GRANELLI Lab

Researching the Internet of the Future

Networking II

Cellular Networks

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Cellular Networks

- Architecture
- Standards (GSM to LTE)
- Focus on LTE

Table of Contents

- Wireless spectrum and cellular bands
- Important cellular concepts
- Overview of cellular standards
- GSM, UMTS, and LTE:
  - Network components, Architecture and Protocols
- Focus on LTE

What is LTE

- LTE is Long Term Evolution
- Fourth generation cellular technology standard from the 3rd Generation Partnership Project (3GPP)
- Deployed worldwide and installations are increasing
- All implementations must meet baseline requirements
  - Increased Speed
  - Multiple Antennas (i.e., MIMO)
  - IP-based network (All circuits are gone/fried!)
  - New air interface: OFDMA (Orthogonal Frequency-Division Multiple Access)
  - Also includes duplexing, timing, carrier spacing, coding…
- LTE is always evolving and 3GPP often drops new "releases"
  - This class is modeled around LTE-Advanced, but we won't dig deep enough to tell

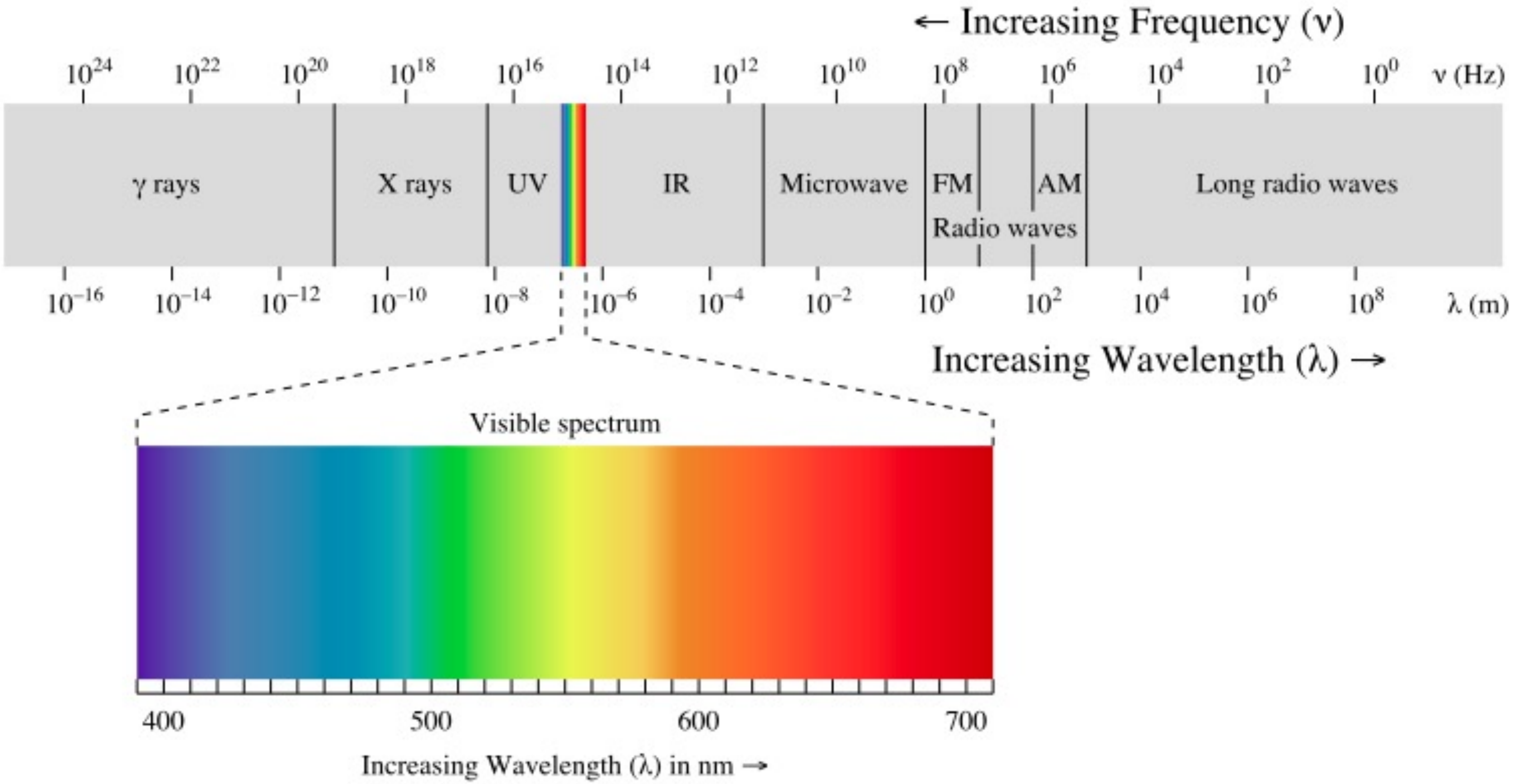
Cellular Network Operators

- Telecommunications company (telco)
  - Purchases spectrum
  - Builds out network (base stations and backhaul network)
  - Verizon, AT&T, T–Mobile, Sprint
- Mobile Virtual Network Operator (MVNO)
  - Does not have to purchase spectrum
  - Rents the towers but runs a distinct network
  - Cricket, Ting, MetroPCS, …

Radio Frequency Spectrum

- Describes a range of frequencies of electromagnetic waves used for communication and other purposes
- RF energy is alternating current that, when channeled into an antenna, generates a specific electromagnetic field.
- This field is can be used for wireless communication
- Typically, cellular spectrum ranges from 300 MHz to 3 GHz

EM Spectrum



Thanks to Wikipedia

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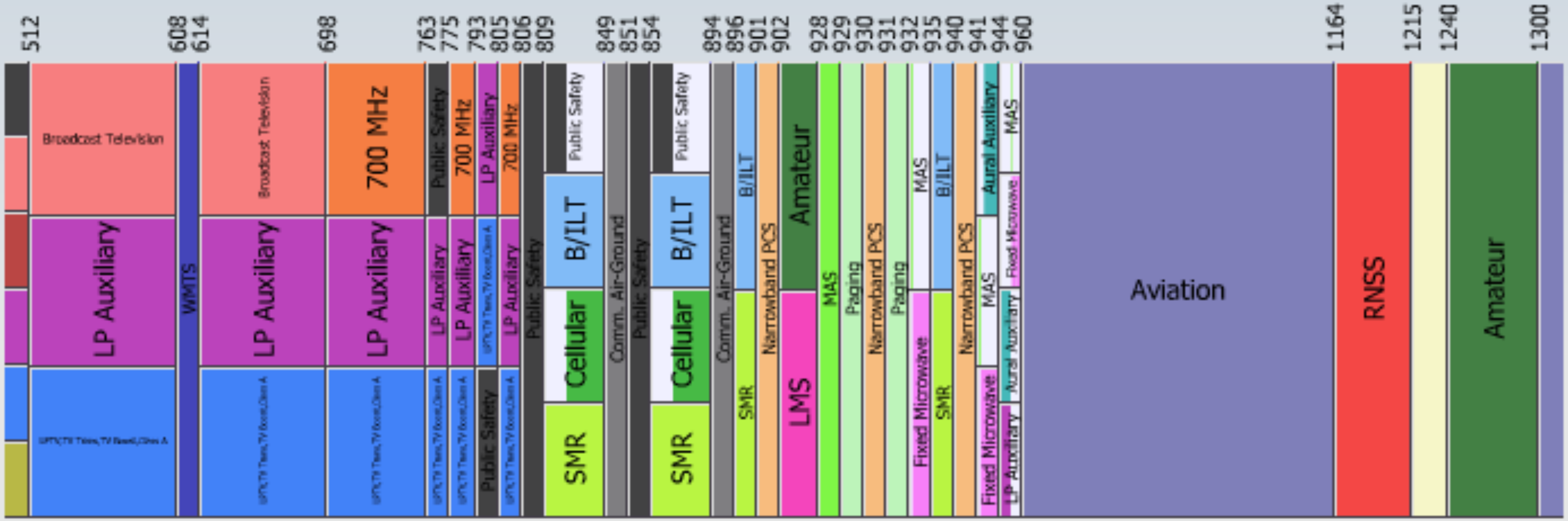
Wireless Spectrum



From an interactive map available via the FCC

Popular Cellular Bands

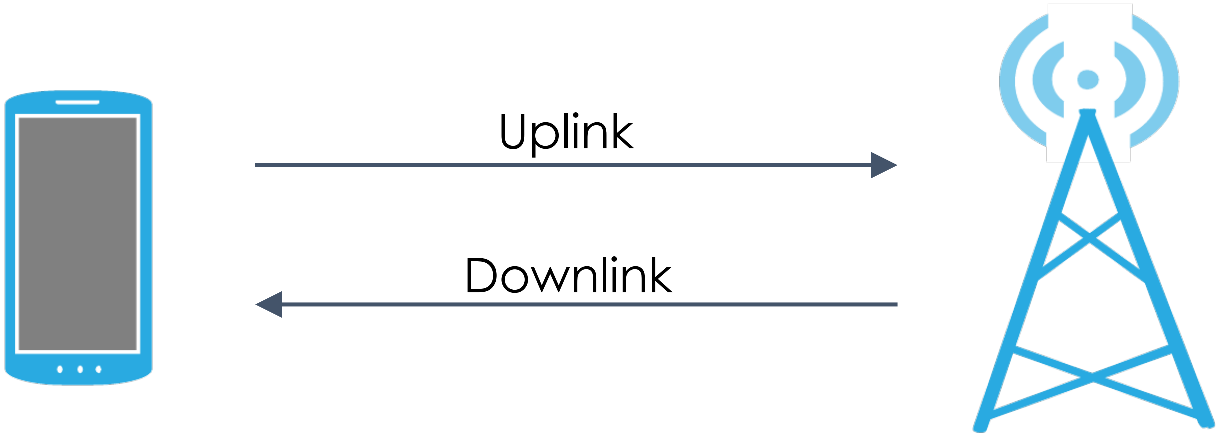
- 700 Mhz Band (Blocks A – E)
  - Considered uniquely useful to cellular activities
  - Verizon, US Cellular, AT&T and others own various portions
  - Will be used for 4G
  - Includes reserved spectrum for public safety
- 850 MHz
  - Great for cellular service
  - Easily bounces off objects
- 1900 MHz band (PCS)
- 2100 MHZ (Blocks A – F)
  - Mostly T-Mobile, but includes Cricket and MetroPCS
- This information changes periodically as spectrum is purchased & released

Chipset

- In the past, phones have typically been tied to a single carrier
- A phone's hardware is tied to a carrier based on many things (like the IMEI), but the major ones are the cellular standard and frequencies the carrier uses
- Phones are manufactured to work on specific radio frequencies
  - Specific chips needed for a given frequency range, thus chipset
- Nowadays, phones concurrently operate on many frequencies (and therefore networks)
  - Modern multi-band chips allow a single device to operate on multiple frequency ranges

Channel Allocation

- Typically there is a downlink channel and an uplink channel
- These channels needs to be spaced in frequency sufficiently far so that they do not interfere with each other



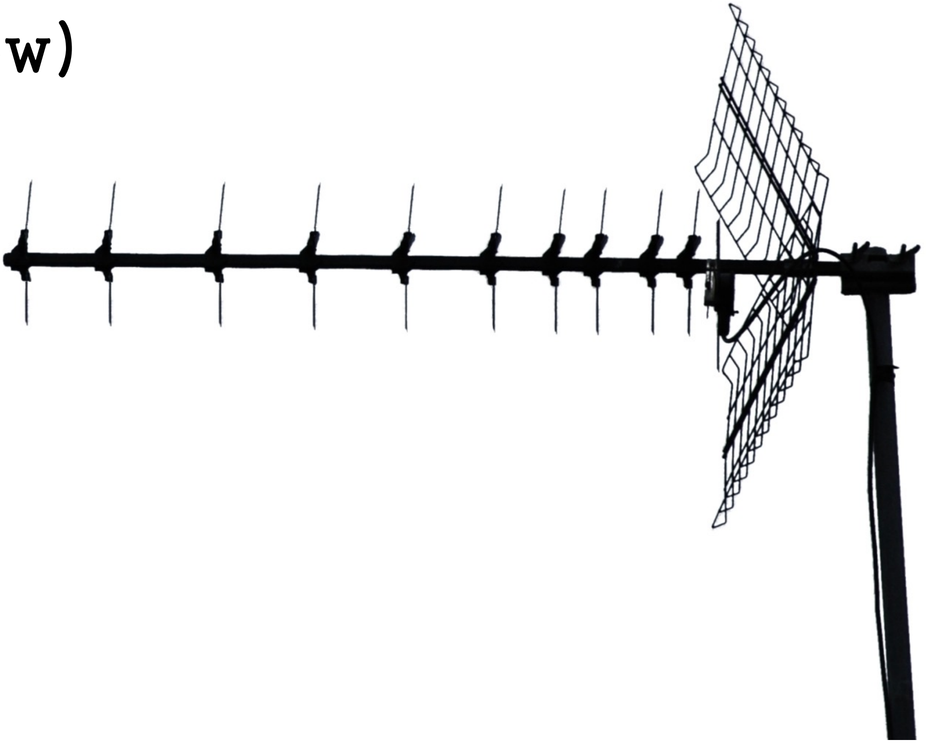
Antenna

- There are 2 main types of antennas, each with unique properties
- Omnidirectional
  - Emits energy in a spherical radius
- Directional
  - Emits energy in the shape of the antenna and in the direction and angle at which it is pointed

Directional Antenna

- Designed to radiate in a specific direction
  - The radiation is focused (see below)

- There are "panel" direction antennas on the front cover of this presentation



Omnidirectional Antenna

- Designed to radiate in across a specific plane
  - The radiation spreads outward from a center point
  - A donut is a reasonable visual

Device Antenna

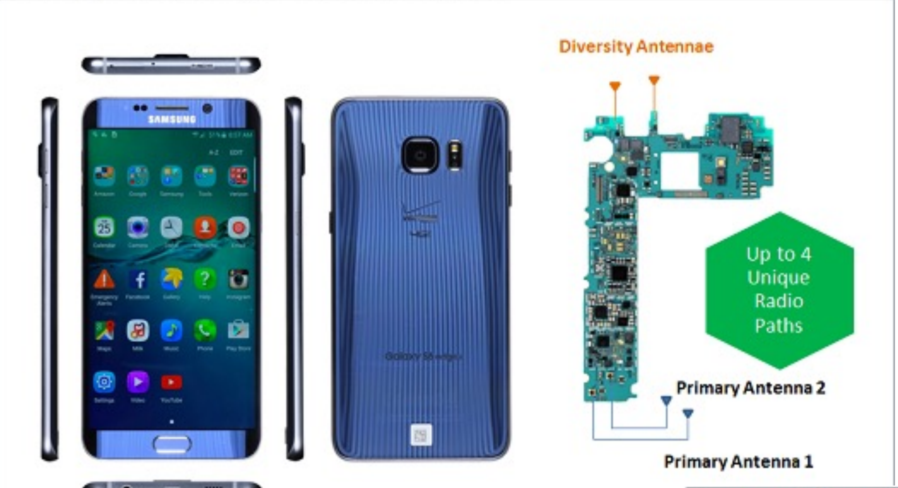
- There are multiple antenna in your mobile device – although some are shared
- Designed to transmit and receive at various frequencies
  - Cellular (300 MHz – 3 GHz)
  - WiFi (Primarily 2.4 GHz, 5 GHz) [there are other odd frequencies specified]
  - Bluetooth (2400–2480 MHz)
  - NFC (13.56 MHz)

Multiple Antennas

- LTE has a feature called Multiple-Input Multiple-Output (MIMO)
- Multiple antennas are on the mobile device and are used simultaneously to transmit and receive
  - Can significantly increase throughput
- Multiple types
  - Spatial diversity
  - Spatial multiplexing
- Further divided:
  - SISO – Single in, single out
  - SIMO – Single in, multiple out
  - MISO – Multiple in, single out
  - MIMO – Multiple in, multiple out

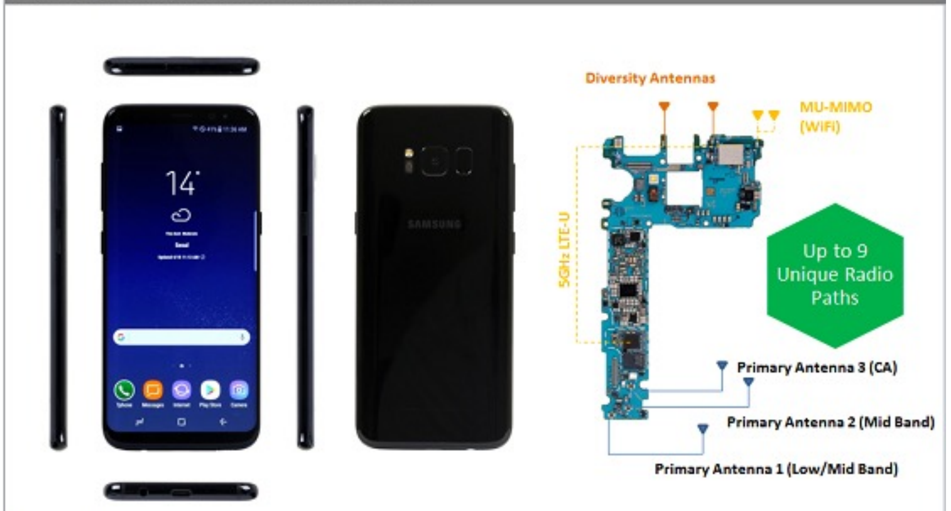
Multiple Antennas

Samsung Galaxy S6 Edge + Antennae Locations



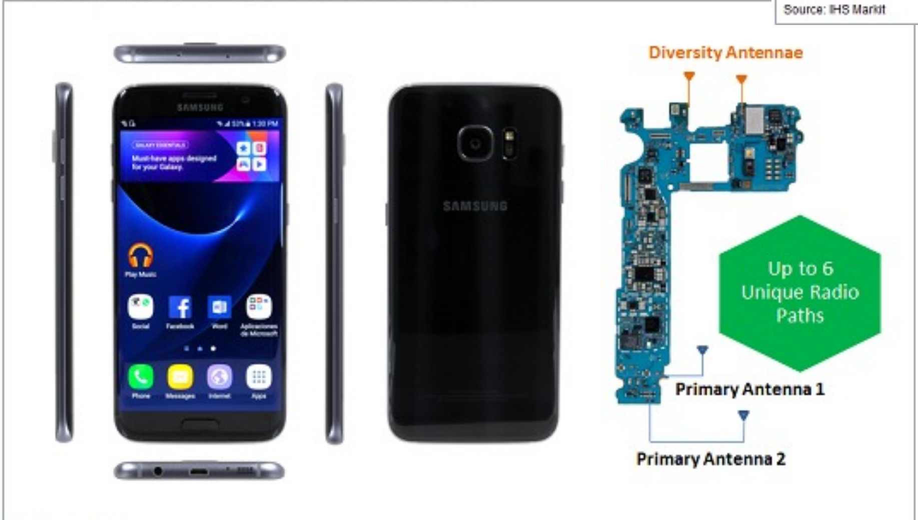
Source: IHS Markit

Samsung Galaxy S8 Antennae Locations


Diversity Antennas
MU-MIMO (WiFi)
5GHz LTE-U
Up to 9 Unique Radio Paths
Primary Antenna 3 (CA)
Primary Antenna 2 (Mid Band)
Primary Antenna 1 (Low/Mid Band)

Source: IHS Markit

Samsung Galaxy S7 Edge Antennae Locations



Source: IHS Markit

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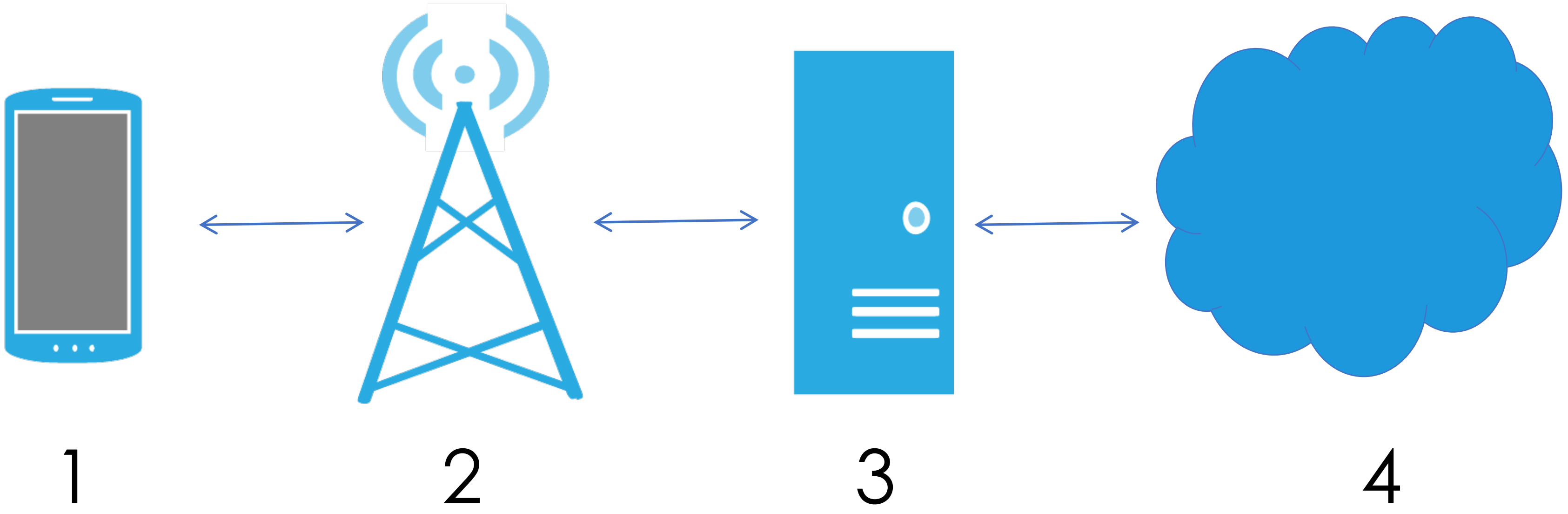
The Big Picture

Mobile devices (1) connect to a base station (2) which connects to a backhaul network (3), which connects to the internet (4).



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Network Components

- The network between mobile devices and base stations is the Radio Access Network (RAN)
  - This name slightly changes with new standards
- Base stations are permanent cellular sites housing antennas
- Base stations and the backhaul network are run by telco, but there are interconnections and shared sites
  - AT&T customers need to be able to contact Verizon (vice versa)
- Base stations often connect to backhaul via wired technologies (i.e., fiber)
  - Base stations often communicate with each other via wireless

Mobile Devices

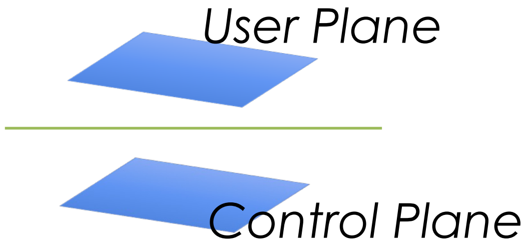
- These are the devices with wireless radios that connect to cell towers
  - Radios are inside phones, tablets, laptops, etc. . .
- LTE uses the term User Equipment (UE), previously ~ Mobile Station (MS)
- The parts of the UE we are concerned with:
  - The handset, aka the ME (Mobile Equipment)
  - USIM (Universal SIM)
  - Baseband processor

Baseband

- Typically a separate processor on the phone
  - From companies like Qualcom, Infineon, etc.
- Handles all of the telecommunications-related functions
  - Sends, receives, processes signals
  - Base station and backhaul network communication
  - Has direct access to microphone, speakers…
- Runs a real time operating system (RTOS)
  - Performance matters!
  - OSs include ThreadX, Qualcomm's AMSS w/ REX kernel, OKL4
- Sometimes shares RAM with application processor (baseband as a modem), sometimes each processor has distinct RAM(shared architecture)
  - In a shared configuration the baseband is often the master
- May be virtualized

Planes of Communication

- Many control systems divide communication into two planes – one for processing information from users and another for how to setup/breakdown the channel and other important functions
- Think of this similar to how FTP uses two ports
  - TCP port 20 – data
  - TCP port 21 – control



- Control Plane (CP)
  - A private communication channel that is distinct from data the UE operator can influence
  - Used to send control messages to components
  - Mobile users should not be able to influence this in any way
- User Plane (UP) signaling
  - Voice and data information
- Cellular networks use this design extensively

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Packets and Circuits

- Pre–LTE, cellular networks used circuit switching technology for voice
  - LTE uses VoLTE which is VoIP over LTE
  - Not implemented currently, calls fall back to previous networks
- Data traffic is sent over nearly distinct interconnected packet switching networks
  - GSM first used GPRS, then moved to EDGE
  - UMTS used HSPA technologies including HSPA+
- Since LTE is completely IP based, it does not use circuits (sort of… e.g. GTP Tunnels)

Network Interconnection

- Circuit switched networks need to be able to connect with packet switched networks and other distinct cellular networks
  - The internet is a good example
  - This is a complex process
- GPRS (General packet radio service)
  - 2.5G packet switched technology
- EDGE (Enhanced Data Rates for GSM Evolution)
  - 2.75G packet switched technology
- HSPA (High Speed Packet Access)
  - 3.5/3.75 packet switched data technology
  - There were a few quick iterations on this technology, thus "variants"

Attachment, Handoff, & Paging

- The first step in a mobile device connecting to a network is referred to as network attachment
  - Mobile devices request network access to a base station, which passes this request onto the backhaul network
  - Authentication of the mobile device is then performed
- If a mobile device is moving (such as on a freeway) a call will need to be transferred from one base station to another
  - This is called handoff
  - This is a very common, yet is complex, process
- Paging is the process of how a backhaul network locates and directs calls a mobile device
  - Base stations provide a list of active devices to the backhaul

Connection Management

- EPS (Evolved Packet System) Connection Management (ECM)
  - describes the signalling connectivity between the UE and the EPC
- UE related information is released after a certain period of time without use or connection
- ECM-states
  - ECM-CONNECTED
  - ECM-IDLE
- TS 23.401 for more information

Subscriber Identity

- GSM, UMTS, and LTE all contain a unique ID for a cellular subscriber
  - International Mobile Subscriber Identity (IMSI)
  - 15 digit number stored on the SIM
- Consists of 3 values: MCC, MNC, and MSIN
  - Possibly a software version (SV) appended (IMSI-SV)
- Mobile Country Code (MCC) – Identifies the country
- Mobile Network Code (MNC) – Identifies the network
- Mobile Subscriber ID number (MSIN) – Identifies a user
- Temporary identities also exist
  - Temporary Mobile Subscriber Identity (TMSI)
  - Globally Unique UE Identity (GUTI)
- This information is stored on the SIM/USIM
- Mobile Subscriber ISDN Number (MSISDN) – The phone number, which is distinct from the MSIN

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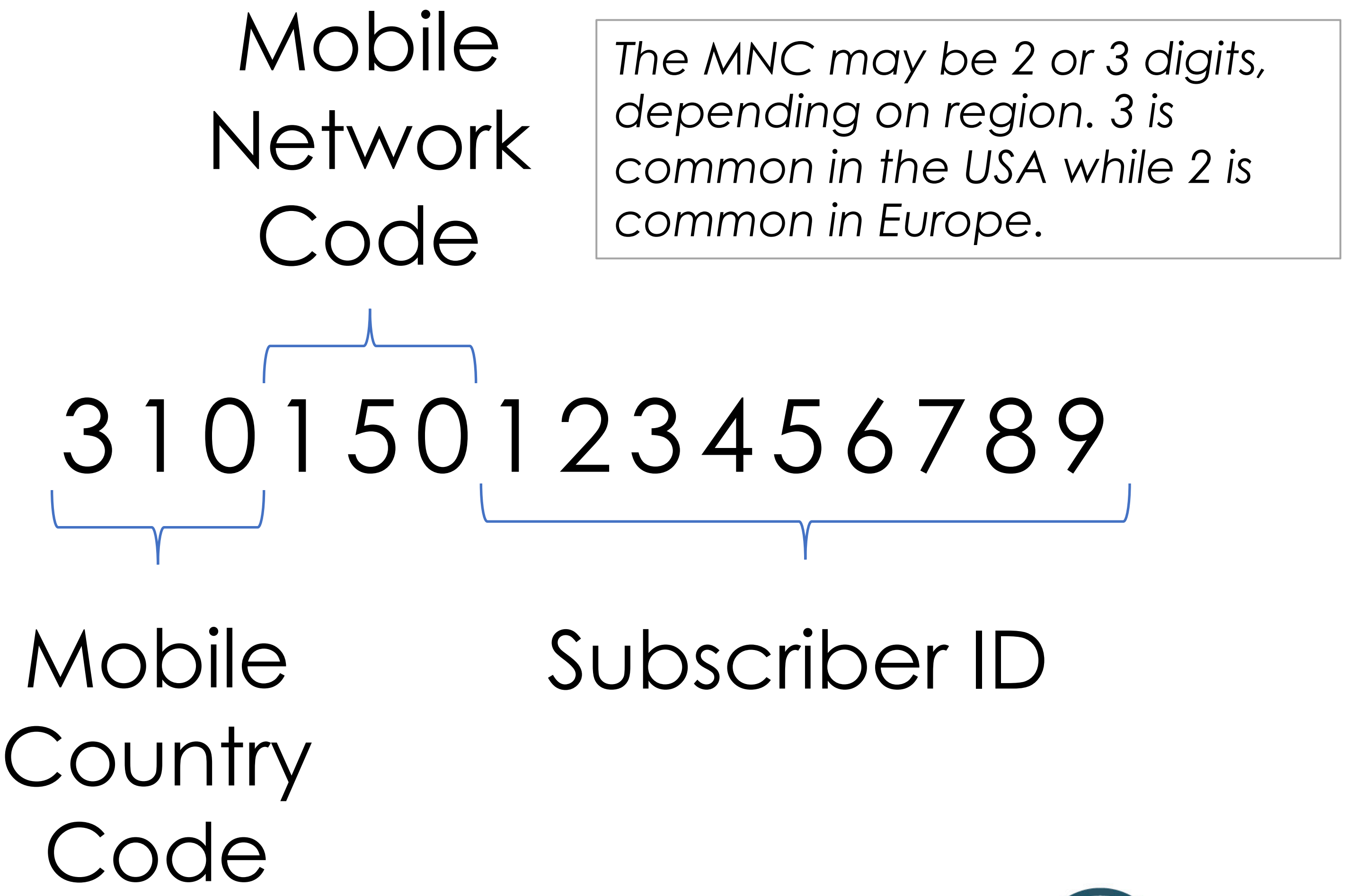
IMSI Example



3 1 0 1 5 0 1 2 3 4 5 6 7 8 9

The MNC may be 2 or 3 digits, depending on region. 3 is common in the USA while 2 is common in Europe.

Thanks to Wikipedia for the sample IMSI

Terminal Identity

- GSM, UMTS, and LTE all contain a unique ID for a terminal ME/UE
    - International Mobile Equipment Identity (IMEI)
- It is 16 digits with the first 14 indicating equipment identity
    - The last 2 indicates software version (SV)
    - Referred to as IMEISV
- Dial *#06# to display your IMEI
- Illegal in some countries to change a phone's IMEI

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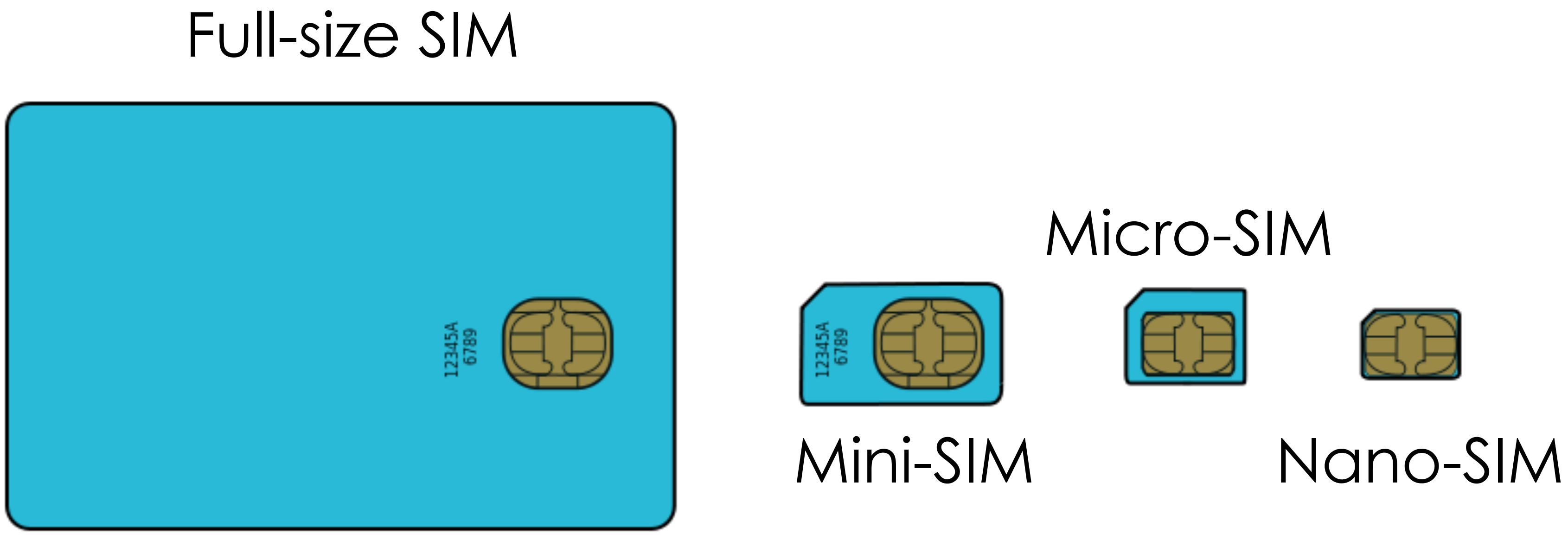
SIM Cards

- A removable hardware token used for GSM, UMTS, and LTE
  - Verizon is changing to LTE and is also using the hardware token
- Over 7 billion SIMs in circulation
- Houses a processor and runs an OS
- Java Card runs atop the OS, which is a type of Java Virtual Machine (JVM) for applications
- Stores cryptographic keys and sometimes SMSs and contacts
- SIM application toolkit (STK) is used to create mobile applications
- SIMs are deprecated – the modern term is USIM
  - The USIM runs atop the UICC which is the physical card

SIM Card



From left to right, we are only removing plastic. The integrated circuit remains static.

Thanks to [Wikipedia]

3GPP

- An international standards body
- Evolves and/or standardizes GSM, UMTS, LTE among others
- From their page:

The 3rd Generation Partnership Project (3GPP) unites [Six] telecommunications standard development organizations (ARIB, ATIS, CCSA, ETSI, TTA, TTC), known as “Organizational Partners” and provides their members with a stable environment to produce the highly successful Reports and Specifications that define 3GPP technologies

- We will primarily discuss 3GPP standards
- Other standards exist from a distinct standards body known as 3GPP2
  - CDMA2000 and the now deprecated UMB

Major Standards

- Multiple standards bodies involved
- Standards grow and evolve from one another

- GSM
- CDMA
- UMTS
- EV-DO
- WiMAX
- LTE

Cellular Standards

2G	GSM		Cdma One	
2.5G		GPRS		
2.75G		EDGE		
3G	UMTS		CDMA 2000	
3.5G		HSPA/+	CDMA EV-DO	
4G		LTE	~~UMB~~	WiMAX

A Note on 3GPP

- LTE is a 3GPP specification
  - Therefore we will be discussing 3GPP specifications in depth
- We will introduce GSM
- We will then build on these concepts from GSM to UMTS to LTE
- Packet switched technologies will be discussed as well
- WiMax Forum standards are not included

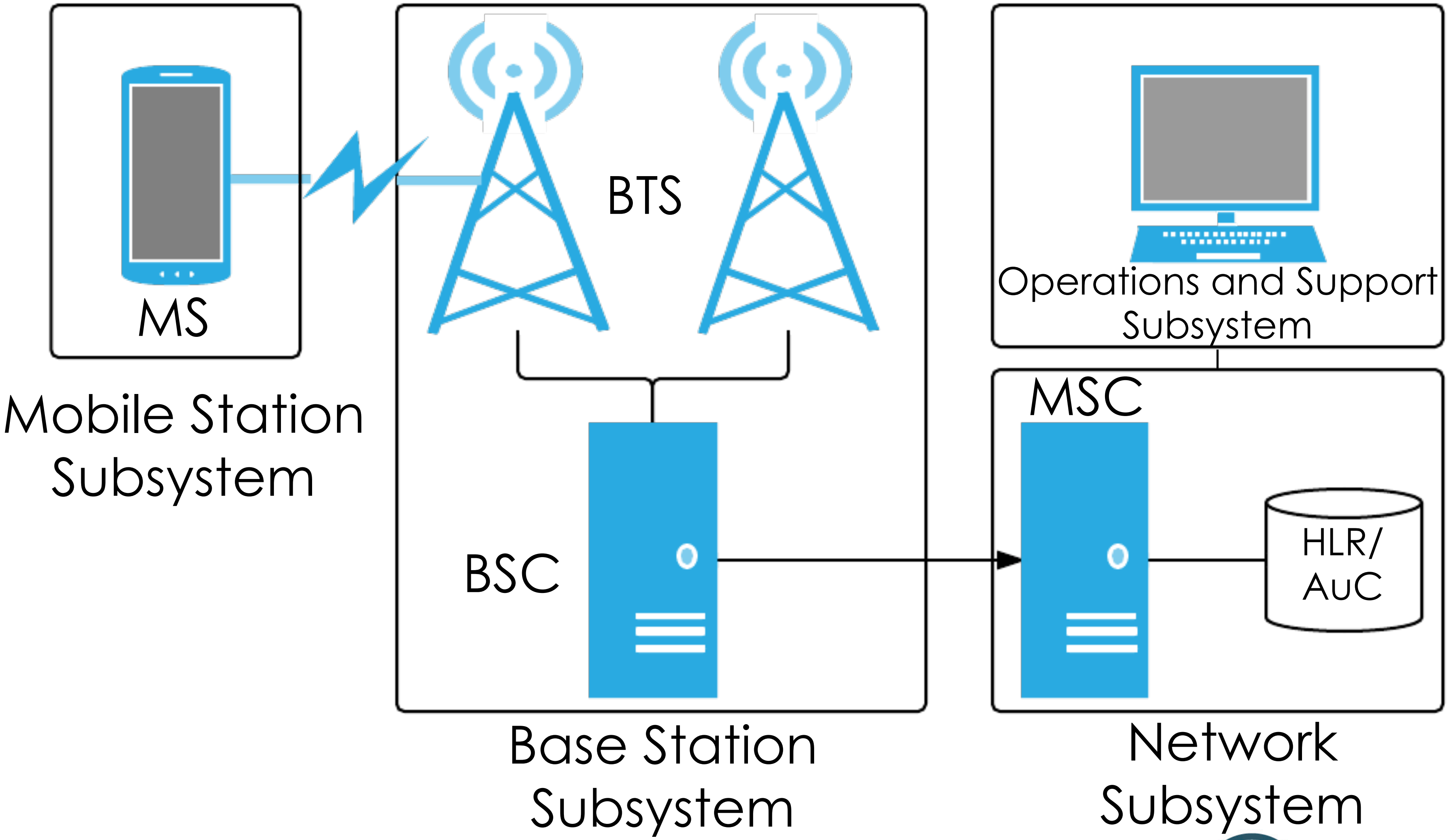
GSM

- Global System for Mobile Communications
- 2G digital voice
- Air interface: TDMA
  - Multiple users on the same channel
- Operates at various spectrums worldwide
- There are 4 separate systems:
  - Base station subsystem (BSS)
  - Network subsystem (NSS)
  - Operations and support subsystem (OSS)
  - Mobile station subsystem (MSS)
- Each subsystem has a distinct purpose

GSM Components Description

- Mobile station subsystem (MSS)
  - Mobile handset and SIM
- The base station subsystem BSS consists of a controller and transceiver
  - Base station transceiver (BTS) is the cell tower
  - Base station controller (BSC) controls 1 or more BTSs
  - Housed at the Mobile Telephone Switching Office (MTSO)
- Network subsystem (NSS):
  - MSC (Mobile Switching Center) and MTSO
  - MTSO–switch connects cell network to PSTN
  - MTSO houses the HLR, which supports the AuC
- Operations and Support (OSS)
  - Manages the network as a whole

GSM Architecture Diagram



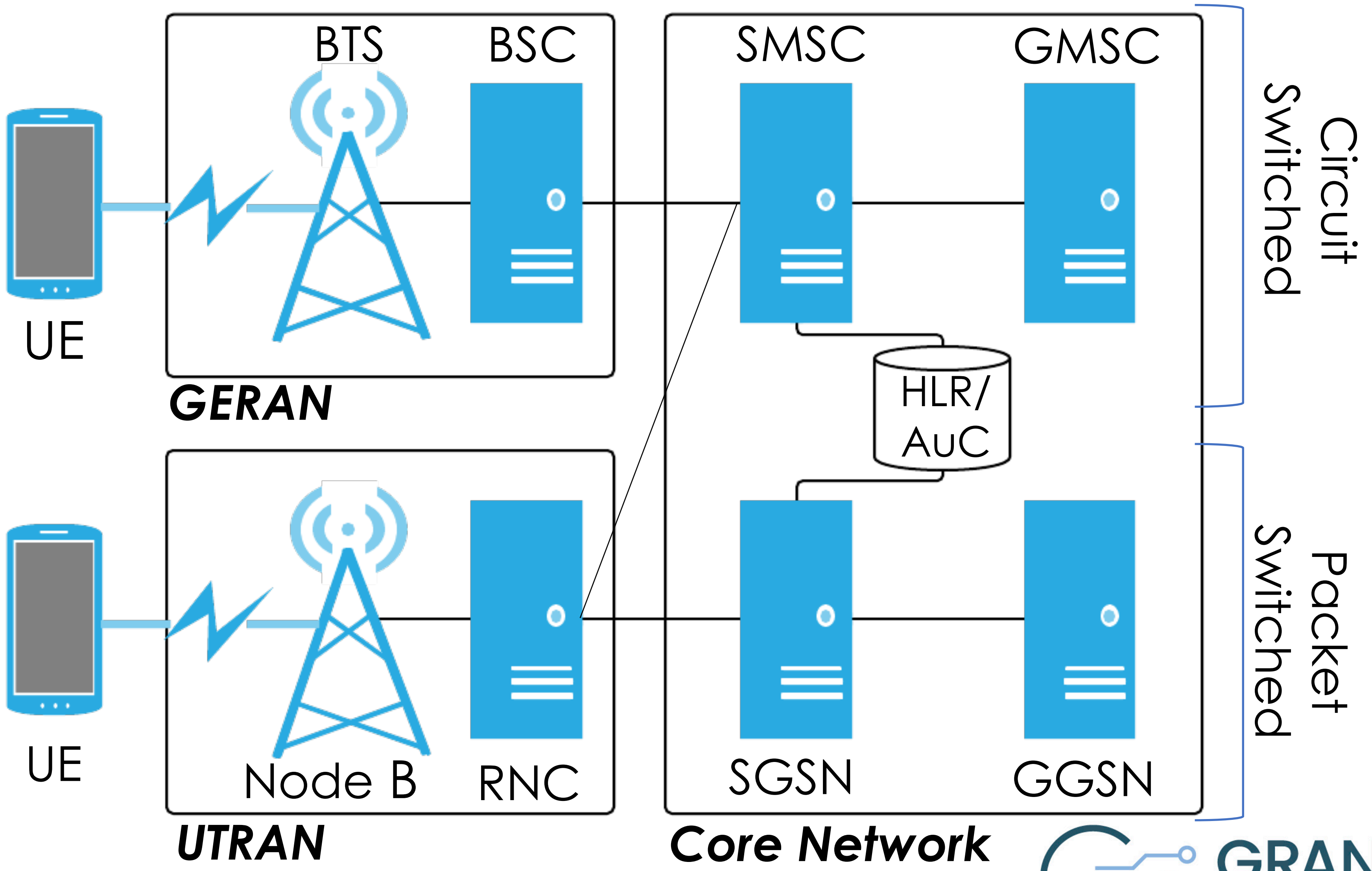
UMTS

- Universal Mobile Telecommunications System
- 3G digital voice
- Air interface: W–CDMA
- Operates at various spectrums worldwide

UMTS Components

- Consists of the core network (CN), Universal Terrestrial Radio Access Network (UTRAN), and UE
- Runs 2G circuit switched and 3G packet switched components concurrently – it looks confusing at first
- The UTRAN contains:
  - Node B (think of the phone as Node A)
  - Radio Network Controller (RNC)
- The CN contains:
  - Serving Mobile Switching Center (SMSC)
  - Gateway Mobile Switching Center (GMSC)
  - Serving GPRS support node (SGSN)
  - Gateway GPRS support node (GGSN)
  - Home Location Register/Authentication Center (HLR/AuC)
- We are not discussing GPRS—related nodes

UMTS Architecture Diagram



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UMTS & GSM Compatibility

- UMTS was designed to work concurrently with GSM
- 2G SIMs were included
- Much of the terminology is slightly modified
  - BTS -> Node B

LTE

- Long Term Evolution
  - Also known as the Evolved Packet System (EPS)
- 4G data **and** voice technology
- Air interface: OFDMA
- 3 main components:
  - Evolved U-TRAN (E-UTRAN) – Radio Network
  - Evolved Packet Core (EPC) – Backhaul
  - IP Multimedia Subsystem (IMS) – Extended backhaul functionality
- Remember: LTE is a completely packet-switched technology for both data and voice
  - LTE can fall back to older networks for voice (Circuit-switched fallback)
- VoLTE (voice over LTE)
  - To activate voice calls over LTE (using IP Multimedia Subsystem)
  - Active in Italy from end of 2015 (Vodafone, TIM)

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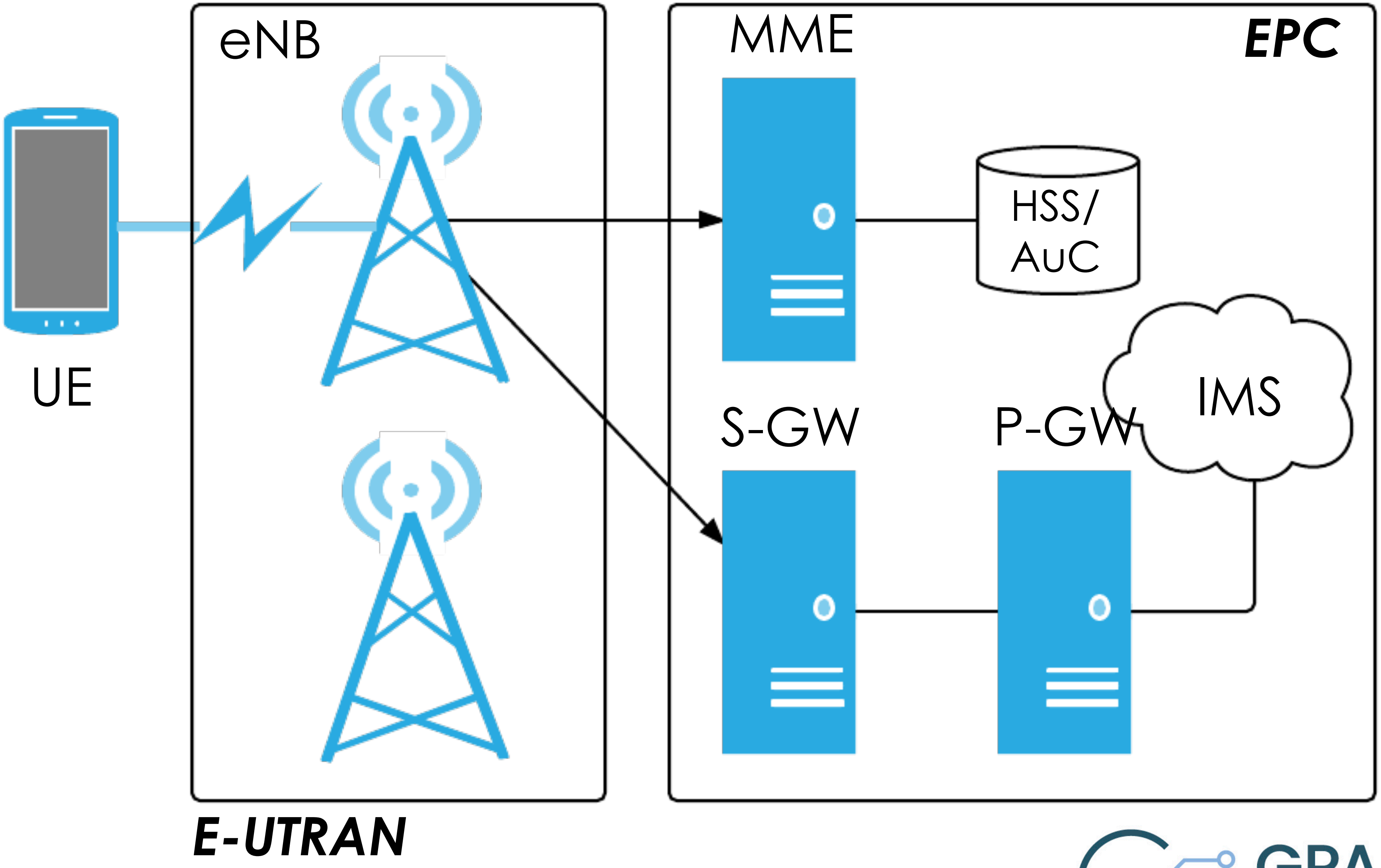
LTE Components

- User equipment (UE)
- Evolved Node B (eNodeB)
- Mobility Management Entity (MME)
- Serving Gateway (S-GW)
- Packet Data Network Gateway (P-GW)
- Home Subscriber Server (HSS)

LTE/EPS Architecture Diagram



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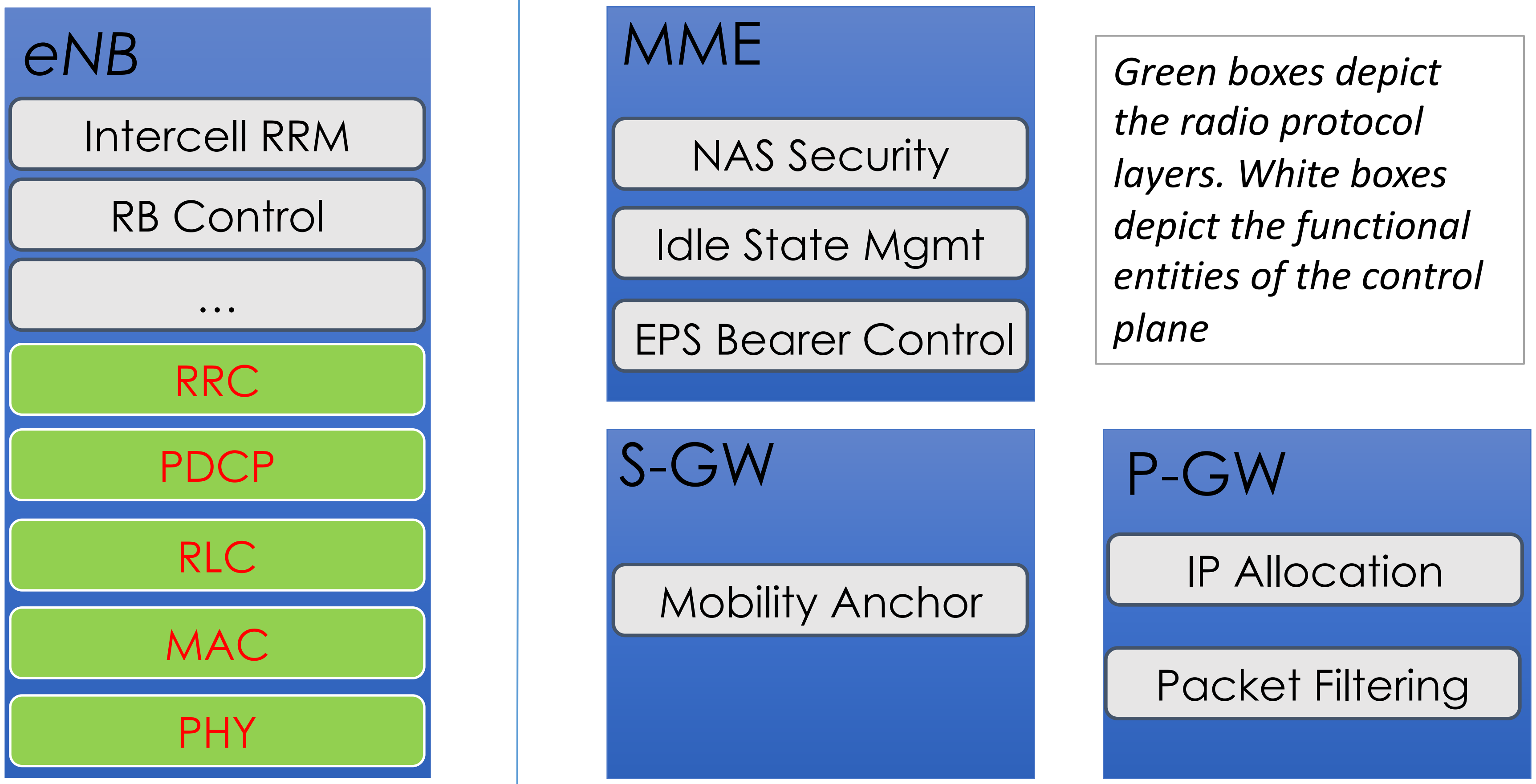
LTE Components Description

- **User equipment (UE)** – The LTE device
- **Evolved Node B (eNodeB or eNB)** – An evolved Node B (BTS)
- **E-UTRAN** – The radio network that exists between UEs and eNBs
- **Mobility Management Entity (MME)** – Primary signaling node (no user traffic). Large variation in functionality including managing/storing UE contexts, creating temporary IDs, sending pages, controlling authentication functions, and selecting the S-GW and P-GWs
- **Serving Gateway (S-GW)**– Carries user plane data, anchors UEs for intra-eNB handoffs, and routes information between the P-GW and the E-UTRAN
- **Packet Data Network Gateway (P-GW)** – Allocates IP addresses, routes packets, and interconnects with non 3GPP networks
- **Home Subscriber Server (HSS)** – This is the master database with the subscriber data
- **Authentication Center (AuC)** – Resides within the HSS, maps an IMSI to K, performs cryptographic calculations during AKA
- **IP Multimedia Subsystem (IMS)** – Paging, connections to the PSTN, and support for VoLTE

E-UTRAN & EPC Protocols



eNB

Intercell RRM

RB Control

...

RRC

PDCP

RLC

MAC

PHY

MME

NAS Security

Idle State Mgmt

EPS Bearer Control

Green boxes depict the radio protocol layers. White boxes depict the functional entities of the control plane

S-GW

Mobility Anchor

P-GW

IP Allocation

Packet Filtering

E-UTRAN

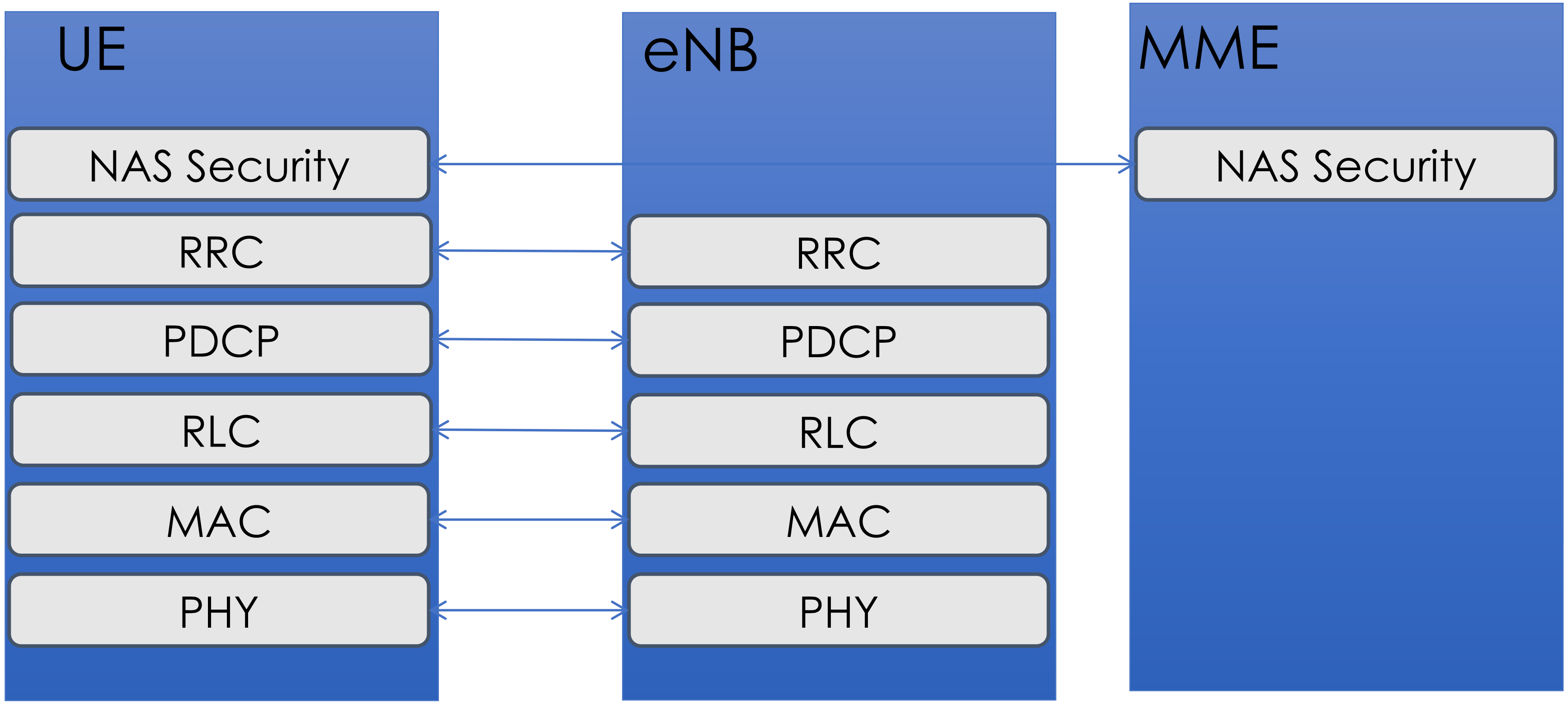
EPC

Adapted from [3GPP TS 36.300]

Protocol Discussion

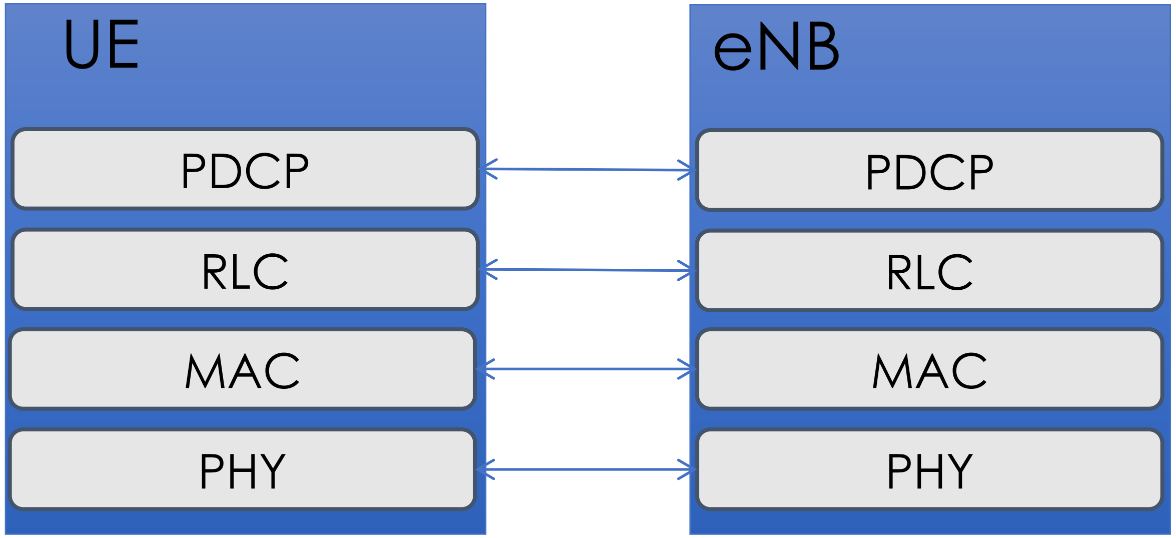
- There are a number of additional capabilities provided by the eNB
  - IP header compression of user data stream
  - Selection of an MME at UE attachment when no routing to an MME can be determined from the information provided by the UE
  - Routing of User Plane data towards Serving Gateway
- **Radio Resource Control (RRC)** – Transfers NAS messages, AS information may be included, signaling, and ECM
- **Packet Data Convergence Protocol (PDCP)** – header compression, radio encryption
- **Radio Link Control (RLC)** – Readies packets to be transferred over the air interface
- **Medium Access Control (MAC)** – Multiplexing, QoS

Control Plane Protocols



Adapted from 3GPP TS 36.300

User Plane Protocols

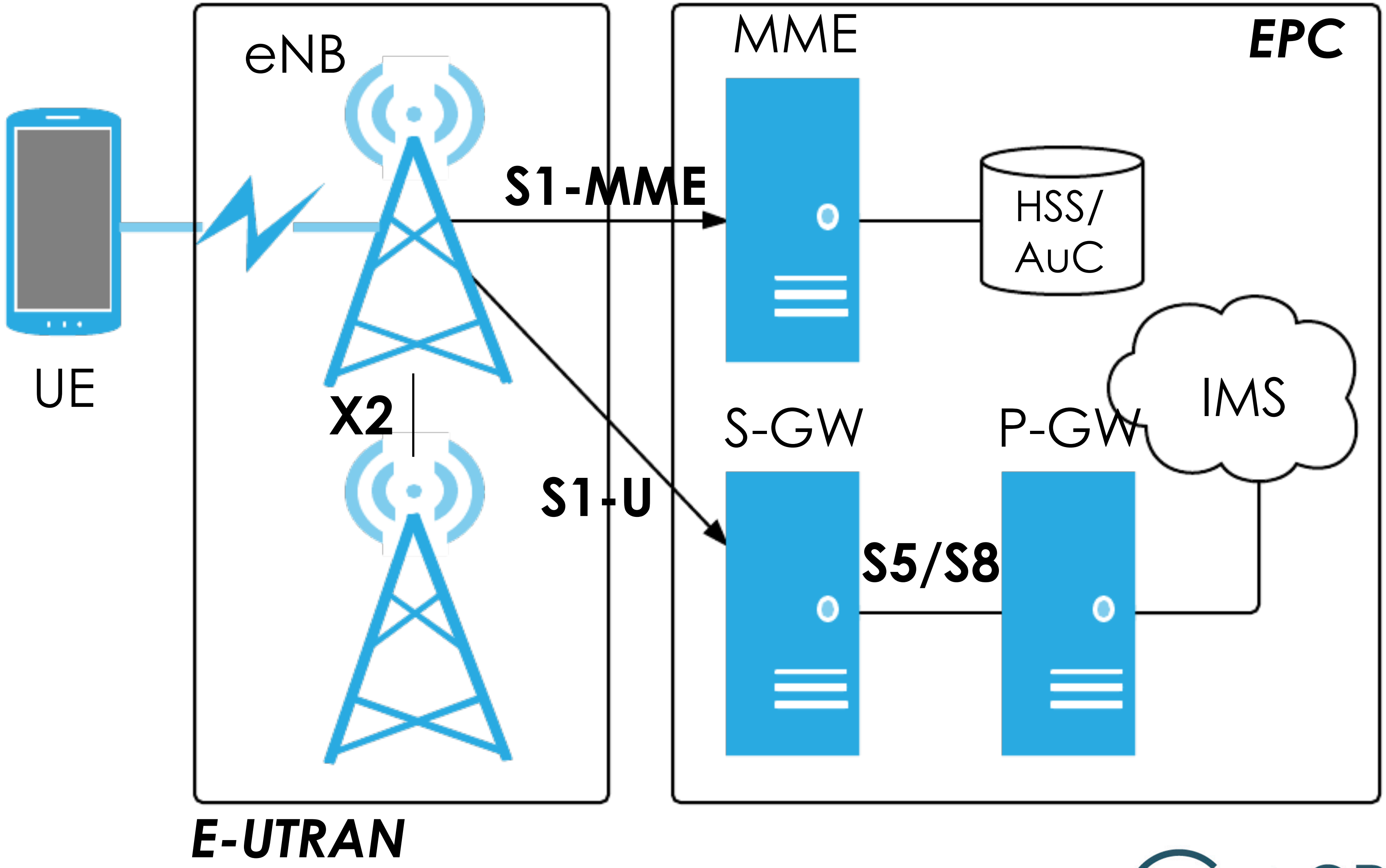


Adapted from 3GPP TS 36.300

Interfaces

- Interfaces are the communications paths LTE components use to communicate
- Each one is provided with its own label
    - There may be unique protocols between various interfaces
- There are many interfaces – we are discussing a subset
    - X2 – eNB to eNB
    - S1-U – eNB to S-GW
    - S1-MME (sometimes S1-C) – eNB to MME
    - S5/S8 – S-GW to P-GW

LTE/EPS Interface Diagram



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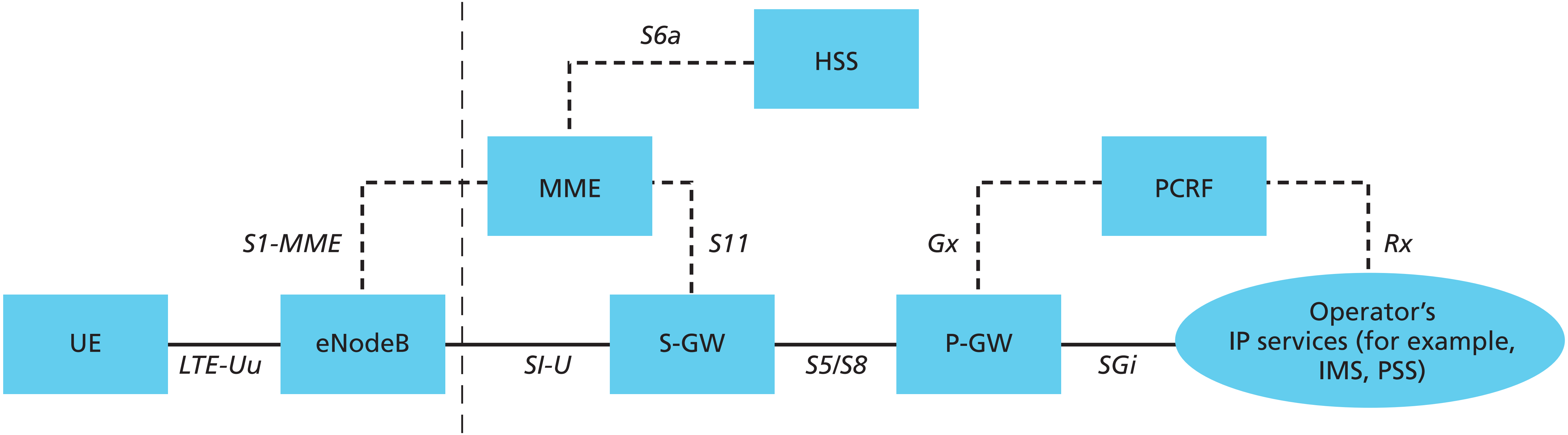
LTE Evolved Packet System



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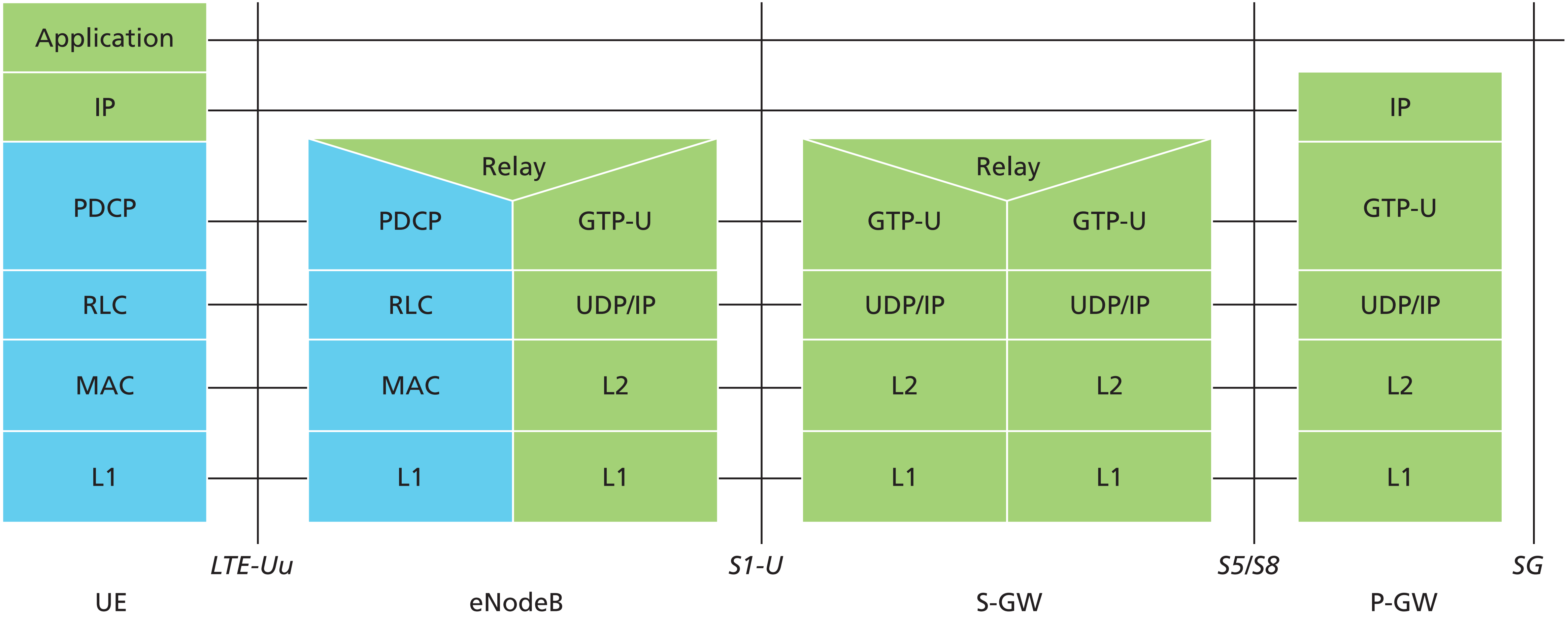
LTE E-UTRAN User space protocols



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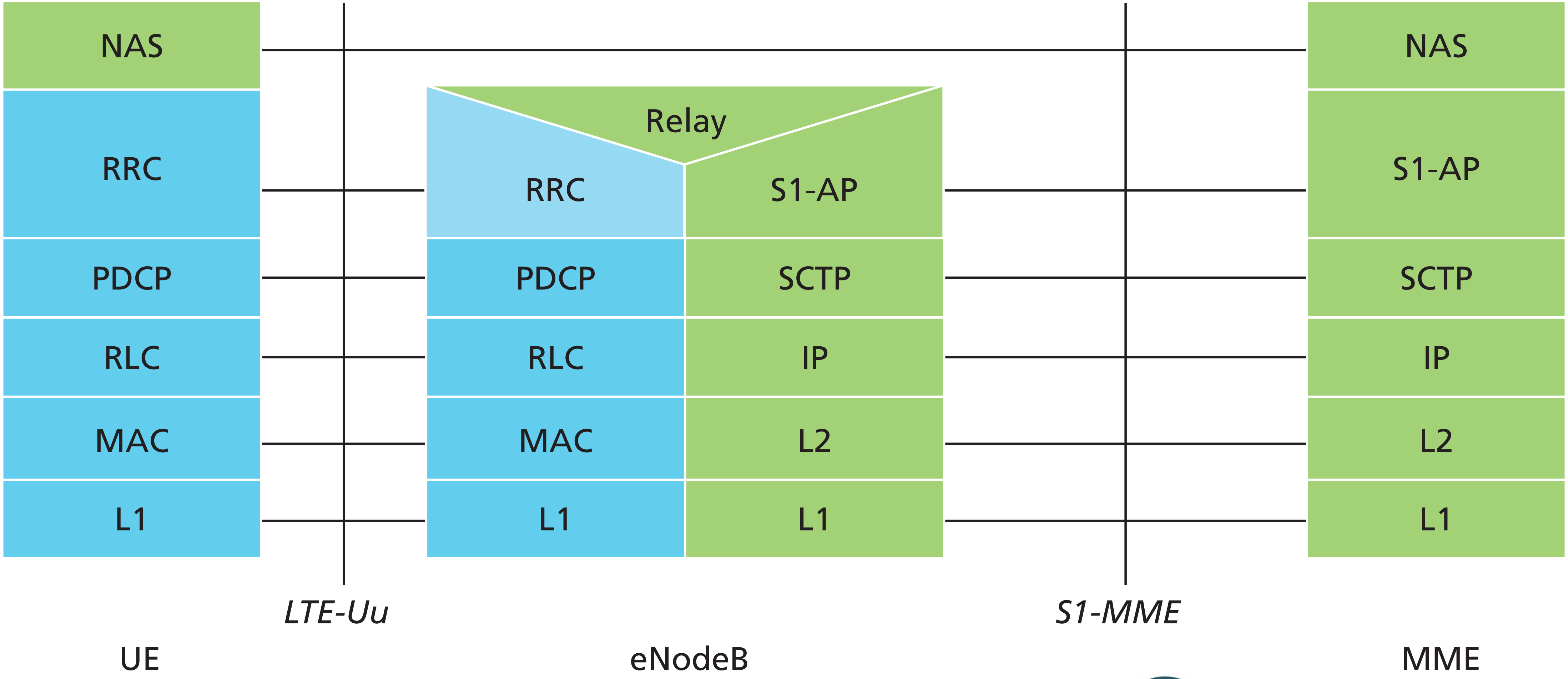
LTE E-UTRAN Control space protocols



LTE PHY Basics

- Six bandwidths
  - 1.4, 3, 5, 10, 15, and 20 MHz
- Two modes
  - FDD and TDD
- 100 Mbps DL (SISO) and 50 Mbps UL
- Transmission technology
  - OFDM for multipath resistance
  - DL OFDMA for multiple access in frequency/time
  - UL SC-FDMA to deal with PAPR ratio problem

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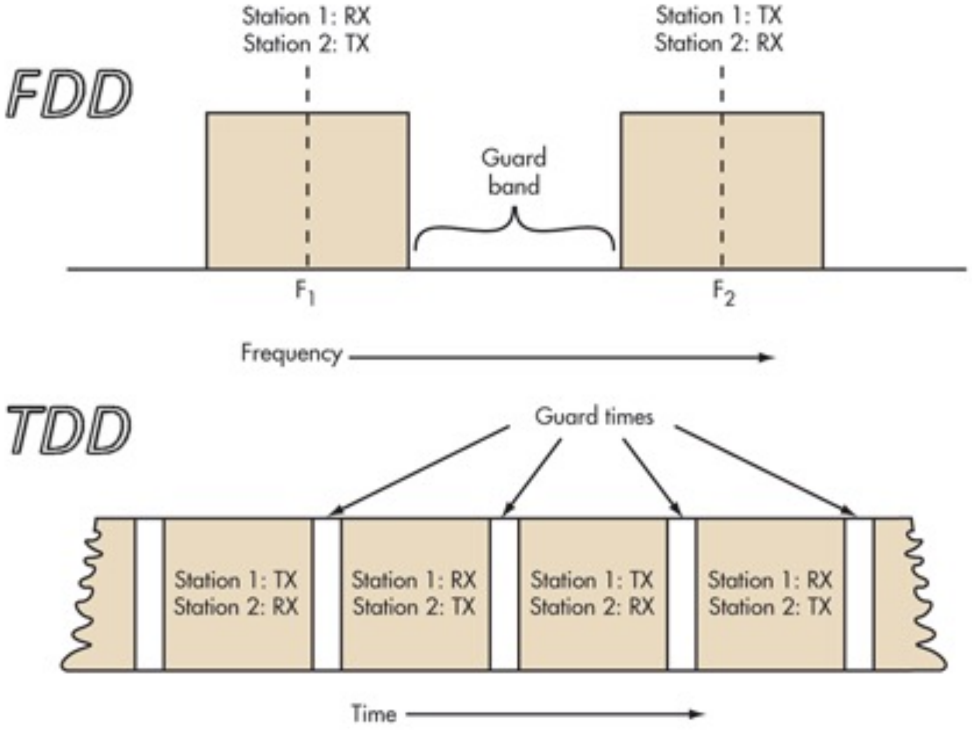
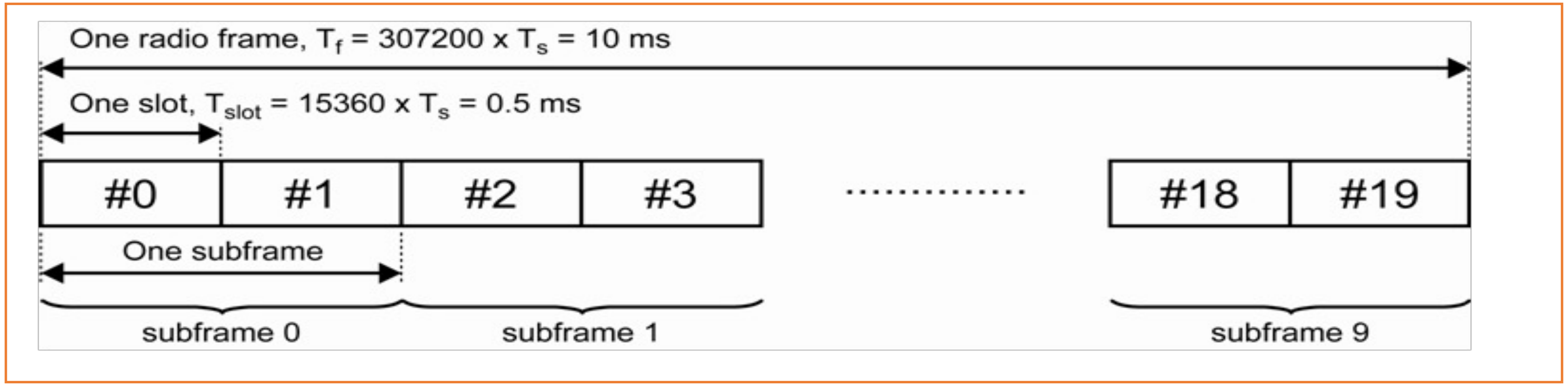
LTE in Italy

- TIM:
    - 800 MHz (B20), 1800 MHz (B3), 2600 MHz (B7);
- Vodafone:
    - 800 MHz (B20), 1800 MHz (B3), 2600 MHz (B7);
- Wind:
    - 800 MHz (B20), 2600 MHz (B7);
- 3 Italia:
    - 1800 MHz (B3), 2600 MHz (B38, TDD-LTE)
- FDD is most popular duplexing



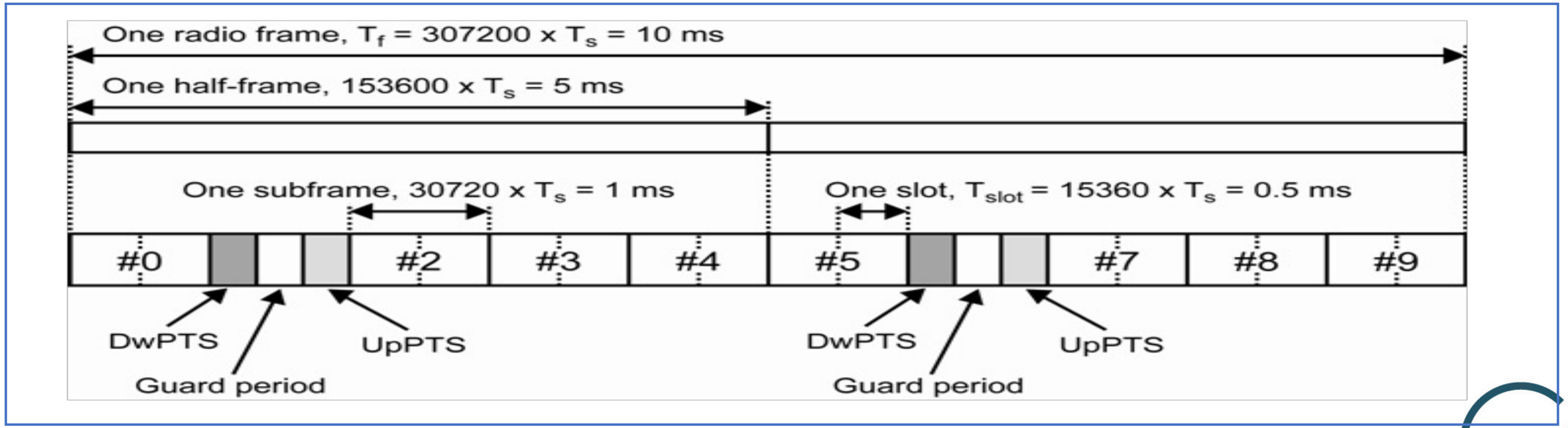
LTE Frame structure

Frame Structure Type 1 (FDD)



One radio frame, $T_f = 307200 \times T_s = 10$ ms
One slot, $T_{slot} = 15360 \times T_s = 0.5$ ms
#0
#1
#2
#3
....
#18
#19
One subframe
subframe 0
subframe 1
subframe 9

Frame Structure Type 2 (TDD)



One radio frame, $T_f = 307200 \times T_s = 10$ ms
One half-frame, $153600 \times T_s = 5$ ms
One subframe, $30720 \times T_s = 1$ ms
One slot, $T_{slot} = 15360 \times T_s = 0.5$ ms
#0
#2
#3
#4
#5
#7
#8
#9
DwPTS
Guard period
UpPTS
DwPTS
Guard period
UpPTS

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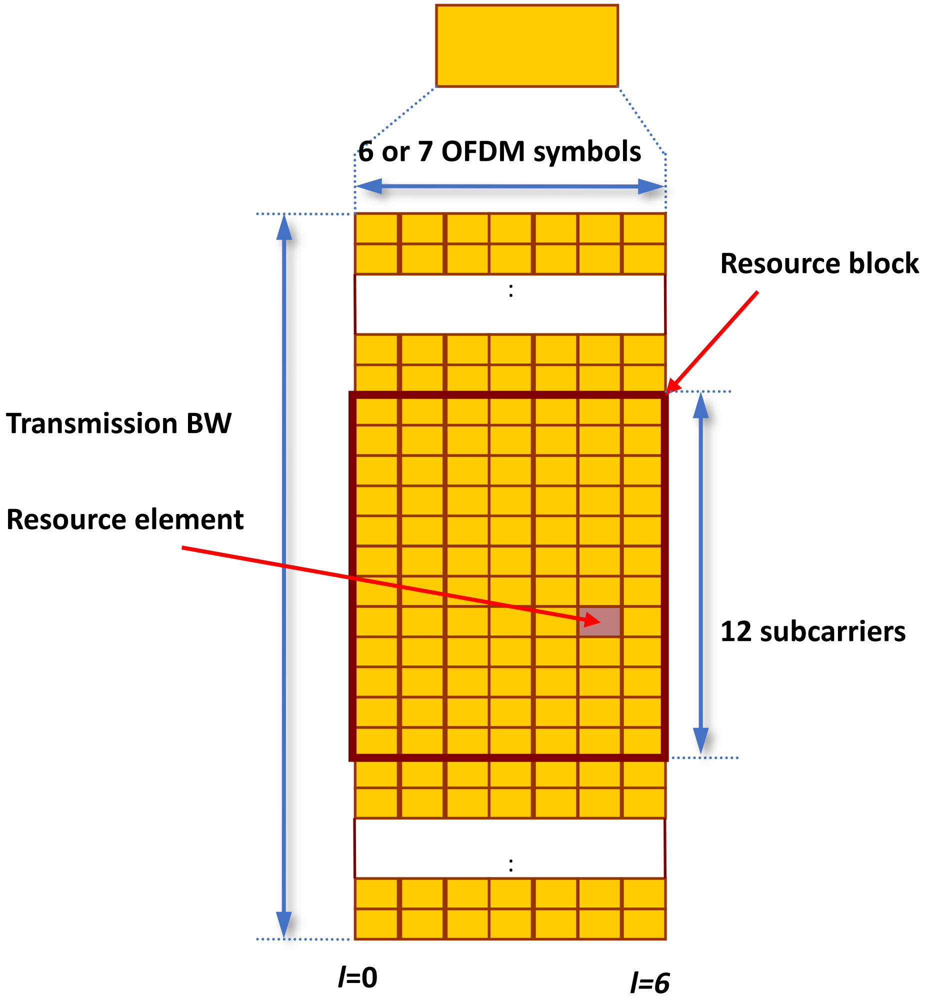
LTE Resource grid



- 6 or 7 OFDM symbols in 1 slot
- Subcarrier spacing = 15 kHz
- Block of 12 SCs in 1 slot = 1 RB
  - *0.5 ms x 180 kHz*
  - Smallest unit of allocation

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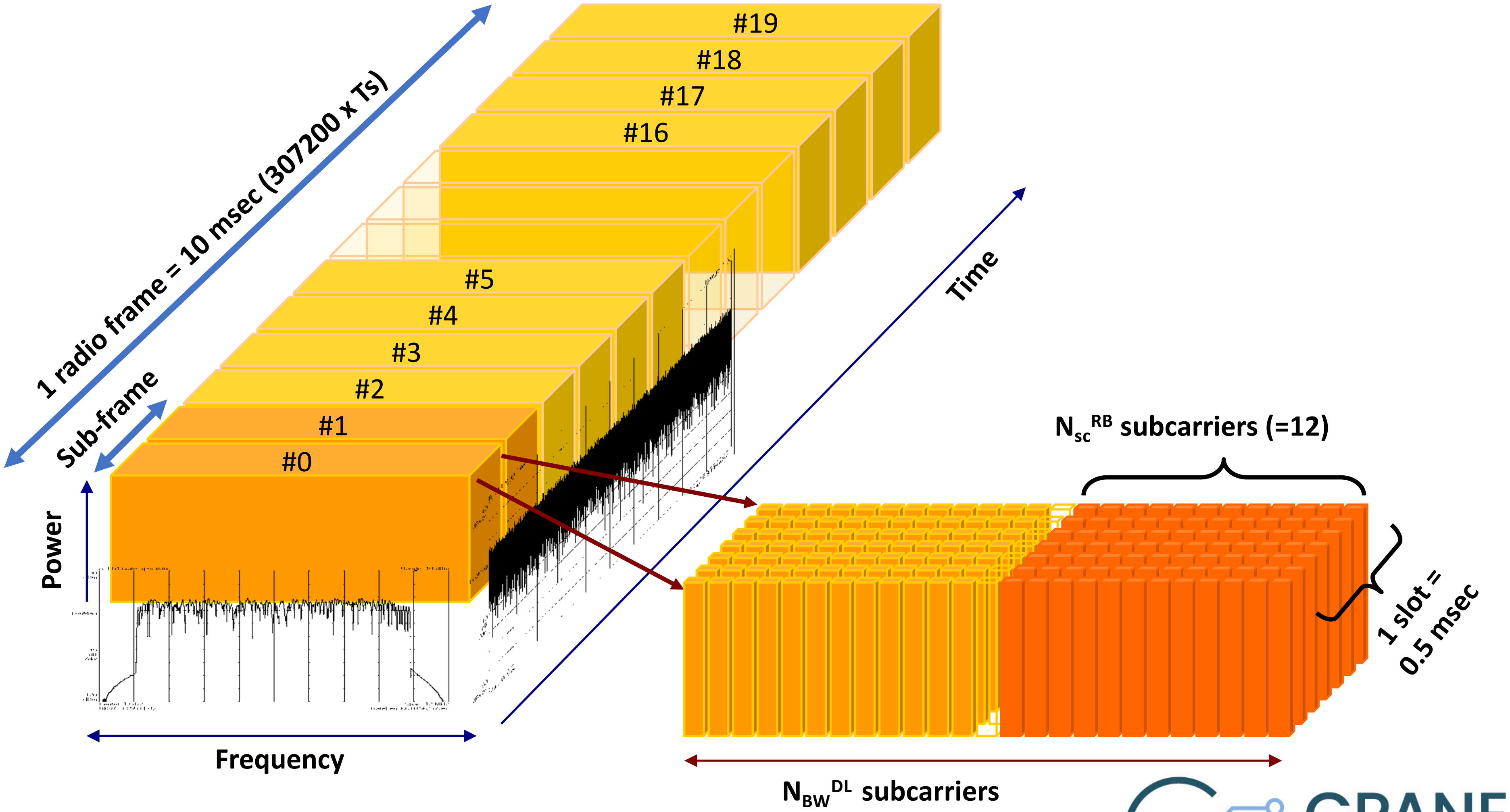
LTE 2D Time and Freq. grid


1 radio frame = 10 msec (307200 x Ts)
Sub-frame
#19
#18
#17
#16
#5
#4
#3
#2
#1
#0
Time
Power
Frequency
N_{sc}^{RB} subcarriers (=12)
1 slot = 0.5 msec
N_{BW}^{DL} subcarriers

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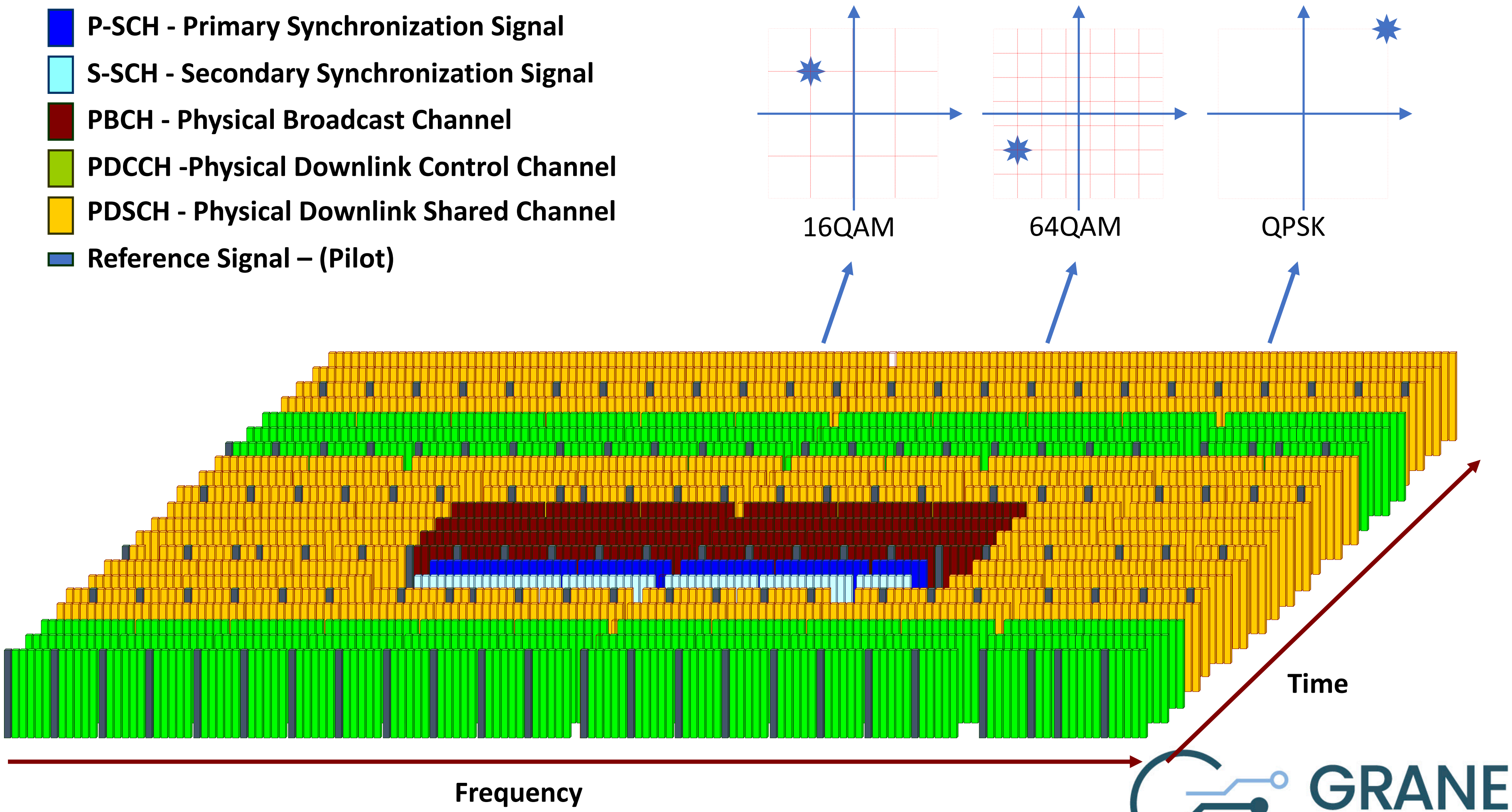
LTE DL PHY Channels

- Signals: generated in PHY layers
  - P-SS: used for initial sync
  - S-SS: frame boundary determination
  - RS: pilots for channel estimation and tracking
- Channels: carry data from higher layers
  - PBCH: broadcast cell-specific info
  - PDCCH: channel allocation and control info
  - PCFICH: info on size of PDCCH
  - PHICH: Ack/Nack for UL blocks
  - PDSCH: Dynamically allocated user data

LTE DL PHY Channels Mapping

- 🟦 P-SCH - Primary Synchronization Signal
- ⬜ S-SCH - Secondary Synchronization Signal
- 🟥 PBCH - Physical Broadcast Channel
- 🟩 PDCCH -Physical Downlink Control Channel
- 🟨 PDSCH - Physical Downlink Shared Channel
- ▬ Reference Signal – (Pilot)



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LTE UL PHY Channels

- Signals: generated in the PHY layer
  - Demodulation RS : sync and channel estimation
  - SRS: Channel quality estimation
- Channels: carry data from higher layers
  - PUSCH: Uplink data
  - PUCCH: UL control info
  - PRACH: Random access for connection establishment

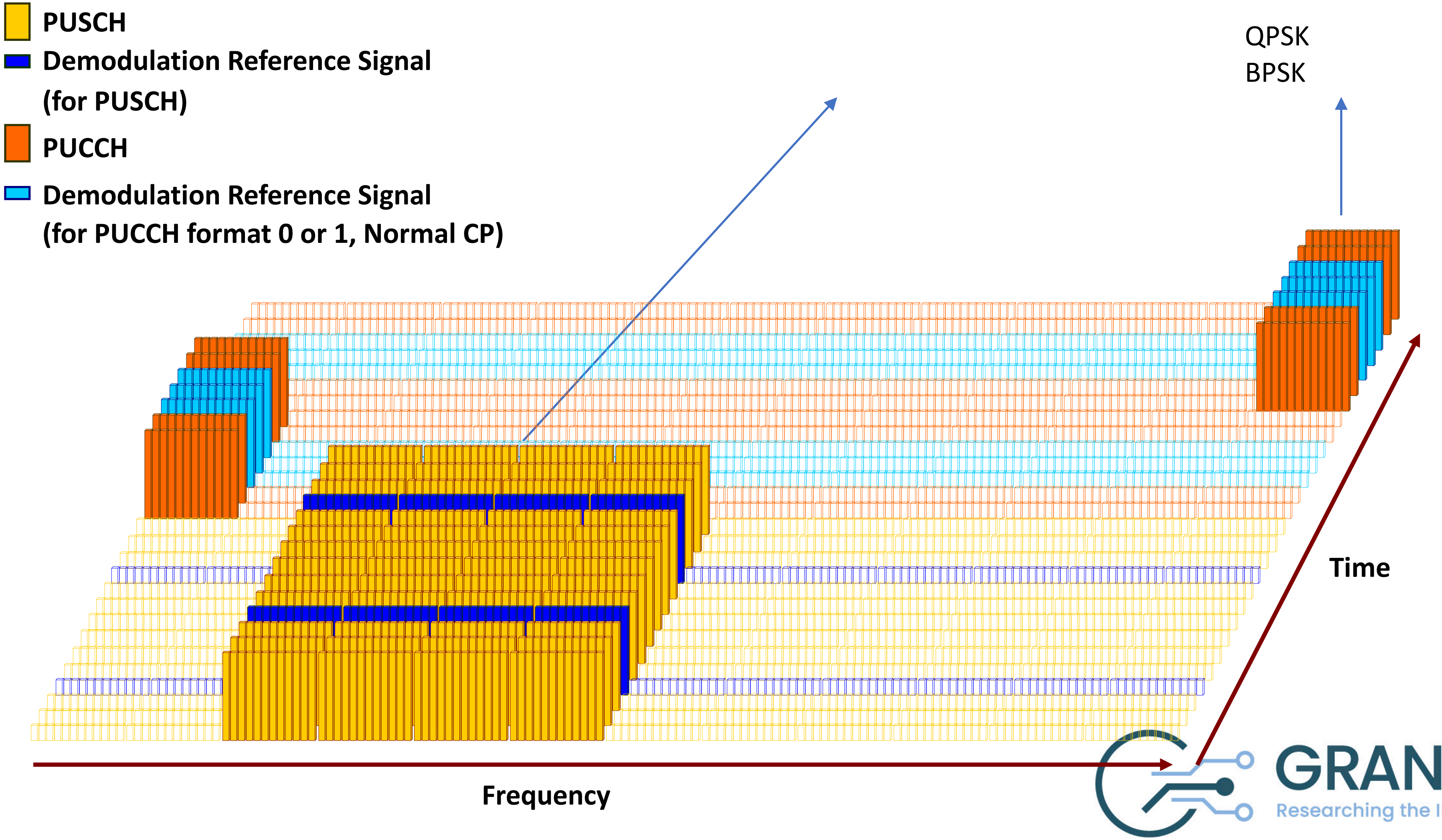
LTE DL PHY Channels Mapping

🟨 **PUSCH**

🟦 **Demodulation Reference Signal (for PUSCH)**

🟧 **PUCCH**

🟦 **Demodulation Reference Signal (for PUCCH format 0 or 1, Normal CP)**



Resources & References

- Muyung, A Technical Overview of 3GPP LTE
- TS 36.300 – Overall description of E-UTRAN
- TS 33.401 – LTE Security Architecture

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Networking II

Cellular Networks

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