

# Introduction to Cellular Systems





**Lecturer: Dr. Rui Wang**

## 1<sup>st</sup> MOBILE RADIO TELEPHONE 1924



Courtesy of Rich Howard

# History of Cellular Networks

<ul style="list-style-type: none"><li>1G FDMA (NMT, AMPS, TACS)<ul style="list-style-type: none"><li>- Voice (analog traffic, digital signaling)</li></ul></li></ul>		80's
<ul style="list-style-type: none"><li>2G TDMA (GSM, D-AMPS, PDC) and CDMA (IS-95)<ul style="list-style-type: none"><li>- Voice, SMS, CS data transfer ~ 9.6 kbit/s (50 kbit/s HSCSD)</li></ul></li></ul>		90's
<ul style="list-style-type: none"><li>2.5G TDMA (GPRS)<ul style="list-style-type: none"><li>- PS data transfer ~ 50 kbit/s</li></ul></li></ul>		00's
<ul style="list-style-type: none"><li>2.75G TDMA (GPRS+EDGE)<ul style="list-style-type: none"><li>- PS data ~ 150kbit/s</li></ul></li></ul>		00's
<ul style="list-style-type: none"><li>3-3.5G WCDMA (UMTS) and CDMA 2000<ul style="list-style-type: none"><li>- PS &amp; CS data transfer ~ 14-42 Mbit/s (HSPA/HSPA+), Voice, SMS</li></ul></li></ul>		00's
<ul style="list-style-type: none"><li>3.9G OFDMA (LTE/SAE)<ul style="list-style-type: none"><li>- VoIP and Data ~ 100Mbit/s</li></ul></li></ul>		10's
<ul style="list-style-type: none"><li>4G IMT Advanced</li></ul>		

# About 3GPP

- “The 3rd Generation Partnership Project (3GPP) unites [Seven] telecommunications standard development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC), known as “Organizational Partners” and provides their members with a stable environment to produce the Reports and Specifications that define 3GPP technologies.”
- “The project covers cellular telecommunications technologies, including **radio access, core network and service capabilities**, which provide a complete system description for mobile telecommunications.”
- “The 3GPP specifications also provide hooks for non-radio access to the core network, and for interworking with non-3GPP networks.”

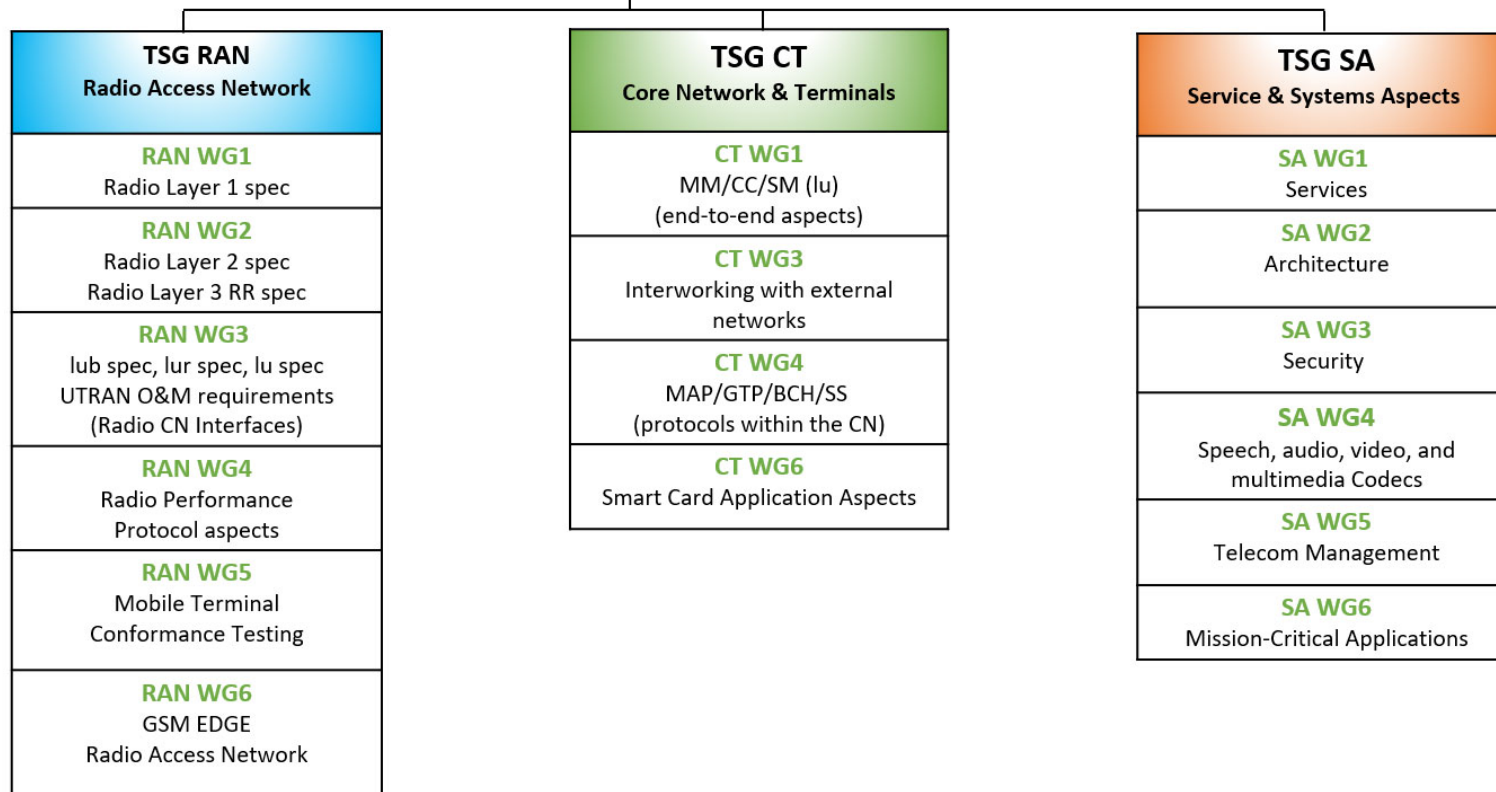
--- <https://www.3gpp.org/about-3gpp/about-3gpp>

# Organization of 3GPP

## Three Technical Specification Groups (TSG) in 3GPP



Project Coordination Group (PCG)

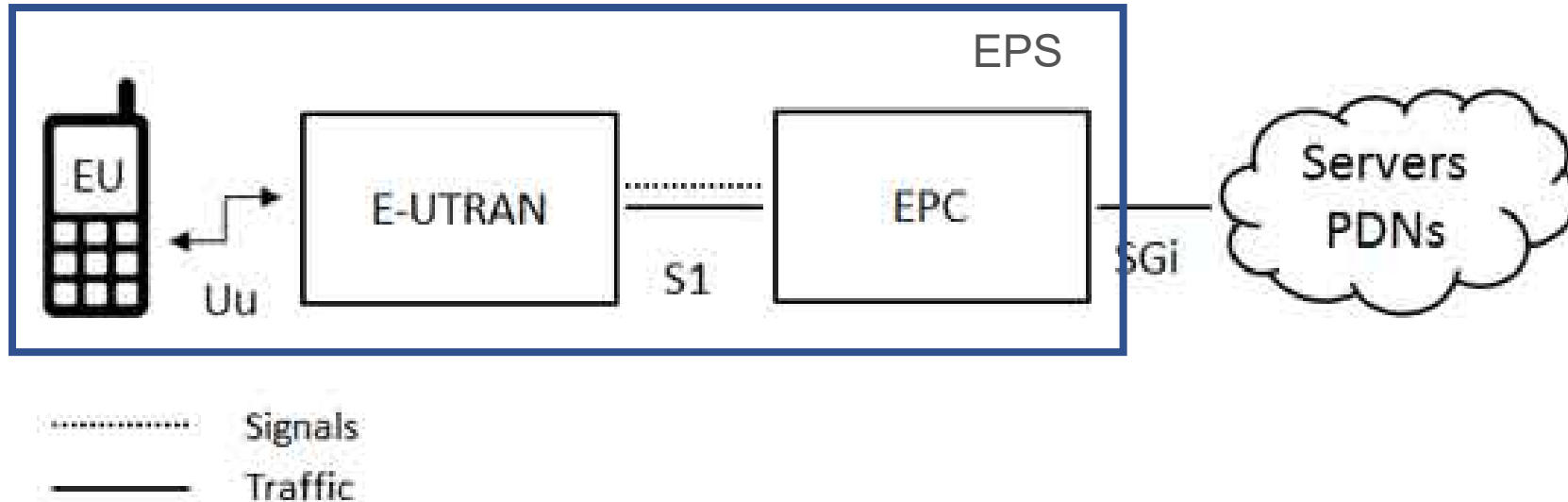


“**The TSG Service and System Aspects (TSG-SA)** is responsible for the overall architecture and service capabilities of systems based on 3GPP specifications and, as such, has a responsibility for cross TSG co-ordination.”

“**The TSG Core Network and Terminals (TSG CT)** is responsible for specifying terminal interfaces (logical and physical), terminal capabilities (such as execution environments) and the Core network part of 3GPP systems.”

**What are the major differences between cellular and Wi-Fi?**

# 4G: EPS Architecture



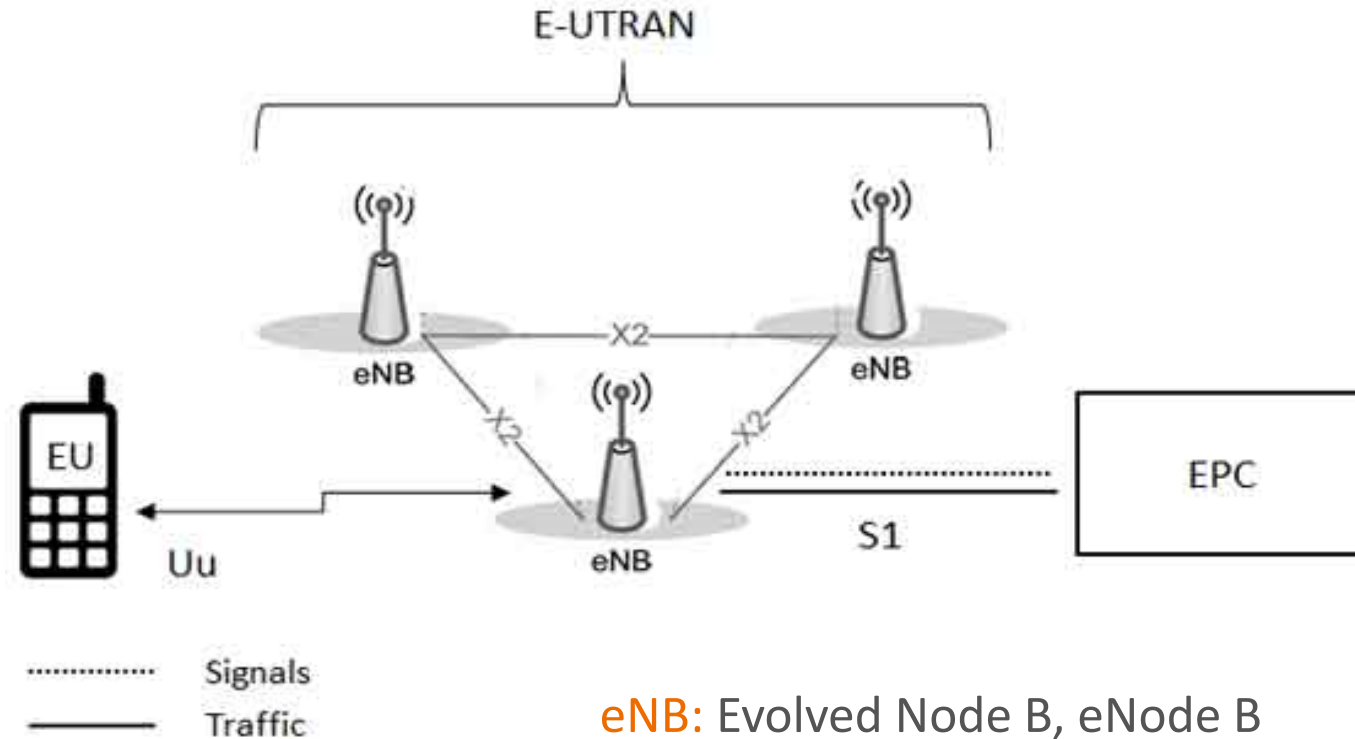
**E-UTRAN:** Evolved UMTS Terrestrial Radio Access Network (LTE)

**EPC:** Evolved Packet Core

**PDN:** Public Data Network

**EPS:** Evolved Packet System

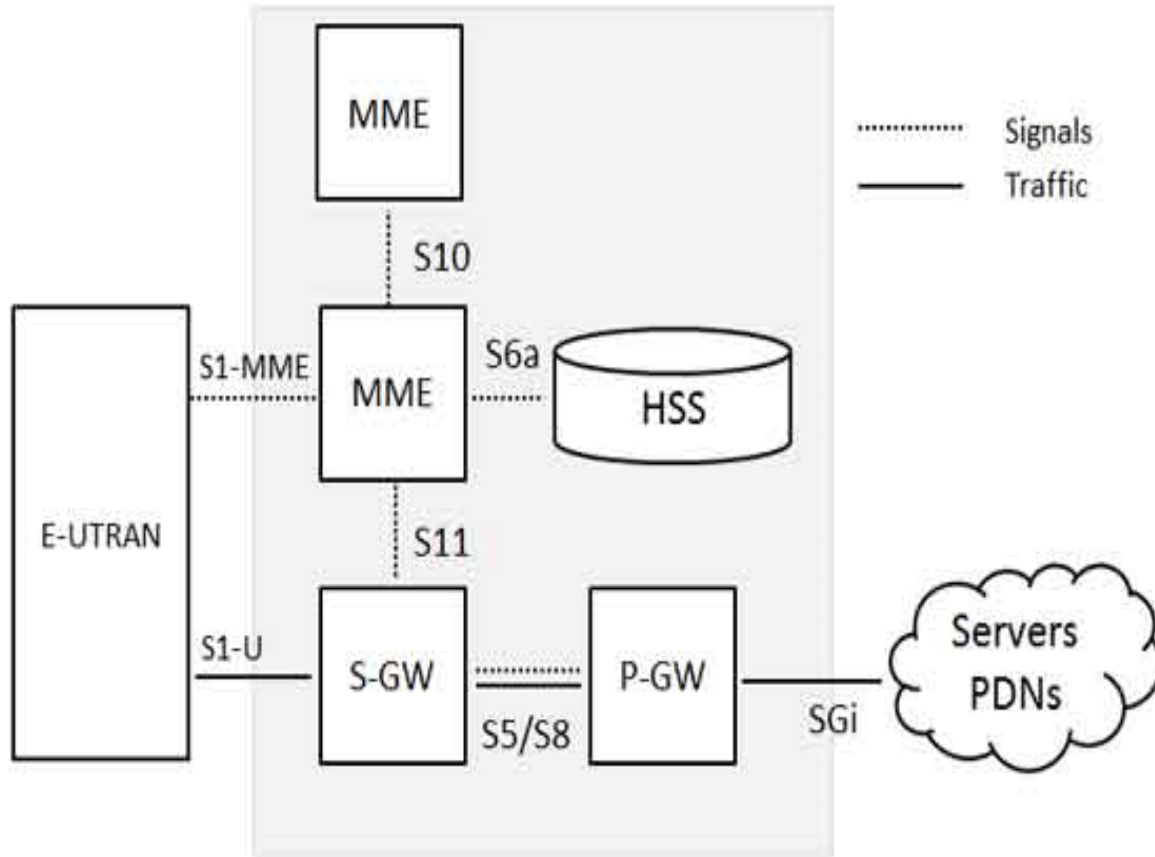
# E-UTRAN



- The eNB sends and receives radio transmissions to all the mobiles.
- The eNB controls the low-level operation of all its mobiles, such as handover commands.



# EPC



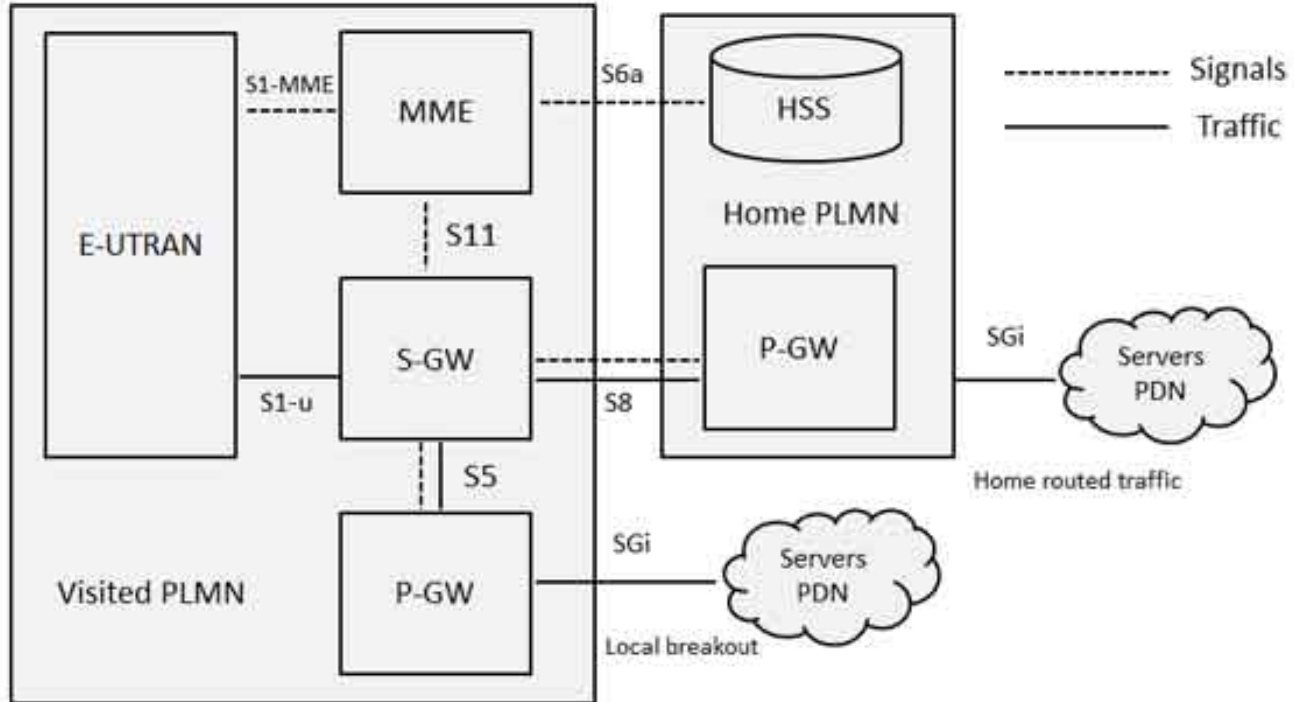
The **Home Subscriber Server (HSS)** contains information about all the network operator's subscribers.

The **Packet Data Network (PDN) Gateway (P-GW)** communicates with the outside world, i.e. packet data networks PDN, using SGi interface.

The **serving gateway (S-GW)** acts as a router, and forwards data between the base station and the PDN gateway.

The **mobility management entity (MME)** controls the high-level operation of the mobile by means of signalling messages and Home Subscriber Server (HSS).

# Roaming

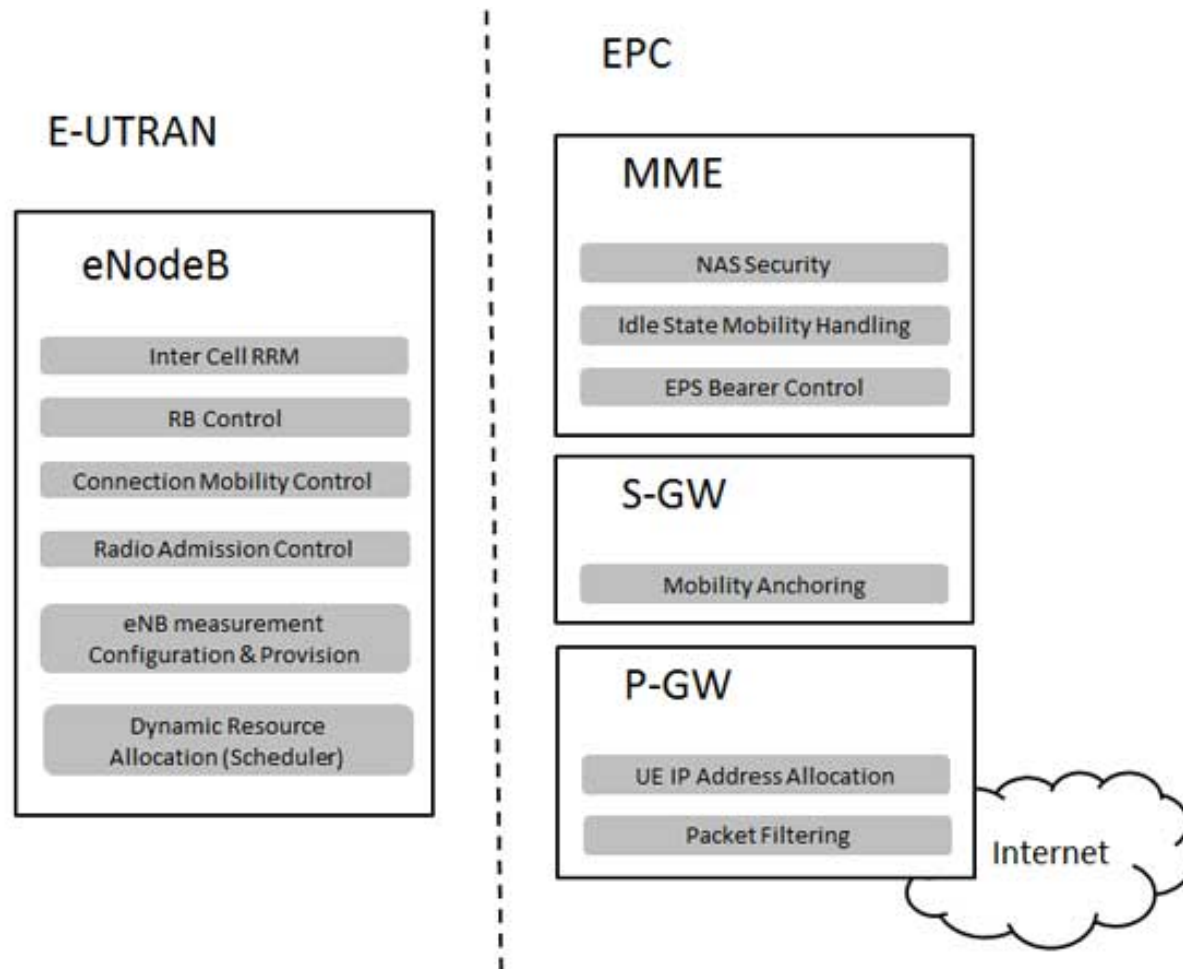


A network run by one operator in one country is known as a **Public Land Mobile Network (PLMN)**

When a subscribed user uses his operator's PLMN then it is said **Home-PLMN**

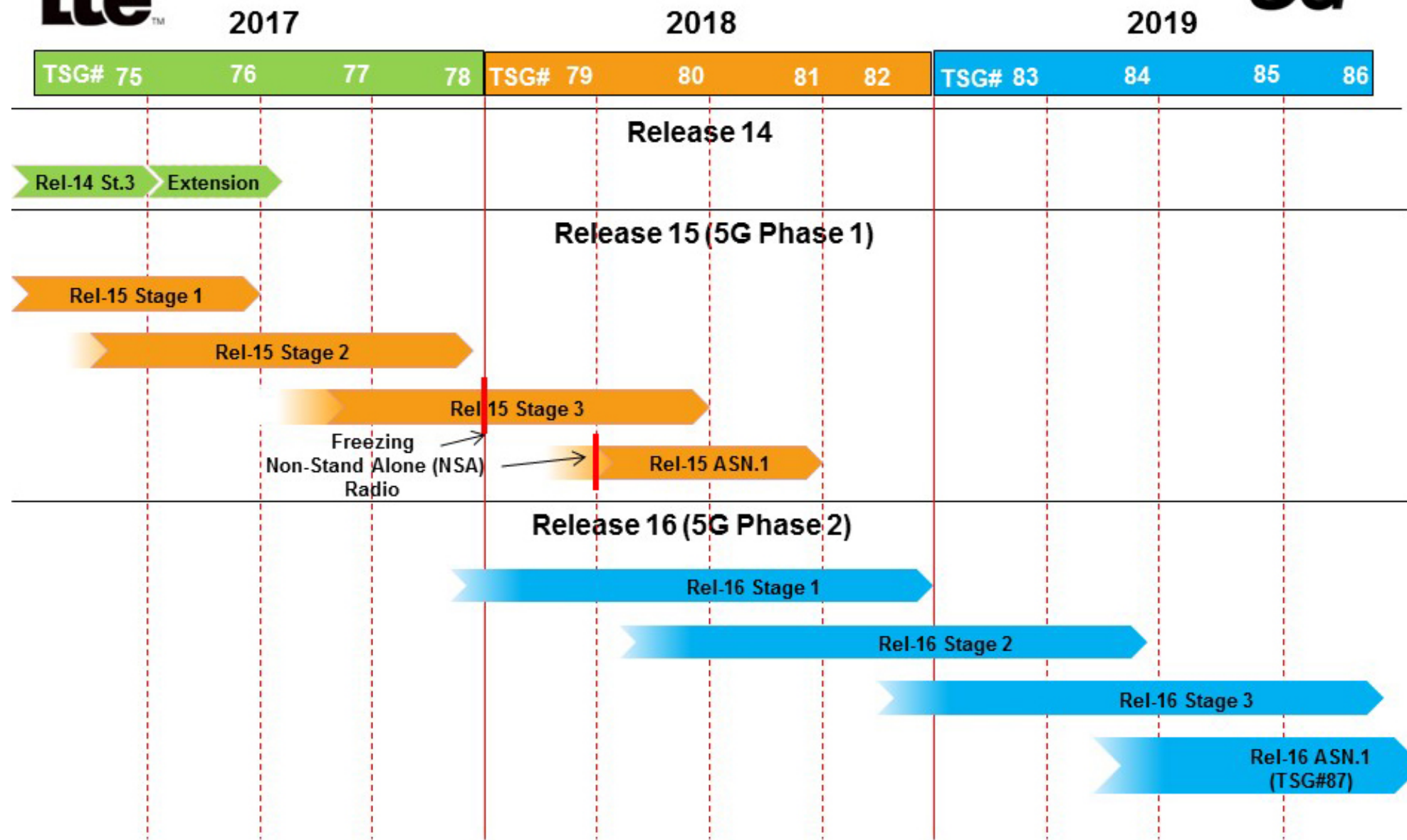
Roaming allows users to move outside their home network and using the resources from other operator's network. This other network is called **Visited-PLMN**.

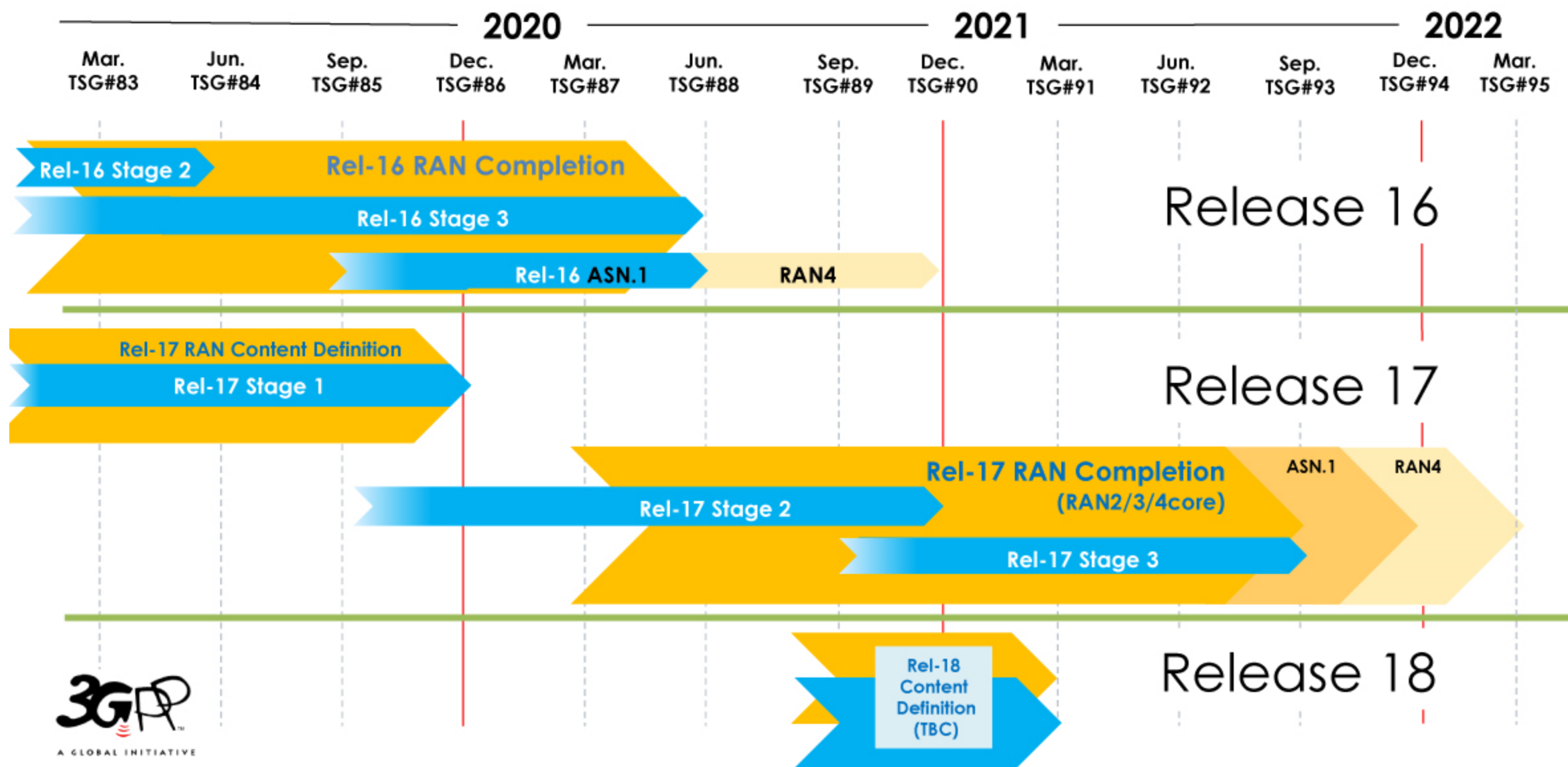
# Functional Split



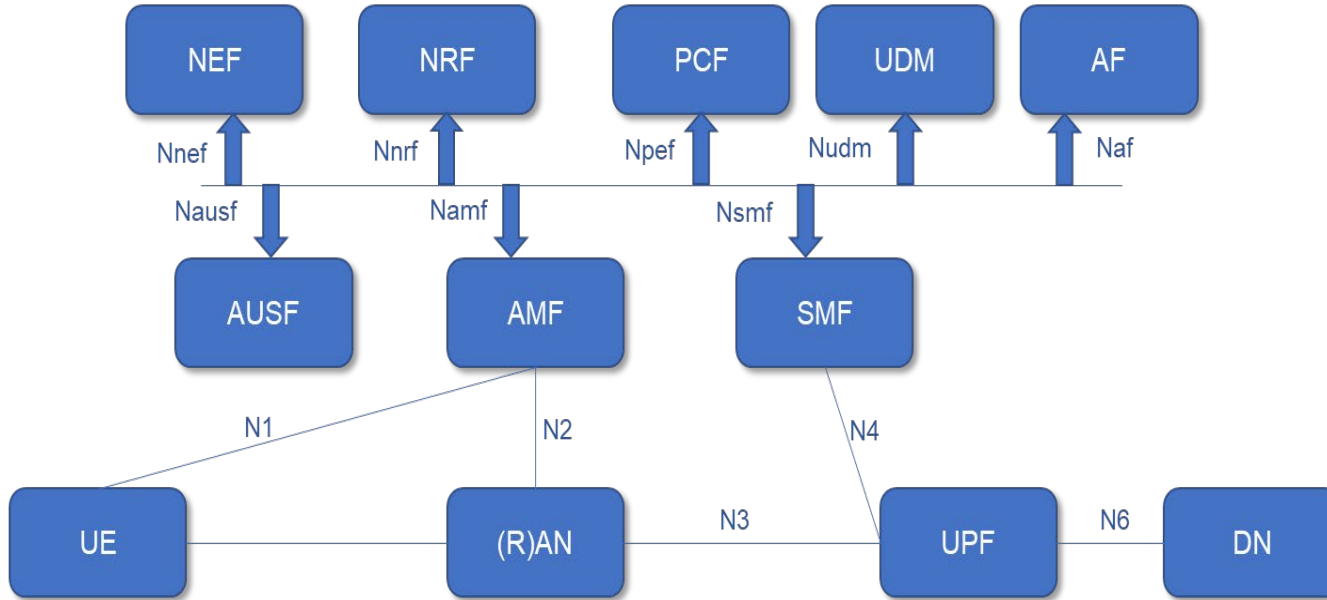
# 3GPP Releases on 4G

Release Number	Description	Date of Frozen
8	LTE Introduced	2008
9	Enhancement to LTE	2009
10	LTE Advanced	2011
11	Enhancement to LTE Advanced	2012
12	Further enhancement to LTE Advanced	2014
13	Meeting the growing throughput demand	2015
14	Start of 5G	2016





# Architecture of 5G Systems



The 5G System (5GS) will have three main components:

- 5G Access Network (5G-AN)
- 5G Core Network (5GC)
- Use Equipment (UE)

Authentication Server Function (AUSF)

**Core Access and Mobility Management Function (AMF)**

Data network (DN)

Network Exposure Function (NEF)

NF Repository Function (NRF)

Policy Control function (PCF)

**Session Management Function (SMF)**

Unified Data Management (UDM)

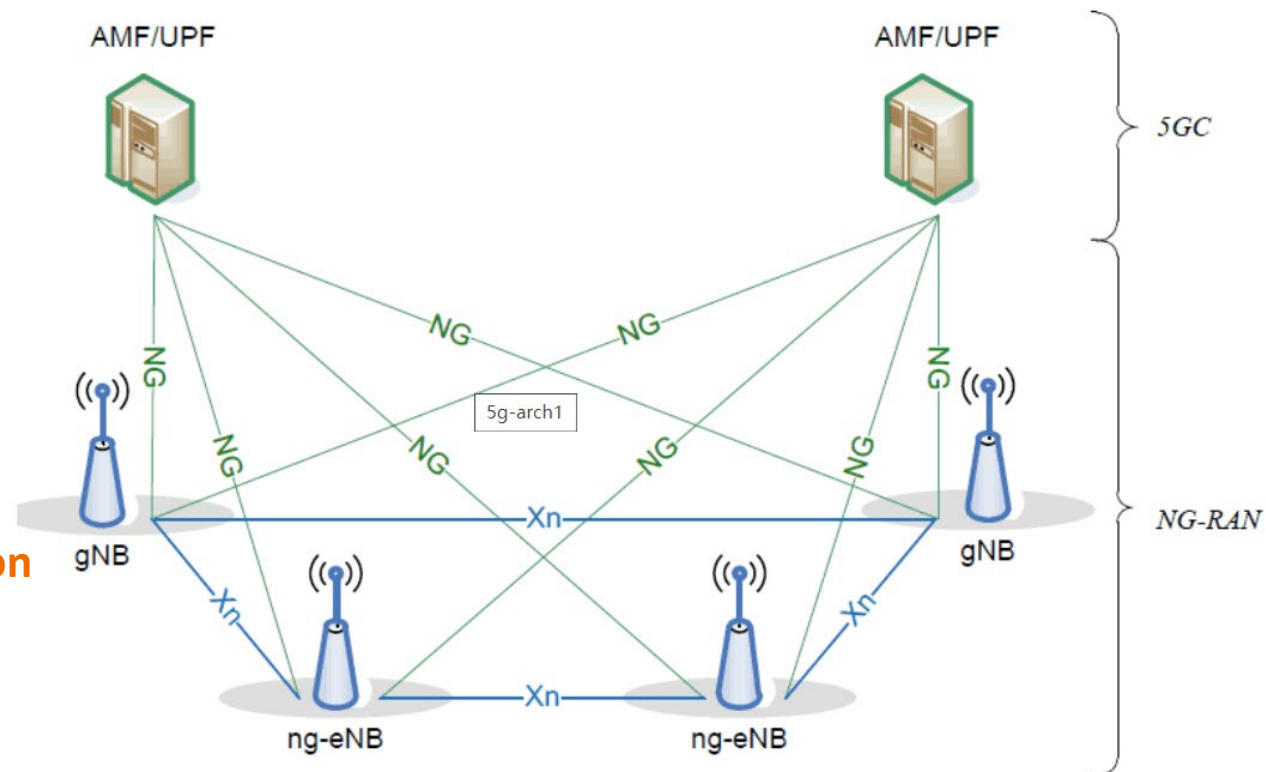
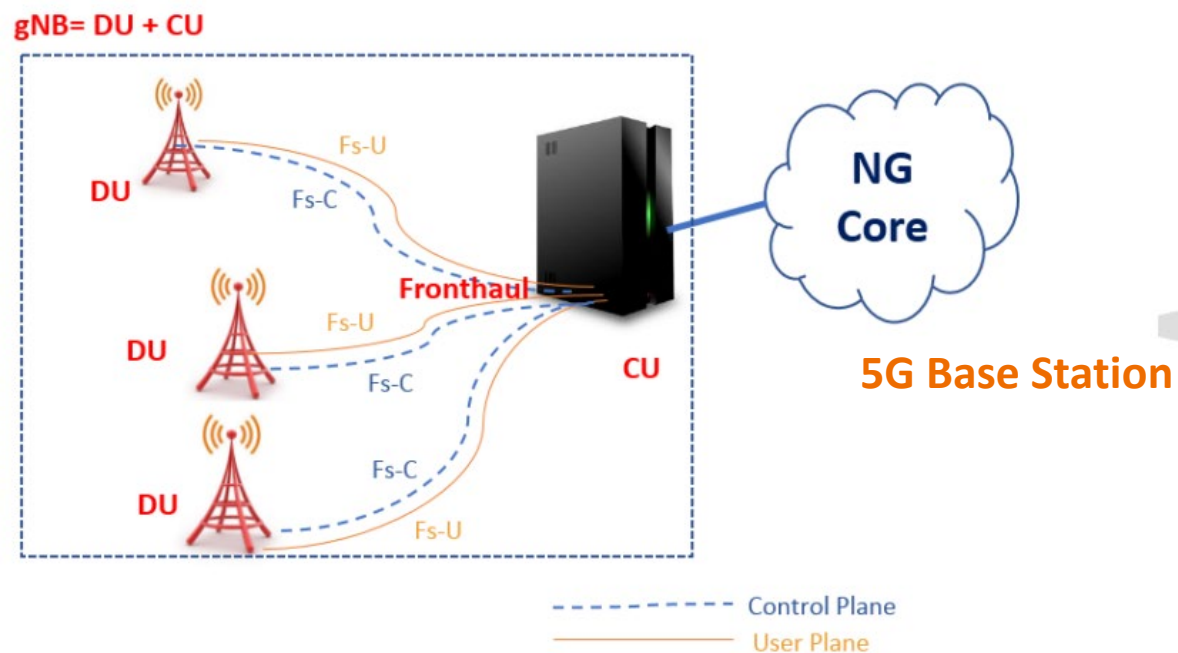
**User plane Function (UPF)**

Application Function (AF)

User Equipment (UE)

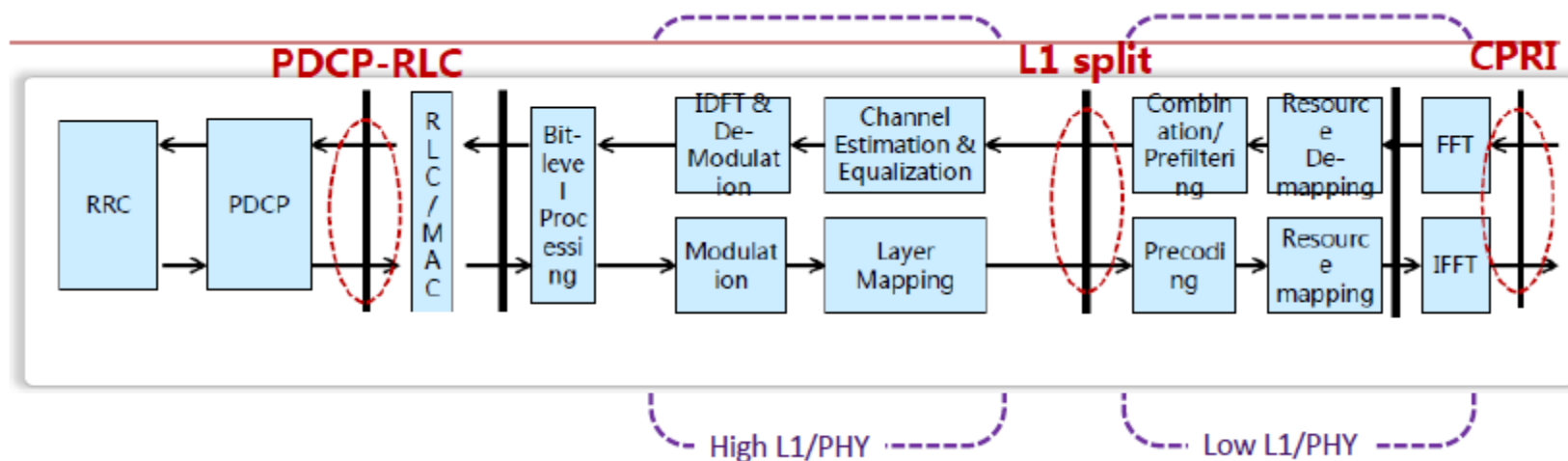
(Radio) Access Network ((R)AN)





Traditional BS is divided into RRH+DU+CU structure

- RRH: Radio transmission and receiving
- DU: baseband close to RRH
- CU: baseband in cloud center





# Specification Numbering

- “All 3GPP specifications have a specification number consisting of 4 or 5 digits. (e.g. 09.02 or 29.002).”
- “The first two digits define the series, followed by 2 further digits for the 01 to 13 series or 3 further digits for the 21 to 55 series.”

---<https://www.3gpp.org/specifications/specification-numbering>

- Each specification defines a component of 3GPP systems. With the development of new releases, the specification version will be updated

Spec no.	Title	Rel-12	Rel-13
<a href="#">36.211</a>	Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation	12.9.0	13.5.0
<a href="#">36.321</a>	Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification	12.9.0	13.5.0
<a href="#">36.423</a>	Evolved Universal Terrestrial Radio Access Network (E-UTRAN); X2 Application Protocol (X2AP)	12.9.0	13.6.0

# How to find the specification

- Specification Release version matrix:  
<http://www.3gpp.org/DynaReport/SpecReleaseMatrix.htm>
- TR: technical report (e.g. TR25.996)
- TS: technical specification
- Locate the specification by number and version

[illegible]

[illegible]

General	Versions	Responsibility	Related	Specification #: 23.501
<b>Release 16</b> (Spec is UCC for this Release) <div>Latest Remark:</div>				
Meetings	Version	Upload date	Comment	
<a href="#">SA#87-E</a>	<a href="#">16.4.0</a>	2020-03-27	Version updated with TSG SA#8...	
<a href="#">SA#86</a>	<a href="#">16.3.0</a>	2019-12-22	Version updated with TSG SA#8...	
<a href="#">SA#85</a>	<a href="#">16.2.0</a>	2019-09-24	Version updated with TSG SA#8...	
<a href="#">SA#84</a>	<a href="#">16.1.0</a>	2019-06-11	Version updated with TSG SA#8...	
<a href="#">SA#83</a>	<a href="#">16.0.2</a>	2019-04-01	MCC correction swapping claus...	
<a href="#">SA#83</a>	<a href="#">16.0.1</a>	2019-04-01	MCC correction of clause 5.29...	
<a href="#">SA#83</a>	<a href="#">16.0.0</a>	2019-03-28	Rel-16 Version created with T...	
<b>Release 15</b> (Spec is UCC for this Release) <div>Latest Remark:</div>				
Meetings	Version	Upload date	Comment	
<a href="#">SA#87-E</a>	<a href="#">15.9.0</a>	2020-03-27	Version updated with TSG SA#8...	
<a href="#">SA#86</a>	<a href="#">15.8.0</a>	2019-12-22	Version updated with TSG SA#8...	
<a href="#">SA#85</a>	<a href="#">15.7.0</a>	2019-09-24	Version updated with TSG SA#8...	
<a href="#">SA#84</a>	<a href="#">15.6.0</a>	2019-10-09	Version updated with TSG SA#8...	
<a href="#">SA#83</a>	<a href="#">15.5.0</a>	2019-03-25	Version updated with TSG SA#8...	
<a href="#">SA#82</a>	<a href="#">15.4.0</a>	2018-12-18	Version updated with TSG SA#8...	
<a href="#">SA#81</a>	<a href="#">15.3.0</a>	2018-09-17	Version updated with TSG SA#8...	
<a href="#">SA#80</a>	<a href="#">15.2.0</a>	2018-06-19	Version updated with TSG SA...	

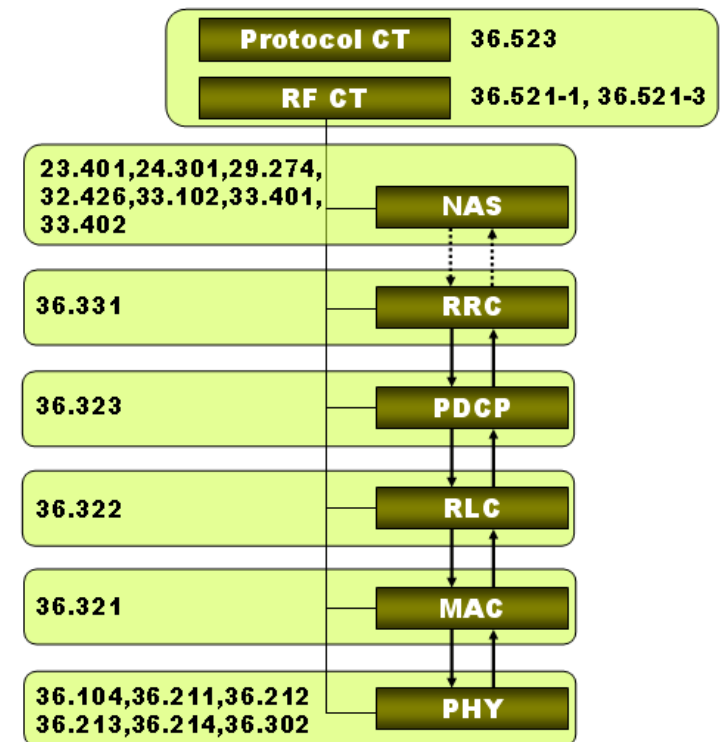
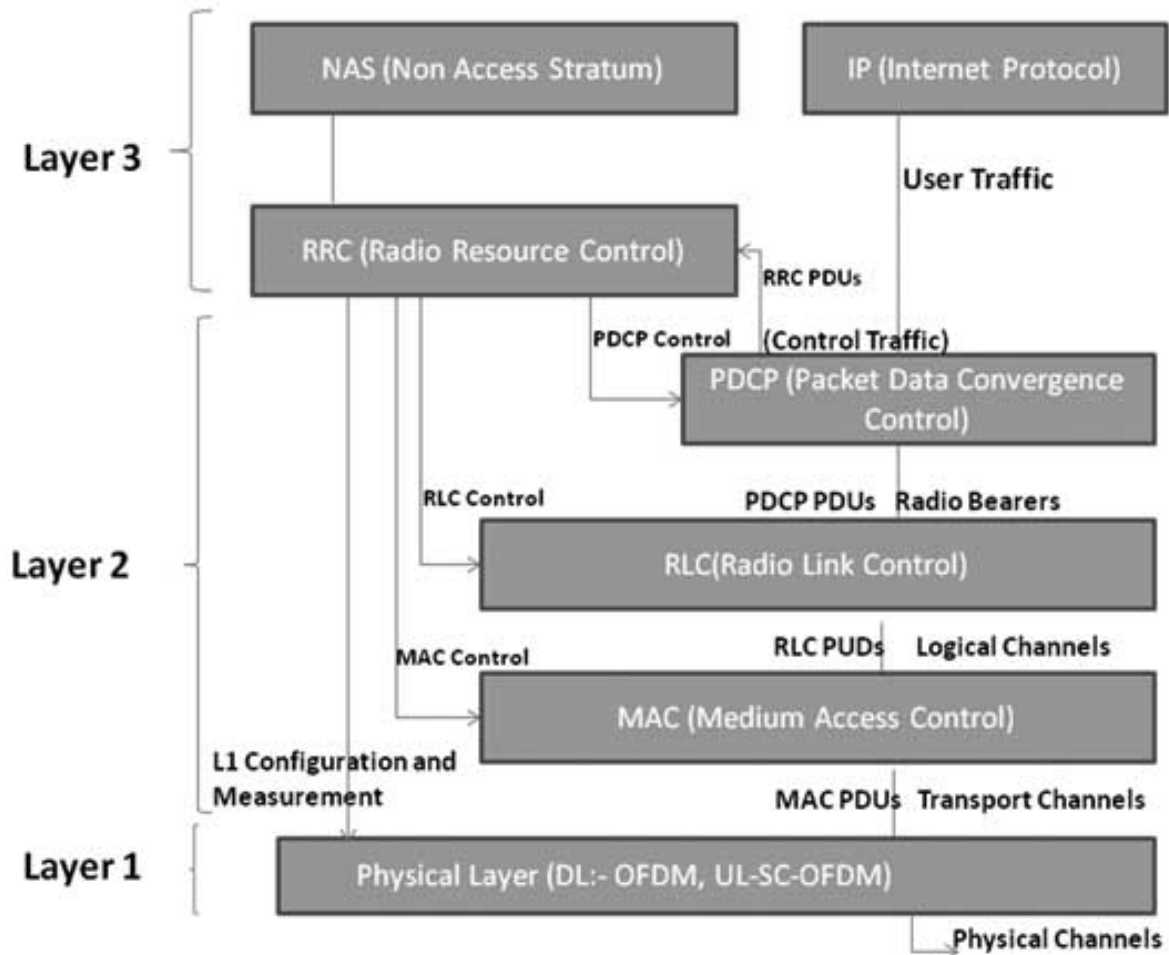
3GPP TS 23.501 V16.4.0 (2020-03)

### Technical Specification

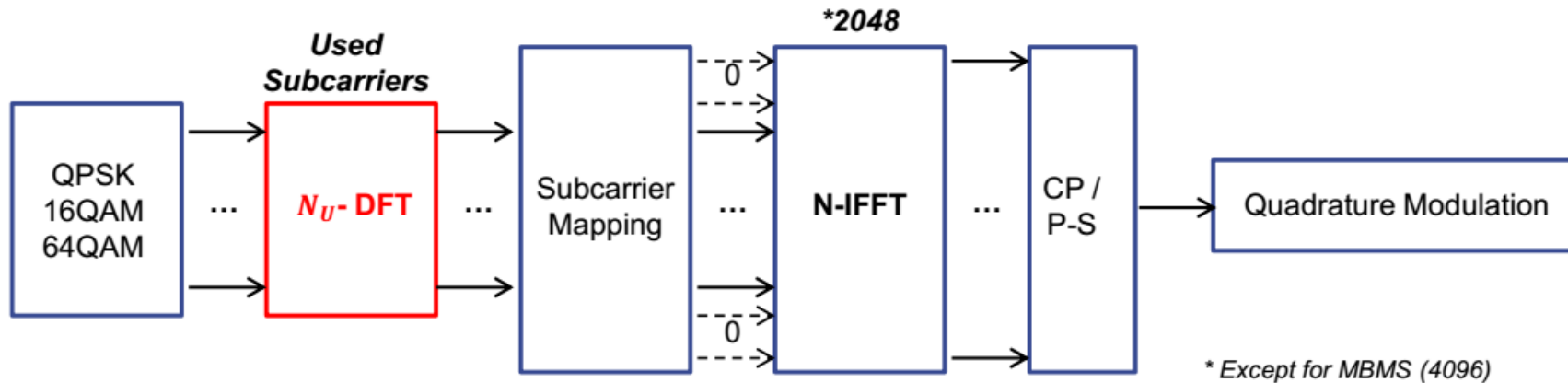
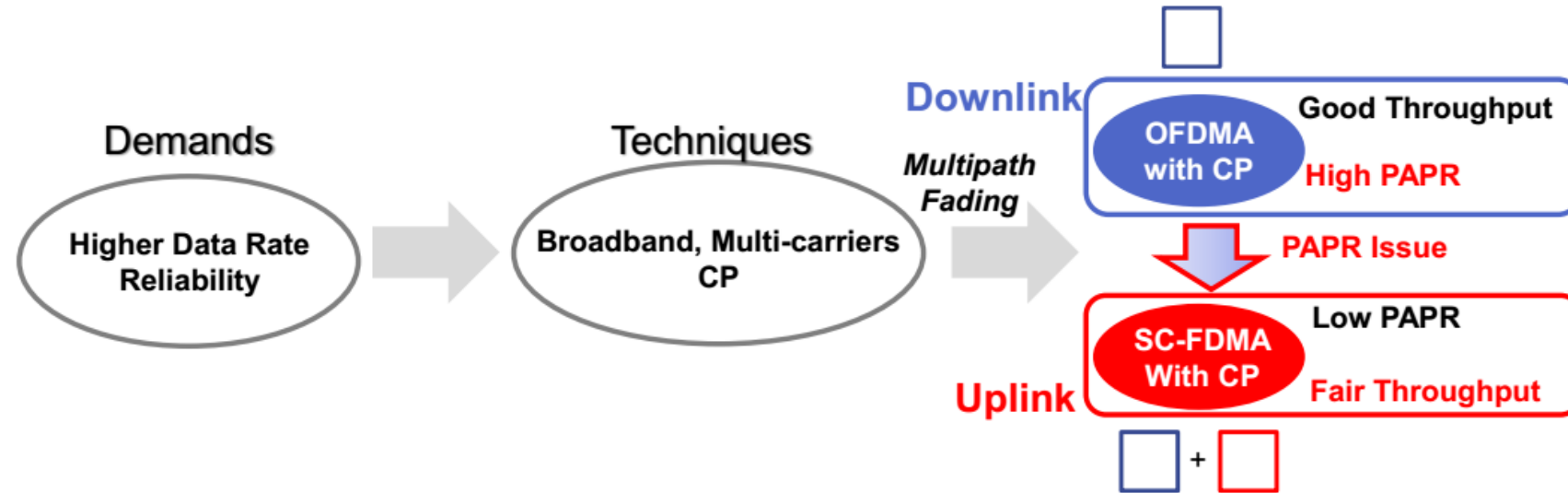
**3rd Generation Partnership Project:  
Technical Specification Group Services and System Aspects:  
System architecture for the 5G System (5GS):  
Stage 2  
(Release 16)**



# LTE Protocol Architecture



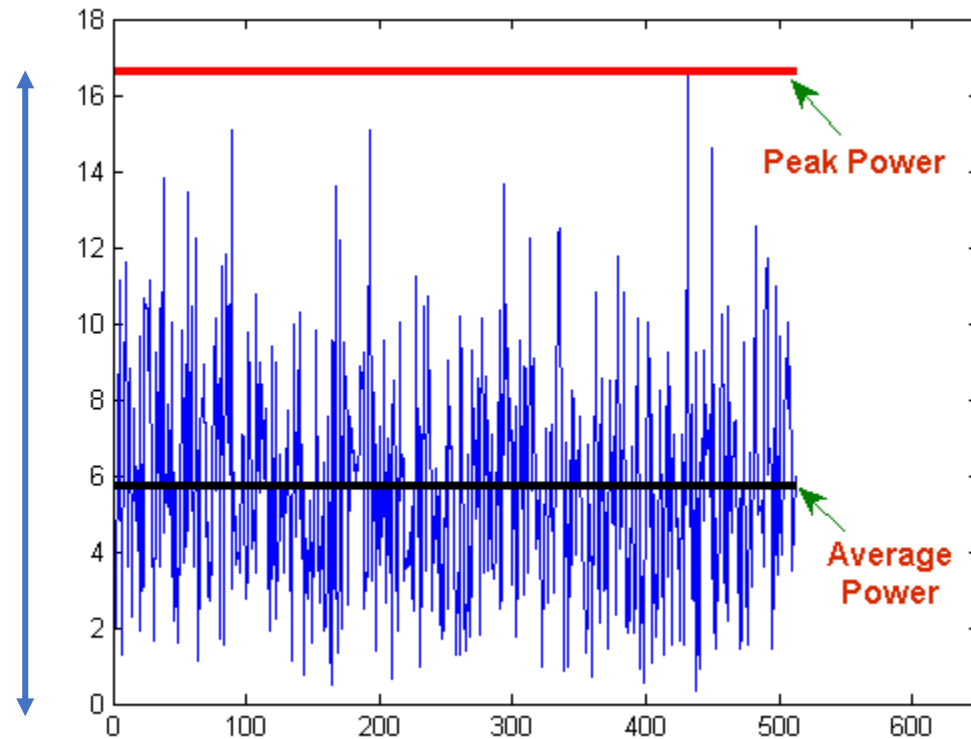
# LTE Signals – OFDM



# Peak-to-Average Power Ratio (PAPR)

Linear Region of Power Amplifier

High PAPR implies high cost on the PAs



# Peak-to-Average Power Ratio

- Inverse DFT:  $x_n = \frac{1}{N} \sum_{k=0}^{N-1} X_k e^{j\frac{2\pi kn}{N}}$
- For the simplicity of analysis, suppose the signal is 1, then  $x_n = [1, 0, 0, 0, \dots]$
- Maximum signal power is 1
- Average signal power is  $1/N$
- PAPR = N increases w.r.t. the number of subcarriers
- SC-FDMA can reduce the PAPR

# UL/DL Parameters

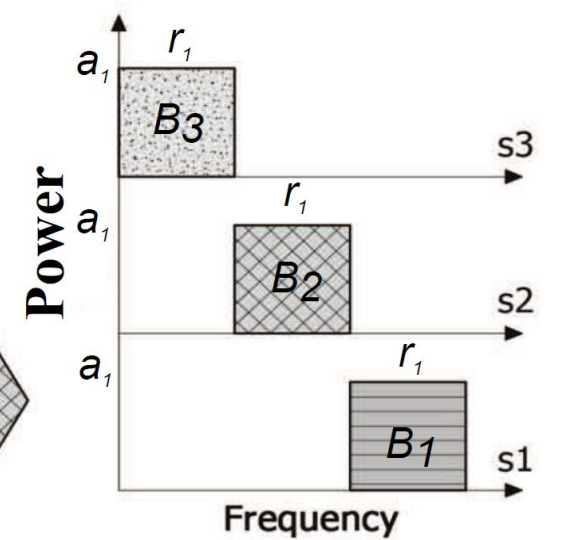
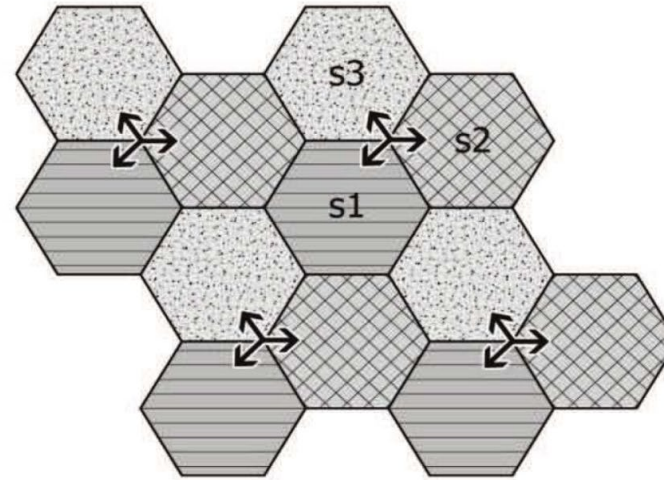
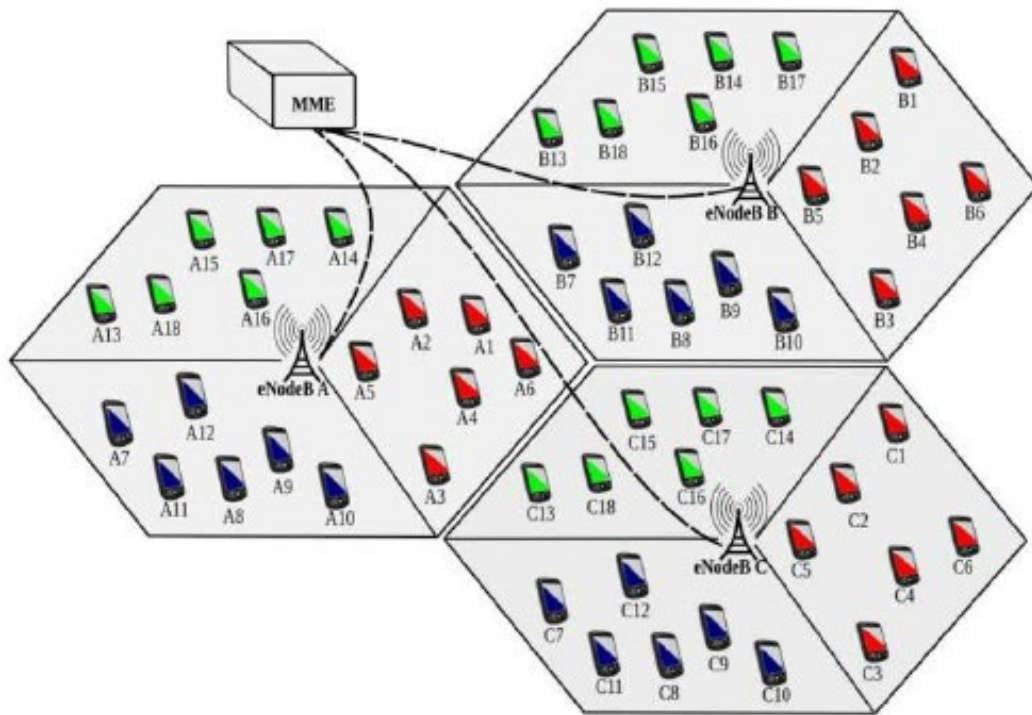
<b>Channel bandwidth [MHz]</b>	1.4	3	5	10	15	20
<b>Number of resource blocks (<math>N_{RB}</math>)</b>	6	15	25	50	75	100
<b>Number of occupied subcarriers</b>	72	180	300	600	900	1200
<b>IDFT(Tx)/DFT(Rx) size</b>	128	256	512	1024	1536	2048
<b>Sample rate [MHz]</b>	1.92	3.84	7.68	15.36	23.04	30.72
<b>Samples per slot</b>	960	1920	3840	7680	11520	15360



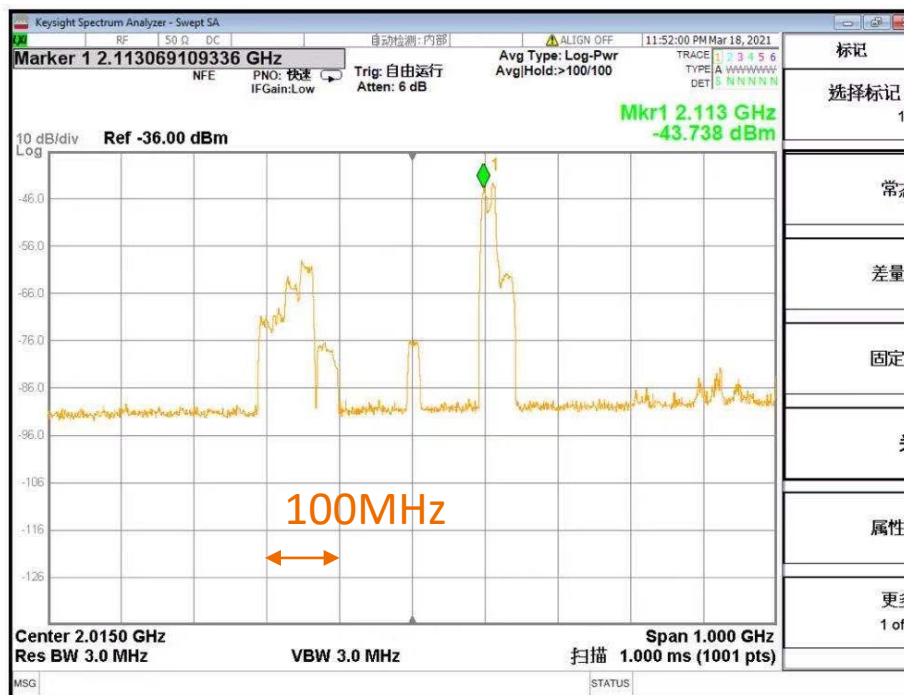
# Some Calculations

- **Bandwidth** = Sample Rate \* # of occupied subcarriers / # of subcarriers
- E.g.,  $1.92\text{M} * 72 / 128 = 1.08\text{MHz} < 1.4\text{MHz}$
- **Subcarrier Spacing** = Sample Rate / # of subcarriers
- E.g.,  $1.92\text{M} / 128 = 3.84\text{M} / 256 = \dots = 15\text{KHz}$
- **OFDM Symbol Duration** = # of subcarriers / Sample Rate = 1 / Subcarrier Spacing
- E.g.,  $1 / 15\text{KHz}$
- Define  **$T_s = \text{OFDM Symbol Duration} / 2048$** , which is basic time unit in LTE

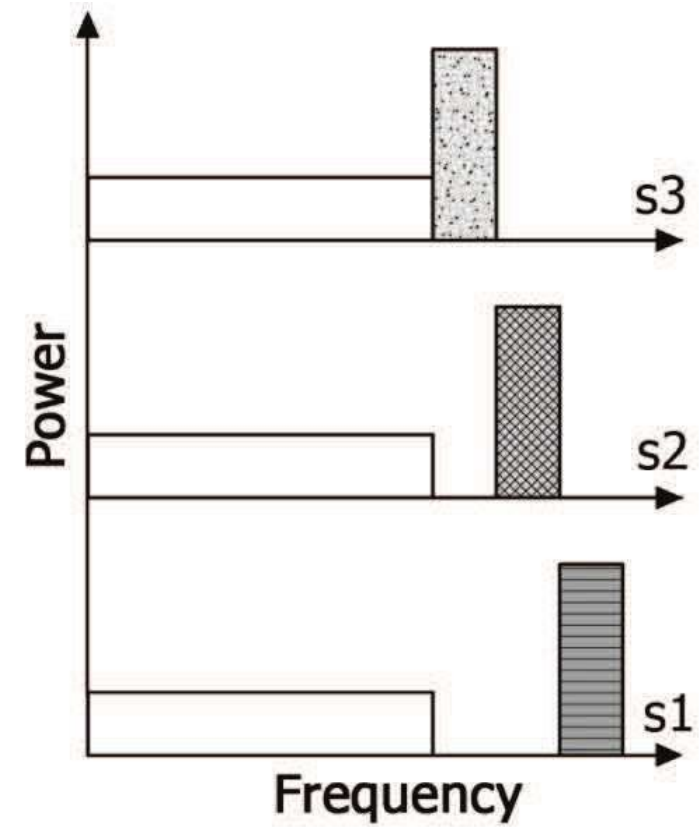
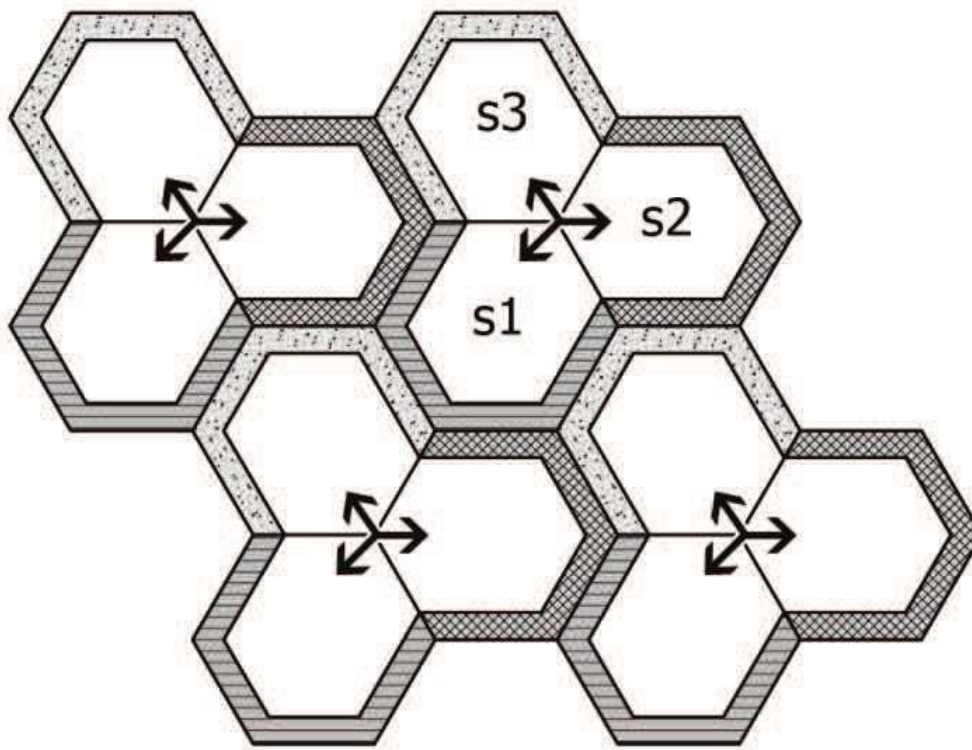
# Sectors and Frequency Reuse



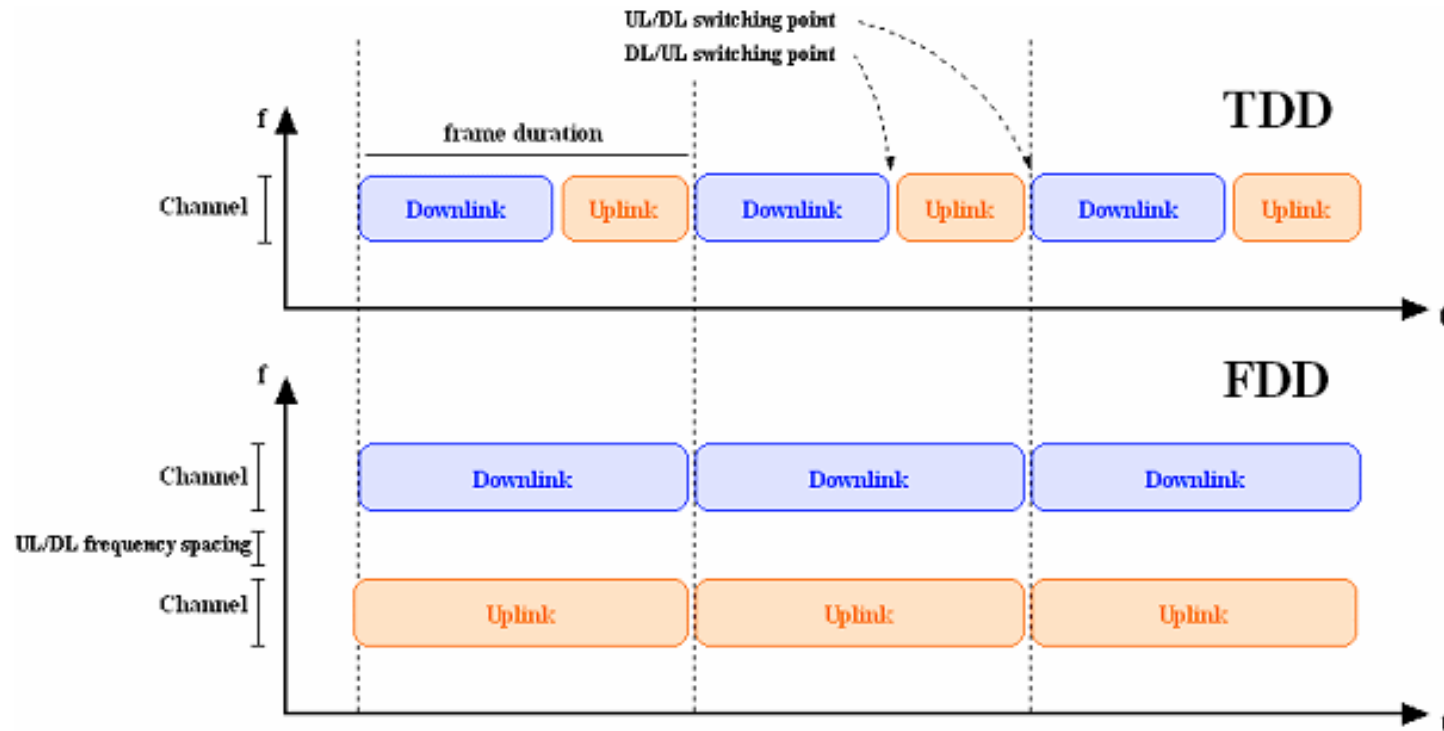
# Sectors and Frequency Reuse



# Soft/Fractional Frequency Reuse



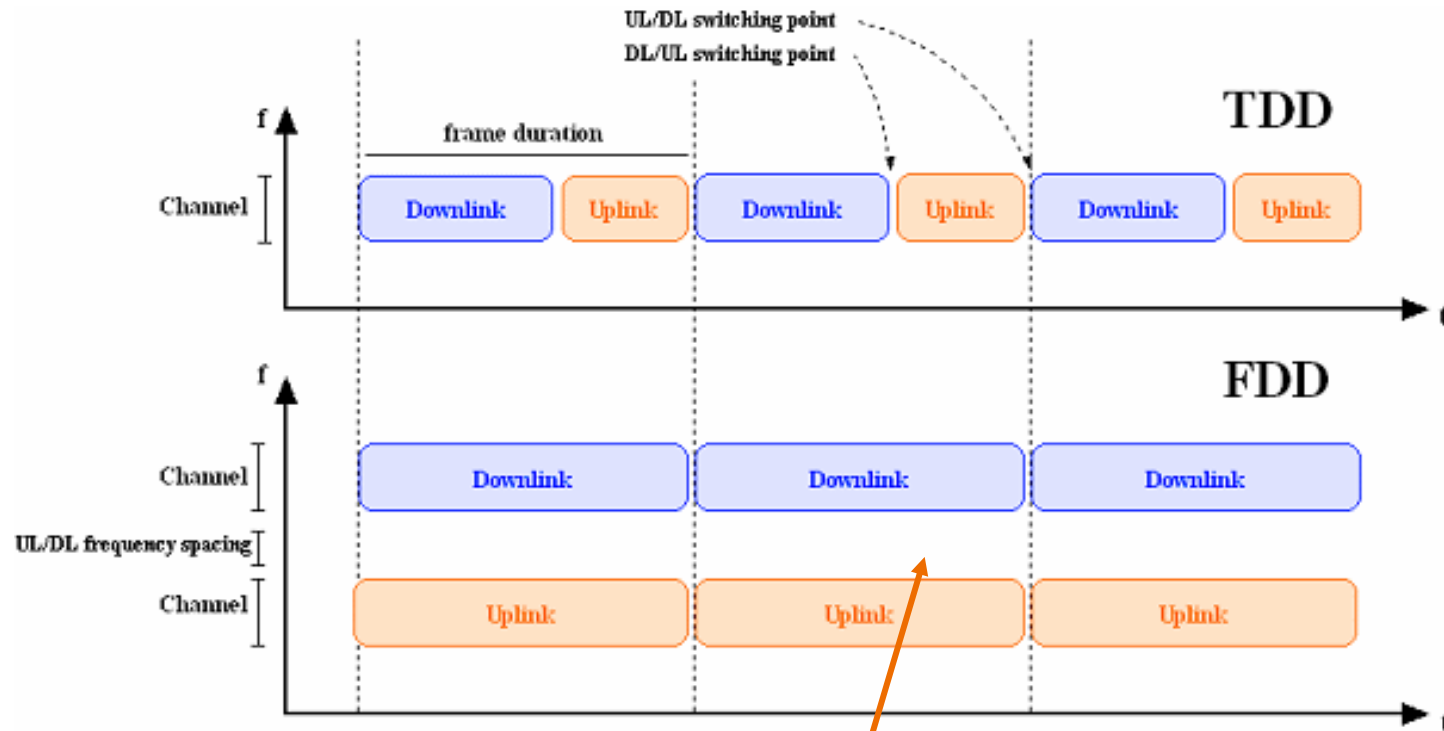
# Duplexing Modes: TDD and FDD



**Time-Division Duplex:** same spectrum different time

**Frequency-Division Duplex:** same time different spectrum

# Duplexing Modes: TDD and FDD



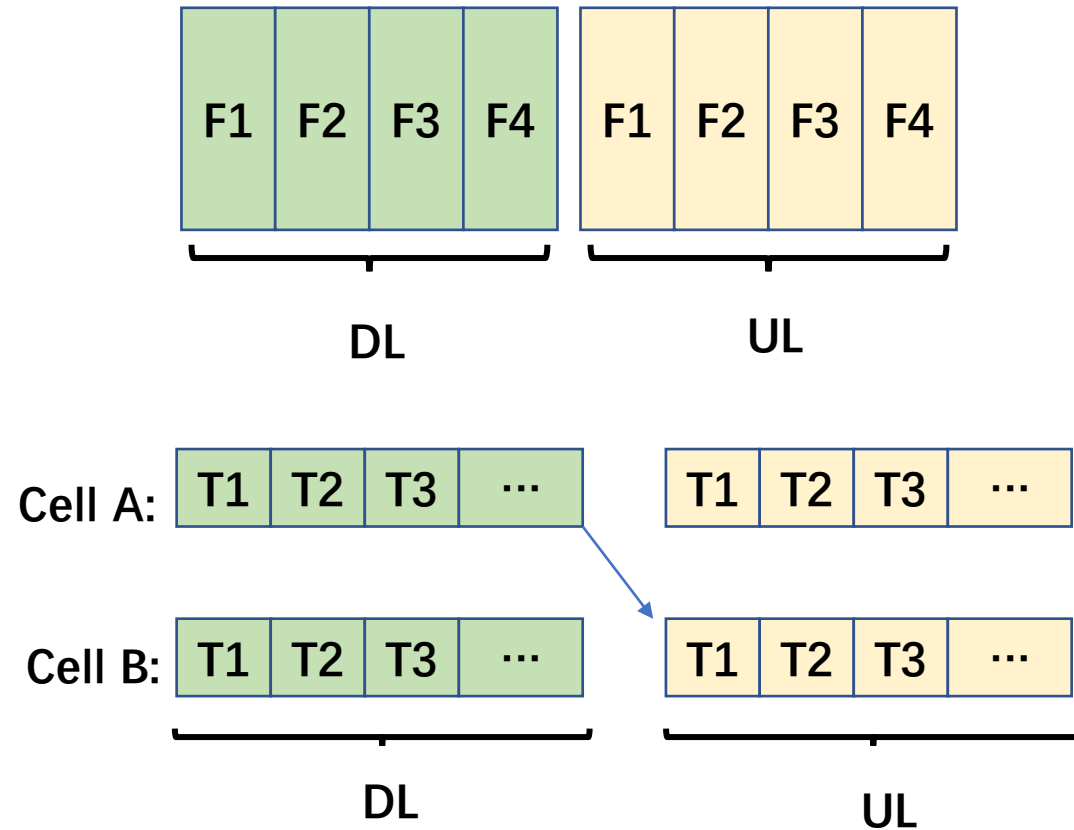
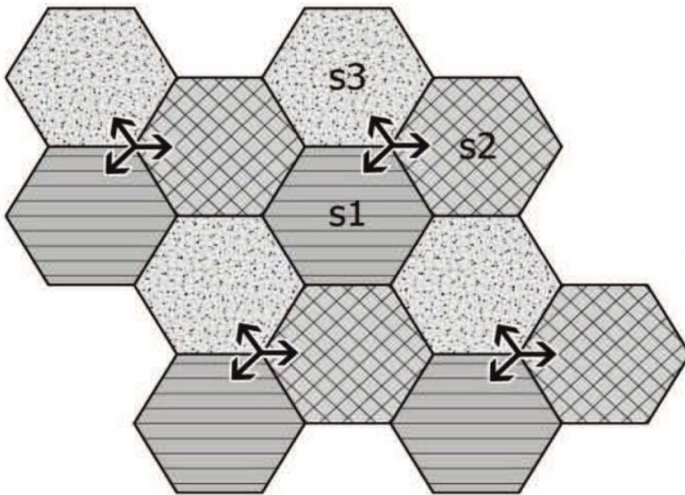
**Time-Division Duplex:** same spectrum different time

**Frequency-Division Duplex:** same time different spectrum

Guard band is required to isolated the mutual interference between downlink and uplink

# TDD or FDD?

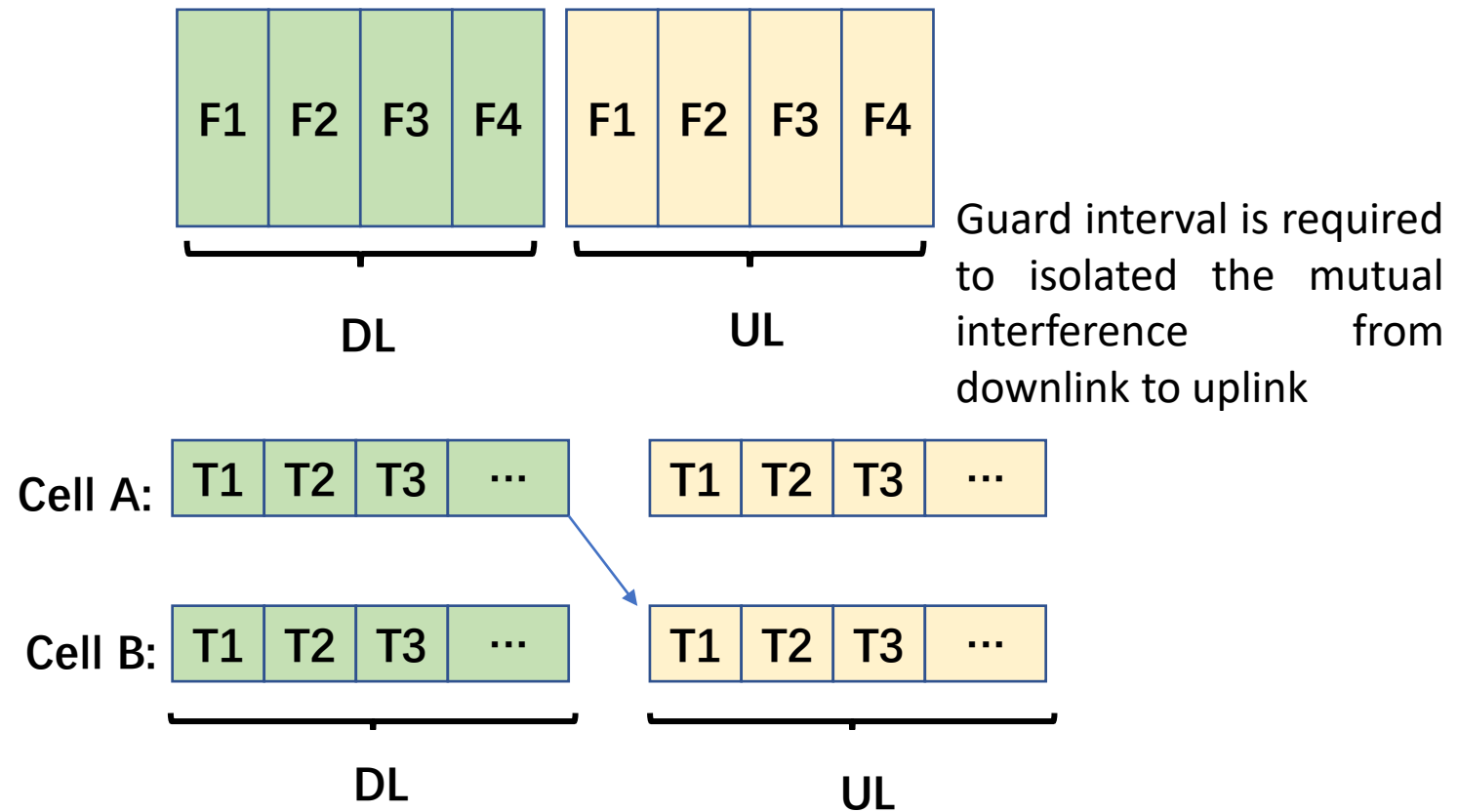
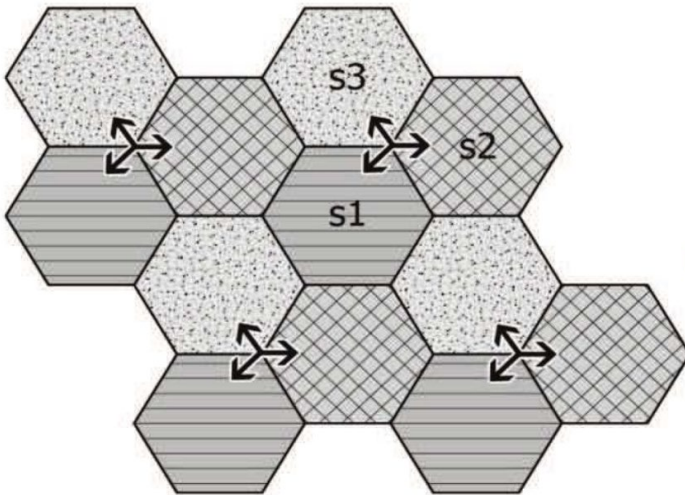
- TDD can dynamically adjust the UL and DL resource, however





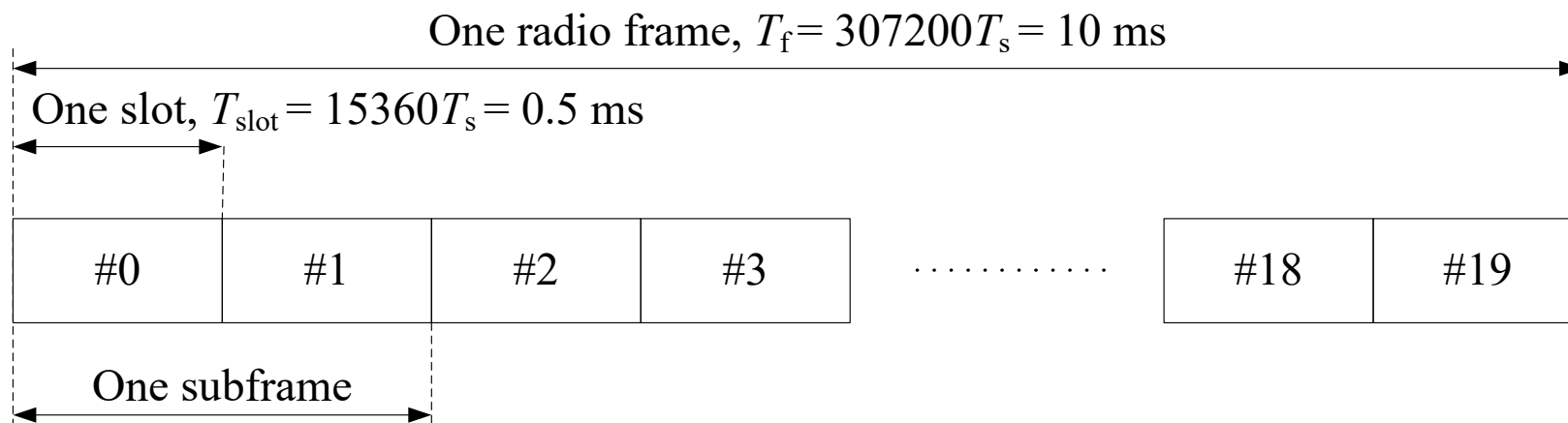
# TDD or FDD?

- TDD can dynamically adjust the UL and DL resource, however





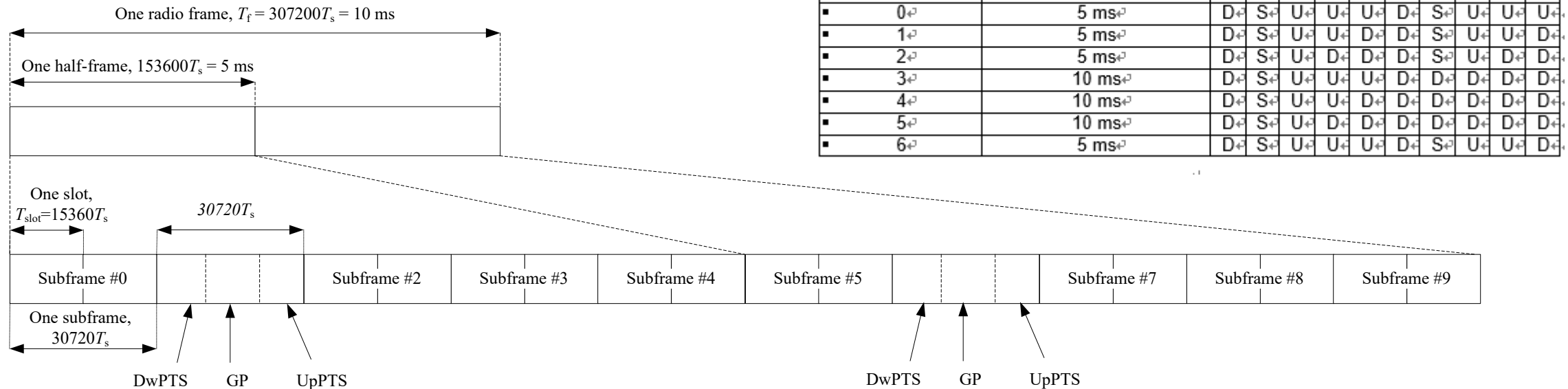
# Frame Structure Type 1 (36.211, 4.1)



“Frame structure type 1 is applicable to both full duplex and half duplex **FDD** only. Each radio frame is  $T_f = 307200 \cdot T_s = 10 \text{ ms}$  long and consists of **10 subframes** of length  $30720 \cdot T_s = 1 \text{ ms}$ , numbered from 0 to 9.”

Each subframe is further divided into two slots, each with length  $15360 \cdot T_s = 0.5 \text{ ms}$

# Frame Structure Type 2 (36.211, 4.1)



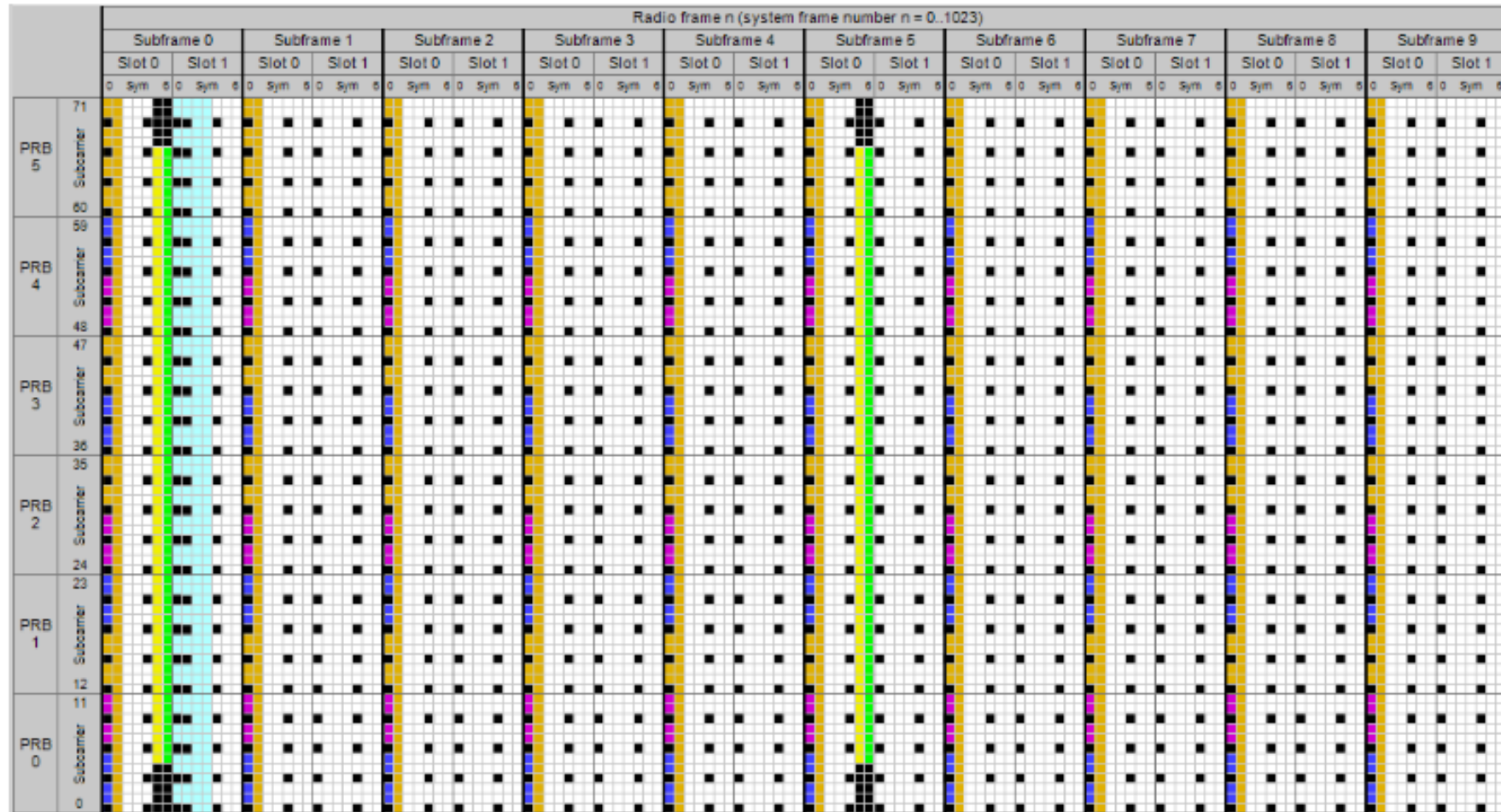
“Frame structure type 2 is applicable to **TDD** only. Each radio frame of length  $T_f = 307200 \cdot T_s = 10\text{ms}$  consists of **two half-frames** of length  $153600 \cdot T_s = 5\text{ ms}$  each. Each half-frame consists of **five subframes** of length  $30720 \cdot T_s = 1\text{ ms}$ .”

Each subframe is further divided into two slots, each with length  $15360 \cdot T_s = 0.5\text{ ms}$

# Cyclic Prefix

- Normal CP: **160Ts** first symbol and **144 Ts** the remaining symbols
- $7 \cdot 2048 + 6 \cdot 144 + 160 = 15360\text{Ts} = 0.5\text{ms}$
- Light speed \* CP = **1.4km**
  
- Extended CP: **521Ts**
- $512 \cdot 6 + 2048 \cdot 6 = 15360\text{Ts} = 0.5\text{ms}$
- Light speed \* CP = **5km**
  
- With normal CP, there are **7** OFDM symbols per slot; with extended CP, there are **6** OFDM symbols per slot.

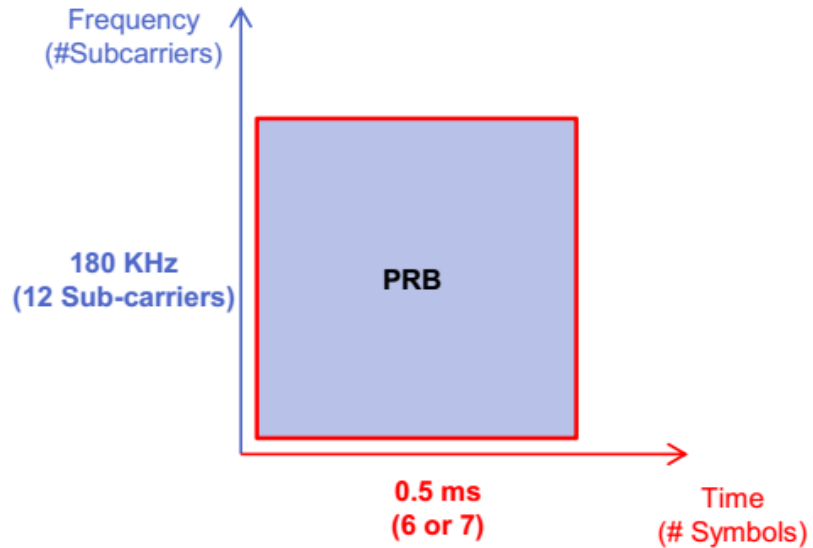
# Resource Element



- PSCH (Primary Synchronization Channel)
- SSCH (Secondary Synchronization Channel)
- PBCH (Physical Broadcast Channel)
- RS (cell-specific Reference Signal) for selected Tx antenna port

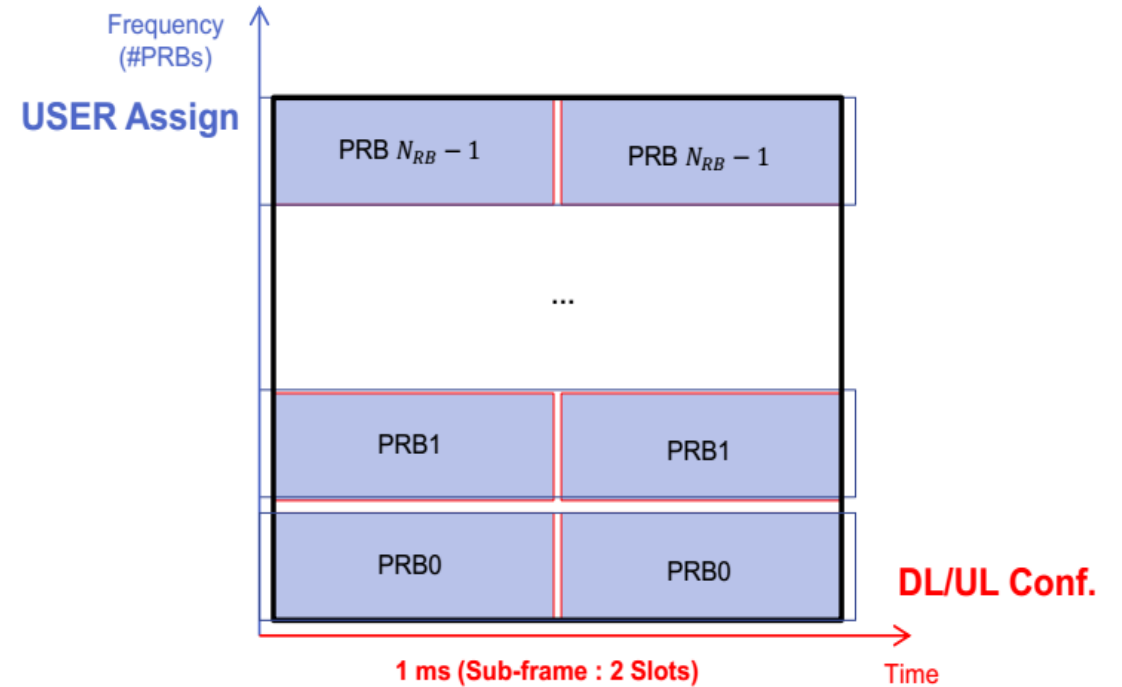
- PCFICH (Physical Control Format Indicator Channel)
- PHICH (Physical Hybrid ARQ (Automatic Repeat reQuest) Indicator Channel)
- PDCCH (Physical Downlink Control Channel)
- Available for PDSCH (Physical Downlink Shared Channel)

# Physical Resource Block



Parameters (Except for MBMS)

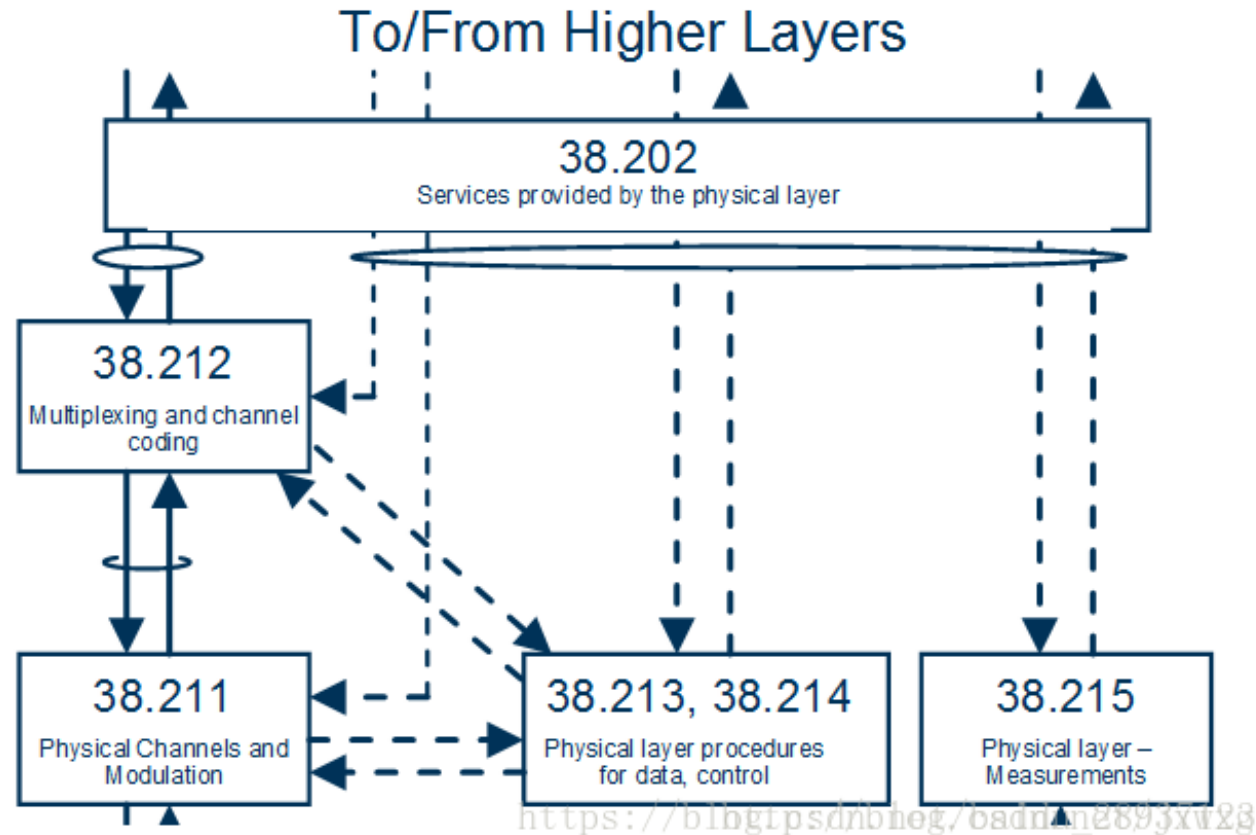
CP Type	# Symbols / Slot
Normal CP	7
Extended CP	6



Parameters (Except for MBMS)

System BW [MHz]	1.4	3	5	10	15	20
# PRBs $N_{RB}$ (# Used Subcarriers $N_u$ )	6 (72)	15 (180)	25 (300)	50 (600)	75 (900)	100 (1200)

# 5G PHY Specifications



# 5G Spectrum

600 MHz	LTE/5G	North America
700 MHz	LTE/5G	APAC, EMEA, LatAm
3.3-3.4	LTE/5G	APAC, Africa, LatAm
3.4-3.6	LTE/5G	Global
3.55-4.2	LTE/5G	US
3.6-3.8	5G	Europe
4.5	5G	Japan China
28	5G	US, Korea Japan
39	5G	US
24.25-27.5	5G	WRC-19 band
31.8-33.4	5G	WRC-19 band (Fra, UK)

Full coverage with <1 GHz

Dense urban high data rates at 3.5 – 4.5 GHz

Hotspot 10 Gbps at 28/39 GHz

Future mmwave options

Macro



small Cell



Ultra small Cell



# 5G Spectrum

5G service  
New Radio (NR)

HD 5G 4G 54% 8:45		
卡槽 1	卡槽 2	WiFi 位置 设备
卡槽		
SIM 运营商		中国移动
ICCID		89860008191509939851
ICCID 信息		中国移动 广东 2015 雅斯拓
电话号码		?1598*****
网络运营商		
中国移动 China Mobile		运营商 中国移动
MCC		460
MNC		00
服务小区		
我的位置:113.991189/22.602459		
数据网		NR
小区类型		NR
NR-PCI		83
NR-CI		51581059075(12593032-3)
NR-ARFCN		504990
NR-FREQ		2524.95 MHz
NR-BAND		41/90 TDD
LAC		1319771
PSC		0
信号强度		
SS RSRP	SS RSRQ	SS SINR
-101	-11	8

4G Band

TDD Mode



# 5G Heterogeneous Coverage



**Let's make 3.7-4.2 GHz available**

- High bands for capacity
- Low band for IoT and low latency critical communication

5G mm-waves



**1000x local capacity**

**20 Gbps / 1000 MHz**

5G 3500 mMIMO



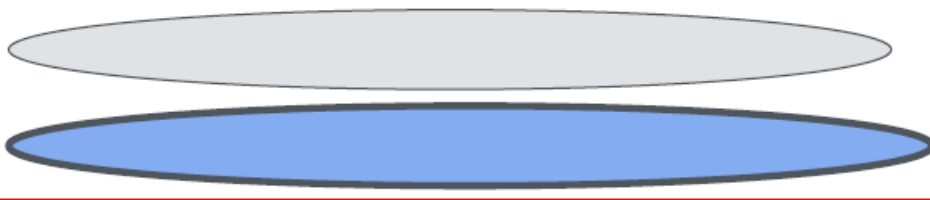
**10x capacity with LTE grid with massive MIMO**

**2 Gbps / 100 MHz**

LTE-AWS

LTE700

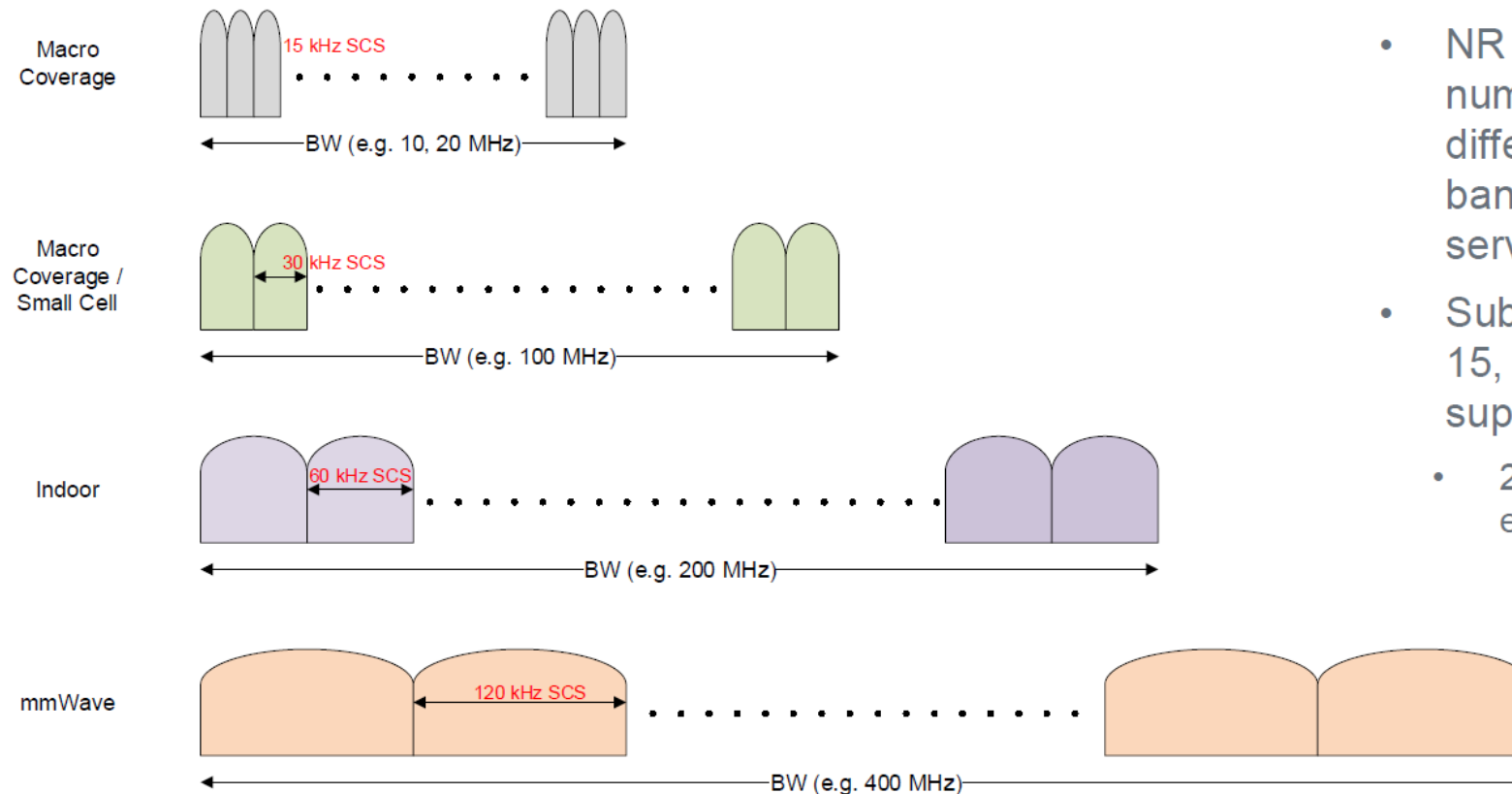
5G600



**IoT and critical communication with full coverage**

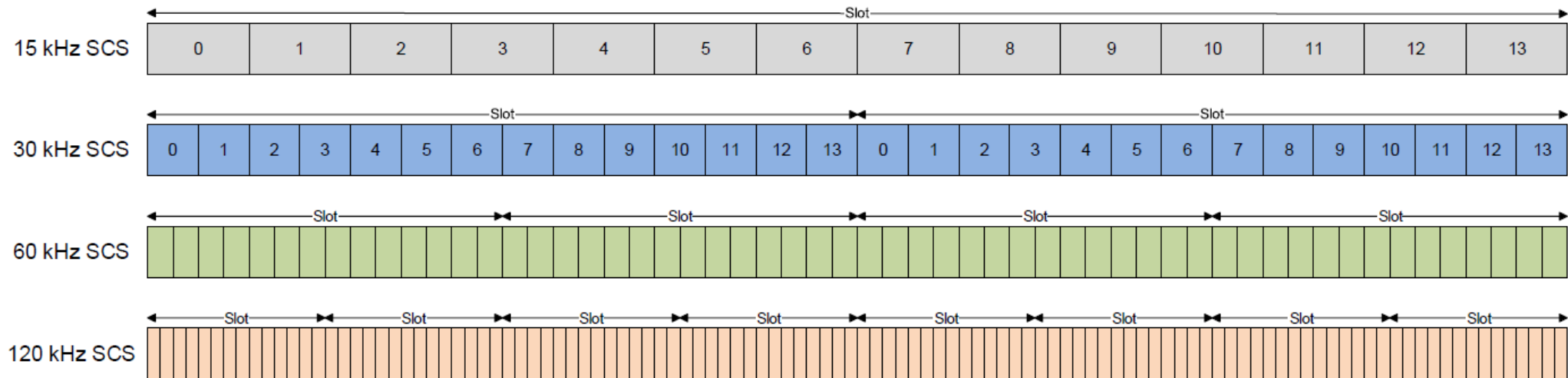
**200 Mbps / 10 MHz**

# Scalable Numerology (38.211, 4.2)



- NR supports scalable numerology to address different spectrum, bandwidth, deployment and services
- Sub-carrier spacing (SCS) of 15, 30, 60, 120 kHz is supported for data channels
  - $2^n$  scaling of SCS allows for efficient FFT processing

# Scalable Numerology



- One slot is comprised of 14 symbols
  - Slot length depends on SCS – 1ms for 15 kHz SCS to 0.125ms for 120 kHz SCS
- Mini-slot (2,4, or 7 symbols) can be allocated for shorter transmissions
- Slots can also be aggregated for longer transmissions

# Reading (April 6<sup>th</sup>)

## 3GPP TS 36.211

- Section 4, 5.1, 5.2, 6.1, 6.2

## 3GPP TS 38.211

- Section 4