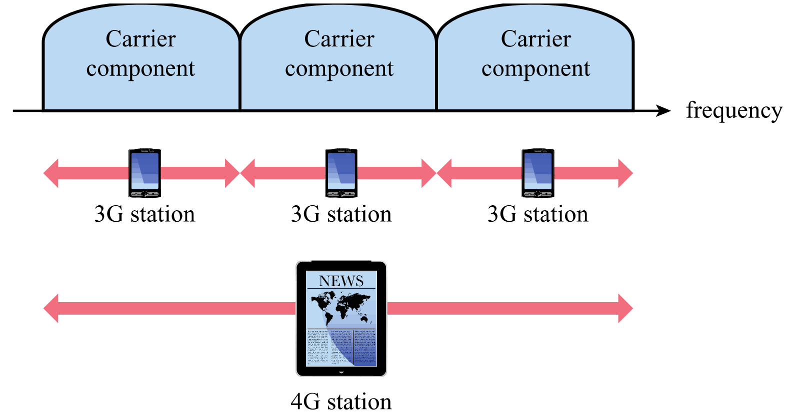


POWER-ON PROCEDURES

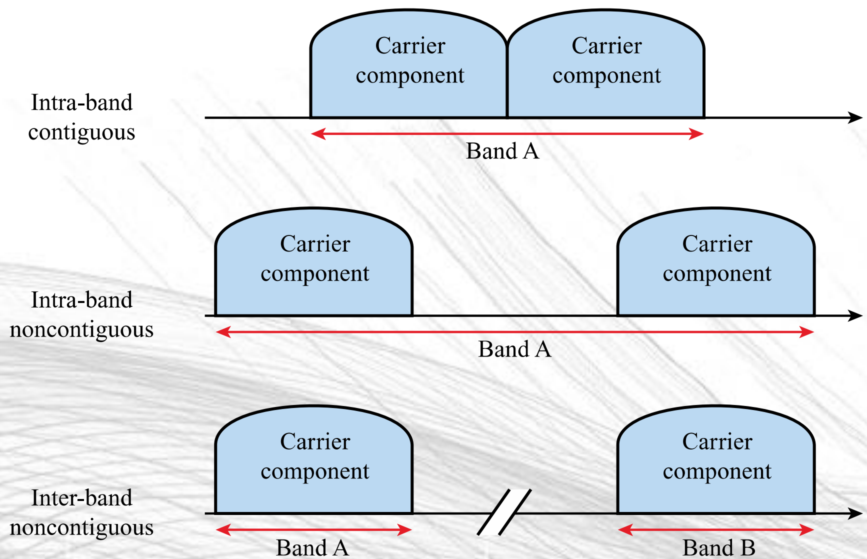
1. Power on the UE
2. Select a network
3. Select a suitable cell
4. Use contention-based random access to contact an eNodeB
5. Establish an RRC connection
6. Attach: Register location with the MME and the network configures control and default EPS bearers.
7. Transmit a packet
8. Mobile can then request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

CARRIER AGGREGATION

- Ultimate goal of LTE-Advanced is 100 MHz bandwidth
  - Combine up to 5 component carriers (CCs)
  - Each CC can be 1.4, 3, 5, 10, 15, or 20 MHz
  - Up to 100 MHz
- Three approaches to combine CCs
  - Intra-band Contiguous: carriers adjacent to each other
  - Intra-band noncontiguous: Multiple CCs belonging to the same band are used in a noncontiguous manner
  - Inter-band noncontiguous: Use different bands



(a) Logical view of carrier aggregation



(b) Types of carrier aggregation

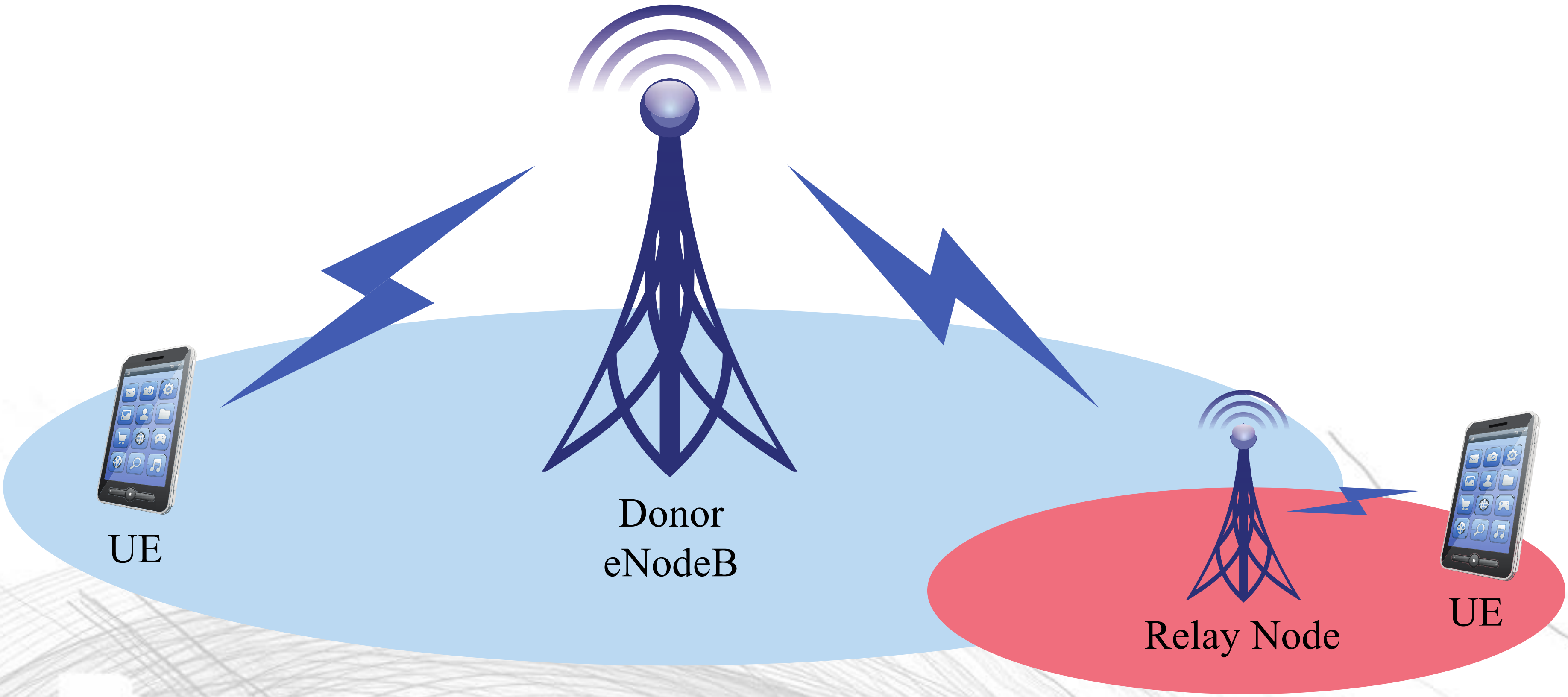
14.14 CARRIER AGGREGATION

ENHANCED MIMO

- Expanded to 8 × 8 for 8 parallel layers
- Or multi-user MIMO can allow up to 4 mobiles to receive signals simultaneously
  - eNodeB can switch between single user and multi-user every subframe
- Downlink reference signals to measure channels are key to MIMO functionality
  - UEs recommend MIMO, precoding, modulation, and coding schemes
  - Reference signals sent on dynamically assigned subframes and resource blocks

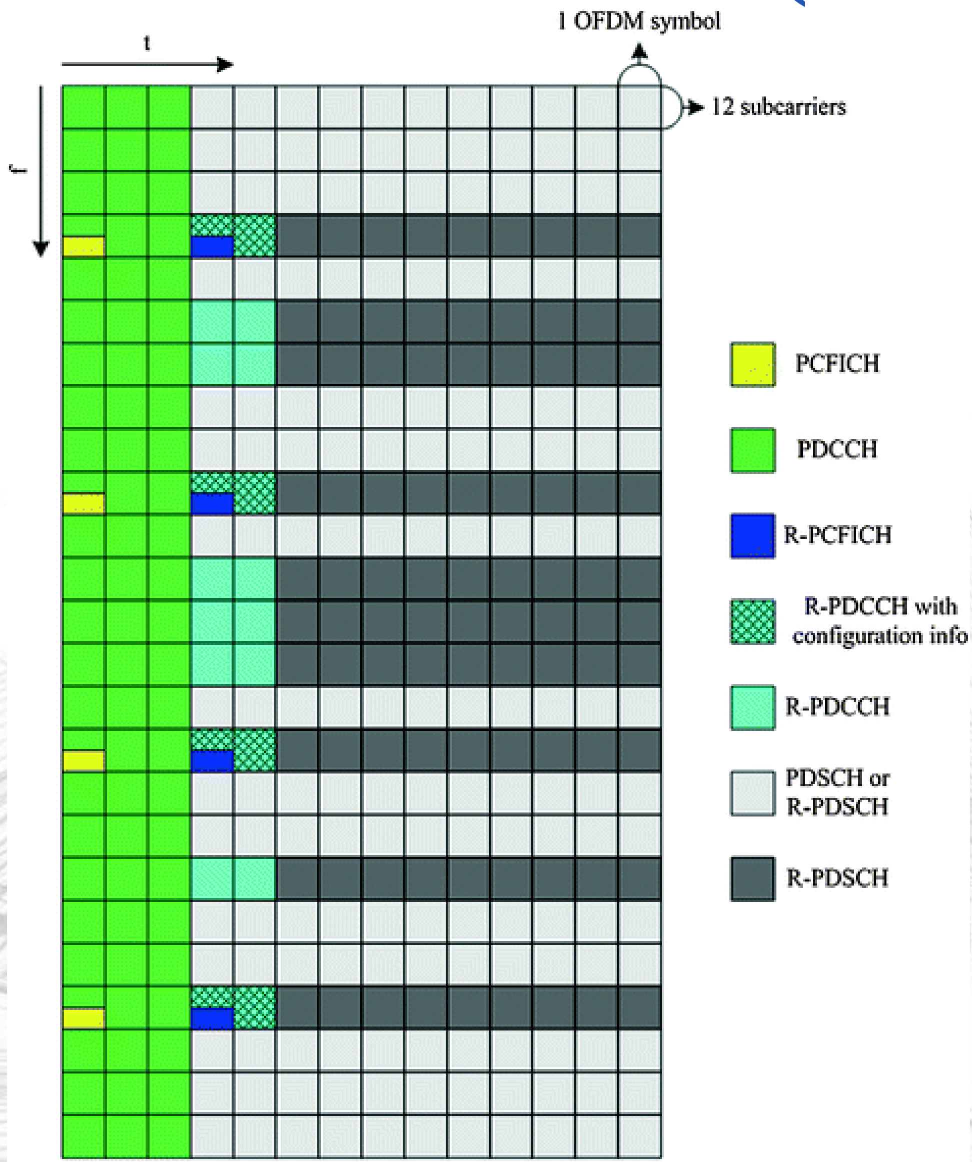
RELAYING

- Relay nodes (RNs) extend the coverage area of an eNodeB
  - Receive, demodulate and decode the data from a UE
  - Apply error correction as needed
  - Then transmit a new signal to the base station
- An RN functions as a new base station with smaller cell radius
- RNs can use out-of-band or inband frequencies



14.15 RELAY NODES

PHY CHANNEL MULTIPLEXING (LTE-A)

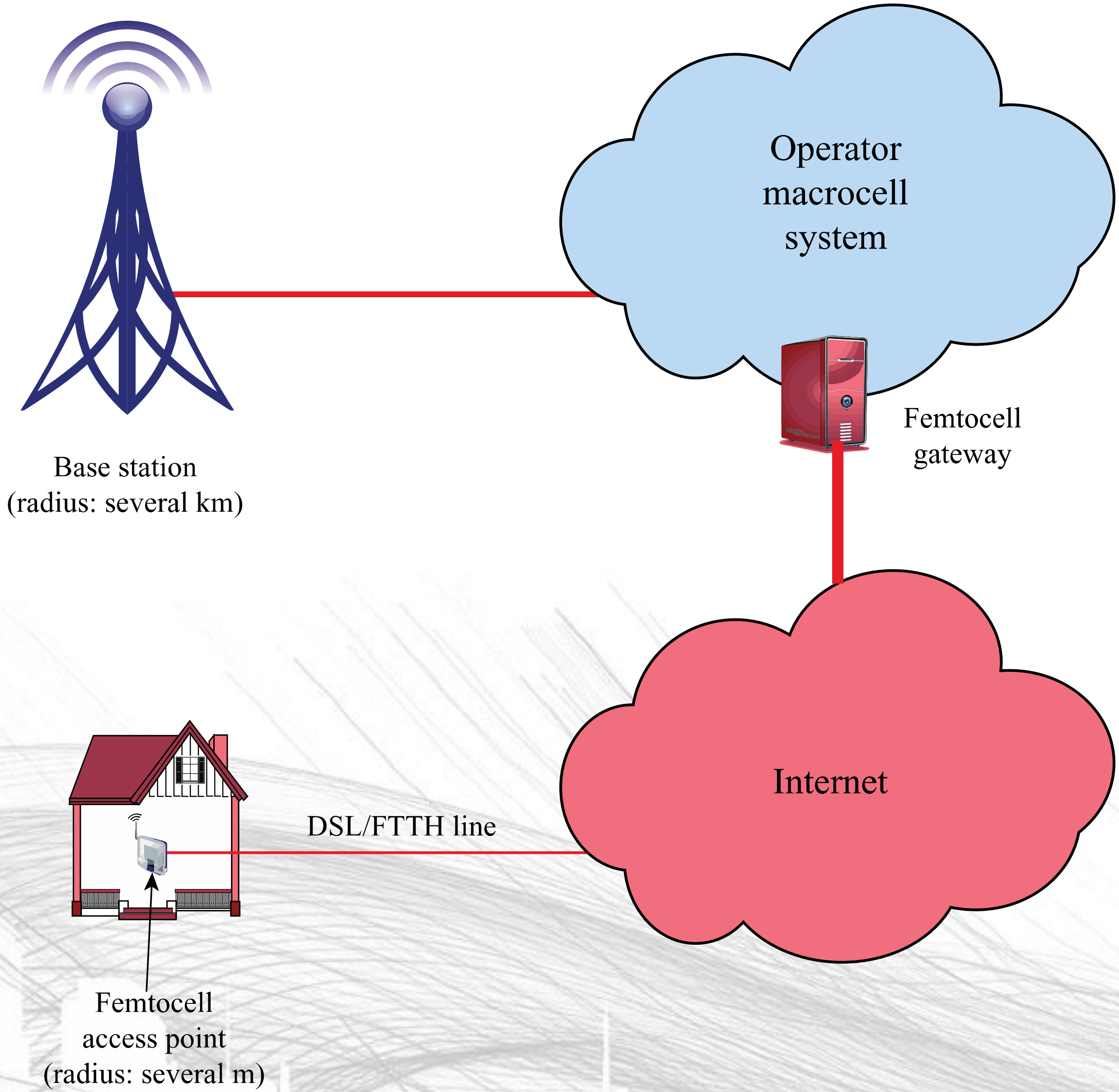


HETEROGENEOUS NETWORKS

- It is increasingly difficult to meet data transmission demands in densely populated areas
- *Small cells* provide low-powered access nodes
  - Operate in licensed or unlicensed spectrum
  - Range of 10 m to several hundred meters indoors or outdoors
  - Best for low speed or stationary users
- *Macro cells* provide typical cellular coverage
  - Range of several kilometers
  - Best for highly mobile users

HETEROGENEOUS NETWORKS

- Femtocell
  - Low-power, short-range self-contained base station
  - In residential homes, easily deployed and use the home’s broadband for backhaul
  - Also in enterprise or metropolitan locations
- *Network densification* is the process of using small cells
  - Issues: Handovers, frequency reuse, QoS, security
- A network of large and small cells is called a *heterogeneous network* (*HetNet*)



14.16 THE ROLE OF FEMTOCELLS

COORDINATED MULTIPOINT TRANSMISSION AND RECEPTION

- Release 8 provides intercell interference coordination (ICIC)
  - Small cells create new interference problems
  - Release 10 provides enhanced ICIC to manage this interference
- Release 11 implemented Coordinated Multipoint Transmission and Reception (CoMP)
  - To control scheduling across distributed antennas and cells
  - *Coordinated scheduling/coordinated beamforming* (CS/CB) steers antenna beam nulls and mainlobes
  - *Joint processing* (JT) transmits data simultaneously from multiple transmission points to the same UE
  - *Dynamic point selection* (DPS) transmits from multiple transmission points but only one at a time

OTHER ENHANCEMENTS IN LTE-ADVANCED

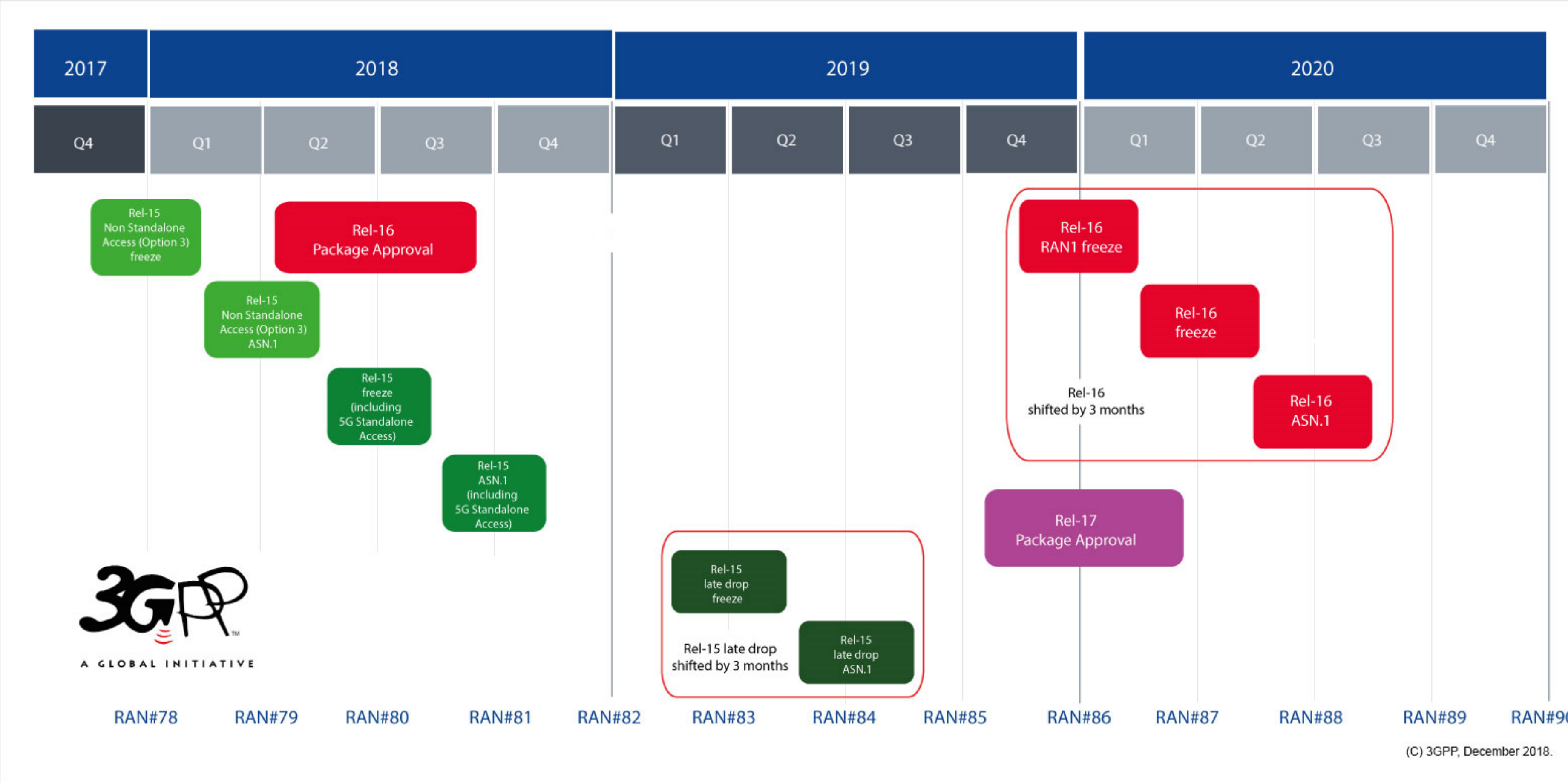
- Traffic offload techniques to divert traffic onto non-LTE networks
- Adjustable capacity and interference coordination
- Enhancements for machine-type communications
- Support for dynamic adaptation of TDD configuration so traffic fluctuations can be accommodated

OTHER ENHANCEMENTS IN LTE-ADVANCED

- Release 12 also conducted studies
  - Enhancements to small cells and heterogeneous networks, higher order modulation like 256-QAM, a new mobile-specific reference signal, dual connectivity (for example, simultaneous connection with a macro cell and a small cell)
  - Two-dimensional arrays that could create beams on a horizontal plane and also at different elevations for user-specific elevation beamforming into tall buildings.
    - Would be supported by *massive MIMO* or *full dimension MIMO*
    - Arrays with many more antenna elements than previous deployments.
    - Possible to still have small physical footprints when using higher frequencies like millimeter waves

VOICE OVER LTE

- The GSM Association is the cellular industry's main trade association
  - GSM Association documents provide additional specifications for issues that 3GPP specifications left as implementation options.
- Defined profiles and services for Voice over LTE (VoLTE)
- Uses the IP Multimedia Subsystem (IMS) to control delivery of voice over IP streams
  - IMS is not part of LTE, but a separate network
  - IMS is mainly concerned with signaling.
- The GSM Association also specifies services beyond voice, such as video calls, instant messaging, chat, and file transfer in what is known as the Rich Communication Services (RCS).



13.13 EVOLUTION OF 5G