University of Antwerp
Faculty of Science

Advanced Wireless & 5G Networks

Prof. Dr. Ir. Michael Peeters — 2023–2024

Topics for today

- **3. From 2 to 5G**
  - We jump 2 generations.

Planning

Session	Date	Topic
1	20231006	~~Introduction, history, market, industry, bands, licensed vs. unlicensed, …~~
2	20231013	~~Technology baselining (a.k.a. refreshing what you should have known): 2G, WiFi, …~~
	20231020	~~Cancelled~~
3	20231027	~~Shannon/Friis continued. 2G as a "low-complexity" example~~
4	~~20231110~~	~~L 2G~~
~~5~~	~~20231117~~	~~L 3GPP 2G-3G-4G-5G architecture evolution. 5G~~
6	20231124	L 5G
7	20231201	U IEEE Wifi Network Architecture: 802.11 abgn
8	20231208	U QoS, 802.11 ac,ax and 802.11 ad,ay
9	**20231215 – 3h**	U short range 802.15.4: Zigbee, BLE, and UWB
10.5	**20231222 – 3h**	U Specials: LoRa, Sigfox (perhaps), proprietary, 802.11p
(12)	TBD	Extra: Technology enablers and acronyms you need to be aware of: ADC, FEM, PA, LSA, and other key analog and digital HW blocks, mMIMO, Beam management, 802.11be, AI, 6G, THz and their implications to the network

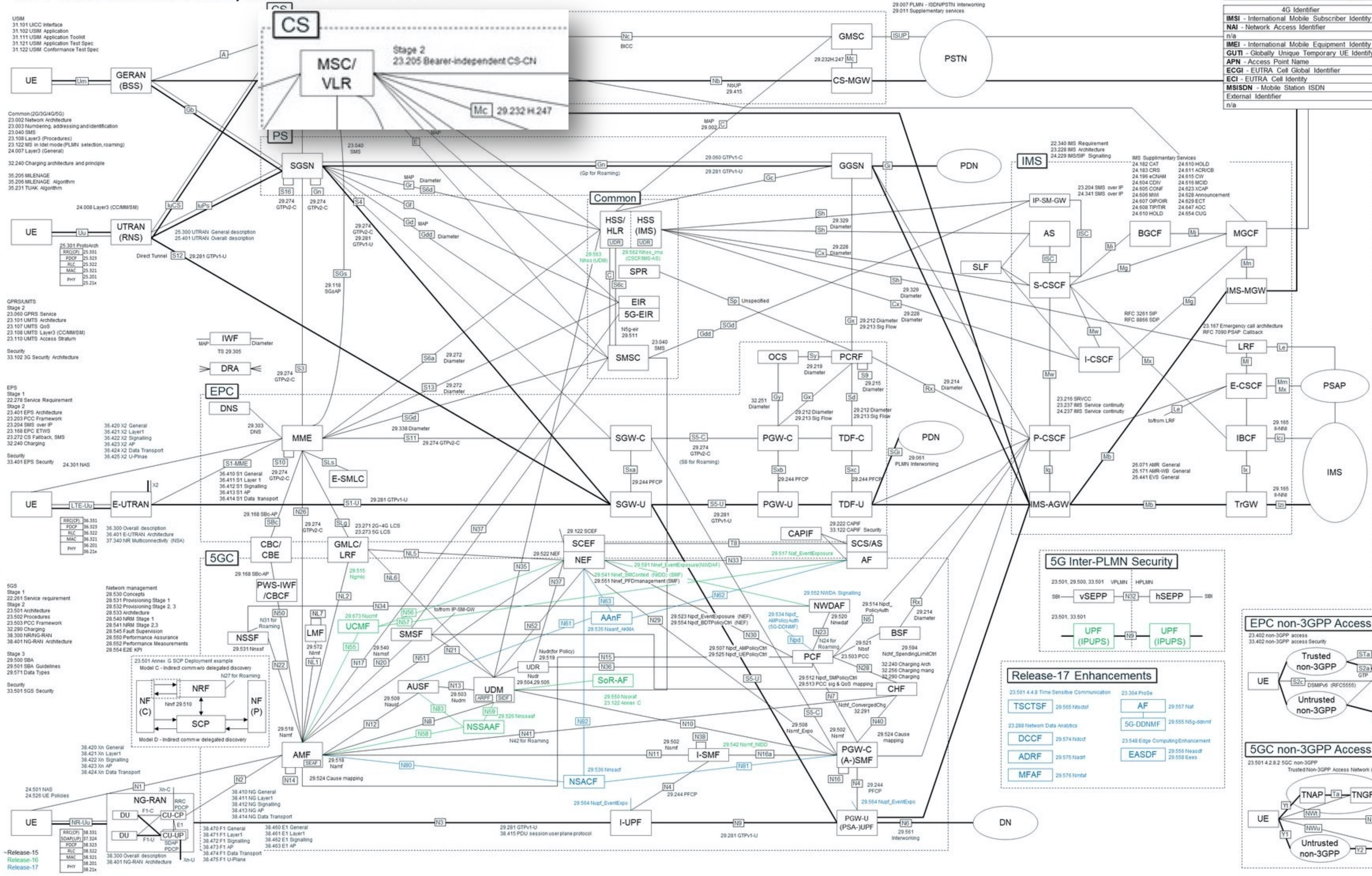
Your expectations

- How it is possible that, in a world where the number of devices continue to grow, every device can get mobile wireless connectivity with the internet without saturating the network.
- How do 4G/5G/... technologies actually work.
- How do you go about designing a good WiFi network, both on the physical end (devices, access point locations, ...) and on the configuration end.
- What are the technologies behind the current advancement in Cellular and Wi-Fi networks?
- Be able to understand the need for improved and efficient networking technologies, and how to approach solving the drawbacks of current technologies.
- What are the limitations of 5G in regard to the latest trends in Ai, AR/VR and technologies that require very low latency.
- What is next?
- Wifi 6 & 7 – new features.
- Link to cloud.
- ~~How do modern mobile networks work and how have they changed from the previous ones?~~
- What are the main problems or limitations faced by different types of networks? If it is possible, what are the best ways to solve them?
- How will wireless and mobile networks possibly evolve in the near future?
- ~~To better understand historical challenges in wireless that companies such as blackberry faced.~~
- To better understand wireless technologies such as Zigbee and LoRaWan and their use in IOT projects.
- What role data science could have in this field?
- Can networks be perfected to the point where we don't need to keep on creating new ones or upgrade the existing ones?
- ~~Can governments stop the development of networks?~~
- ~~Will connectivity ever be available underwater or underground?~~
- Security of wireless networks.

3. 2G to 5G

(concepts & toy examples)

3GPP Overall Architecture and Specifications



4G and 5G Identifier mapping

4G Identifier	5G Identifier
IMSI - International Mobile Subscriber Identity	**SUPI** - Subscription Permanent Identifier
NAI - Network Access Identifier	**SUPI** - Subscription Permanent Identifier
n/a	**SUCI** - Subscription Concealed Identifier
IMEI - International Mobile Equipment Identity	**PEI** - Permanent Equipment Identifier
GUTI - Globally Unique Temporary UE Identify	**5G-GUTI** - 5G Globally Unique Temporary UE Identify
APN - Access Point Name	**DNN** - Data Network Name
ECGI - EUTRA Cell Global Identifier	**NCGI** - NR Cell Global Identity
ECI - EUTRA Cell Identity	**NCI** - NR Cell Identity
MSISDN - Mobile Station ISDN	**GPSI** - Generic Public Subscription Identifier
External Identifier	**GPSI** - Generic Public Subscription Identifier
n/a	**S-NSSAI** - Single-Network Slice Selection Assistance Information

5G Network Function Abbreviations

Release-15

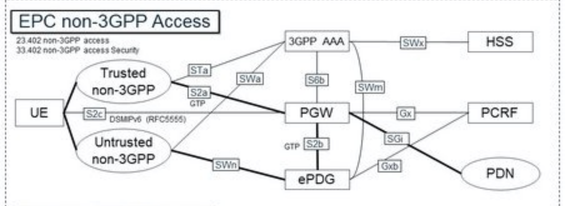
5G-EIR - 5G-Equipment Identity Register
AAnF - AKMA(Authentication and Key Management for Applications) Anchor Function
AF - Application Function
AMF - Access and Mobility Management Function
AUSF - Authentication Server Function
ARPF - Authentication credential Repository and Processing Function
BSF - Binding Support Function
CAPIF - Common API Framework for 3GPP northbound APIs
CHF - Charging Function
I-SMF - Intermediate SMF
I-UPF - Intermediate UPF
LMF - Location Management Function
LRF - Location Retrieval Function
N3IWF - Non-3GPP InterWorking Function
NEF - Network Exposure Function
NRF - Network Repository Function
NSSF - Network Slice Selection Function
NWDAF - Network Data Analytics Function
PCF - Policy Control Function
SCP - Service Communication Proxy
SEAF - SEcurity Anchor Function.
SEPP - Security Edge Protection Proxy
SIDF - Subscription Identifier De-concealing Function;
SMF - Session Management Function
SMSF - Short Message Service Function
TNAP - Trusted Non-3GPP Access Point
TNGF - Trusted Non-3GPP Gateway Function
TWIF - Trusted WLAN Interworking Function
UDM - Unified Data Management
UDR - Unified Data Repository
UDSF - Unstructured Data Storage Function
UPF - User Plane Function

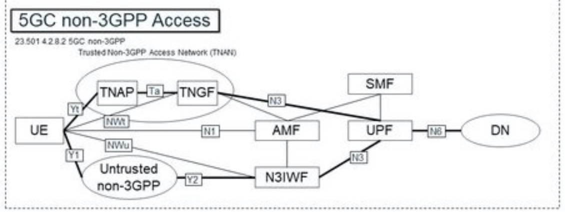
Release-16

IPUPS - Inter PLMN UP Security
NSSAAF - Network Slice-specific and SNPN Authentication and Authorization Function
UCMF - UE radio Capability Management Function
SoR-AF – Steering of Roaming Application Function

Release-17

5G DDNMF - 5G Direct Discovery Name Management Function
ADRF - Analytics Data Repository Function
MFAF - Messaging Framework Adaptor Function
DCCF - Data Collection Coordination Function
NSACF - Network Slice Admission Control Function
TSCTSF - Time Sensitive Communication and Time Synchronization function



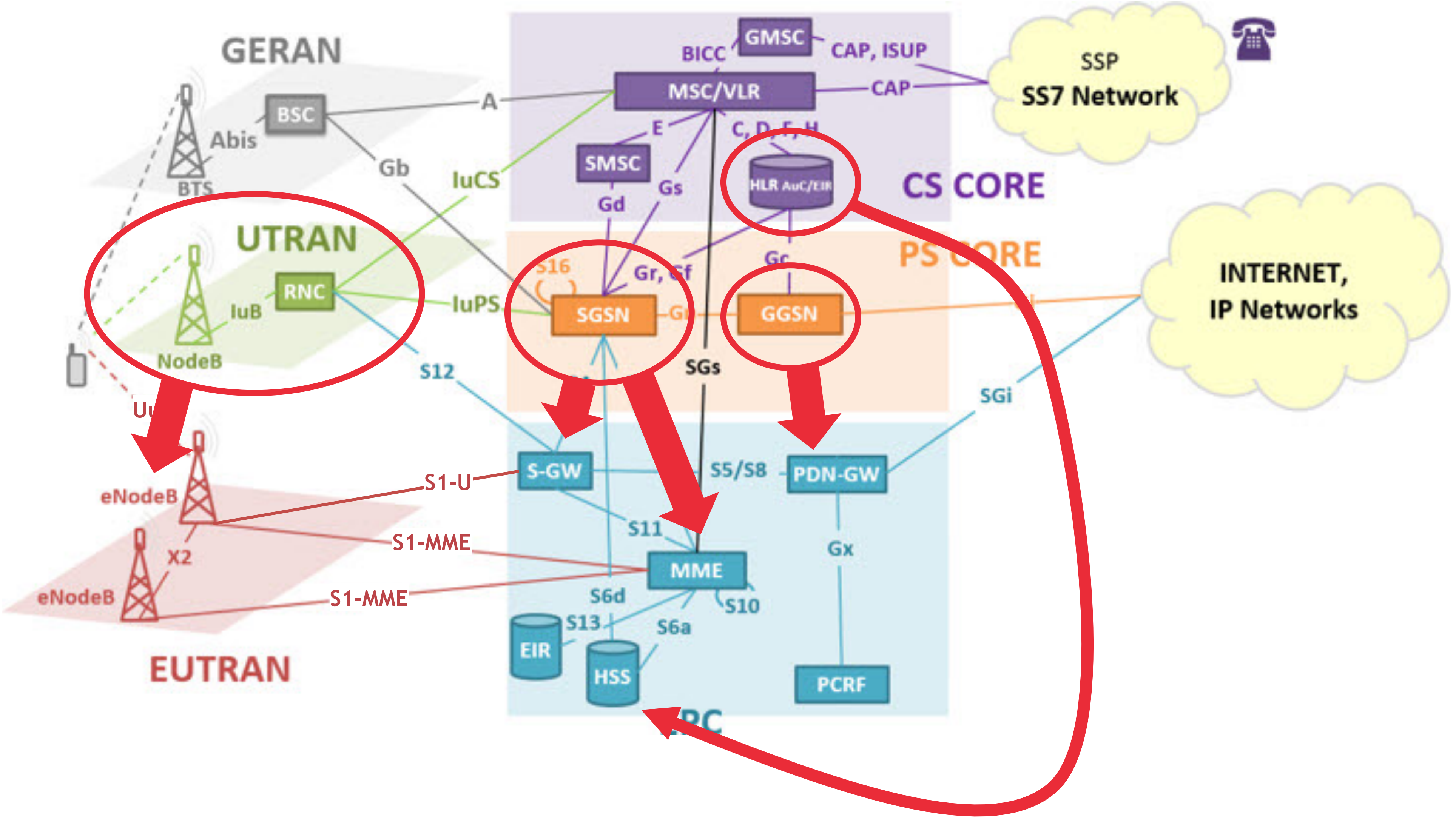


Historical evolution

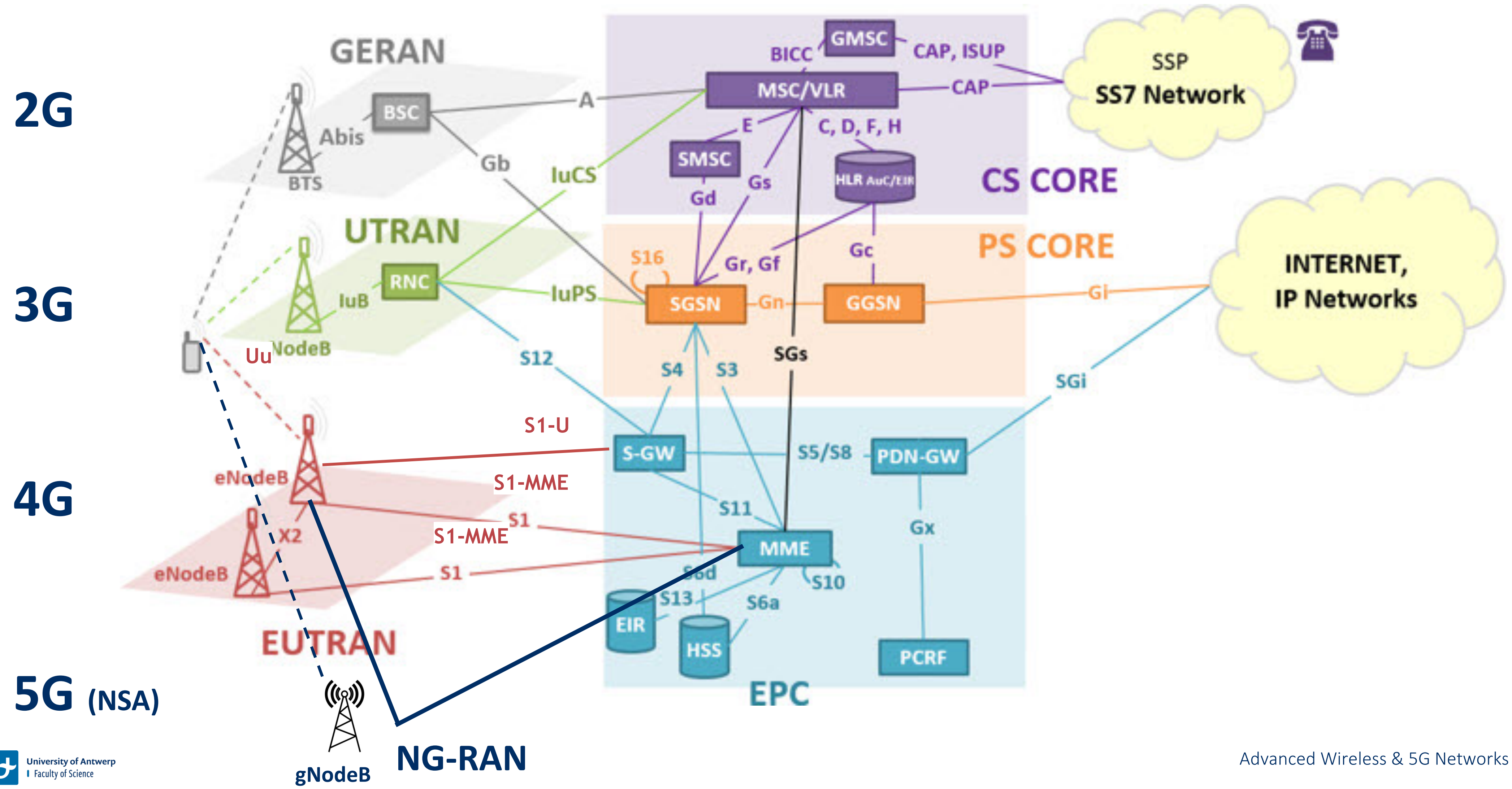
2G

3G

4G



The 3GPP Universe: from GPRS to …



What are the steps?

1. Switch on the mobile (& infrastructure)
2. Select a frequency band to receive & send
3. Pick a way to send and receive digital bits
4. Define how we are going to organize the bits for multiple users
5. Listen to synchronize and get system information
6. Random Access
7. Get a channel
8. Authenticate
9. Ask to send data (or get some data)
10. Ask to make a call
11. Move around
12. … (location update, release call, handover, etc …)

But what is the infrastructure?

- **Due to the time it took to standardize 5G, and the expectation of the market, the industry decide to take this in two steps:**
  1. Standardize a new RAN with an new air interface, **“New Radio” (NR),** and make sure it can work with the existing 4G core. This is called **Non-Stand-Alone (NSA)** as the 5G still needs a 4G network to get its act together. This is what most operators call 5G today.
  2. Standardize a new CORE that incorporates all of the new ideas of modern infrastructure, **5G Core network (5GC),** which is completely based on what is called a **Service-Based Architecture** (SBA), which implements IT network principles and a cloud-native design approach. **This is 5G Stand-Alone (SA).**
- **This however does mean we need to understand some 4G to talk about 5G… @#%&$(!!!**

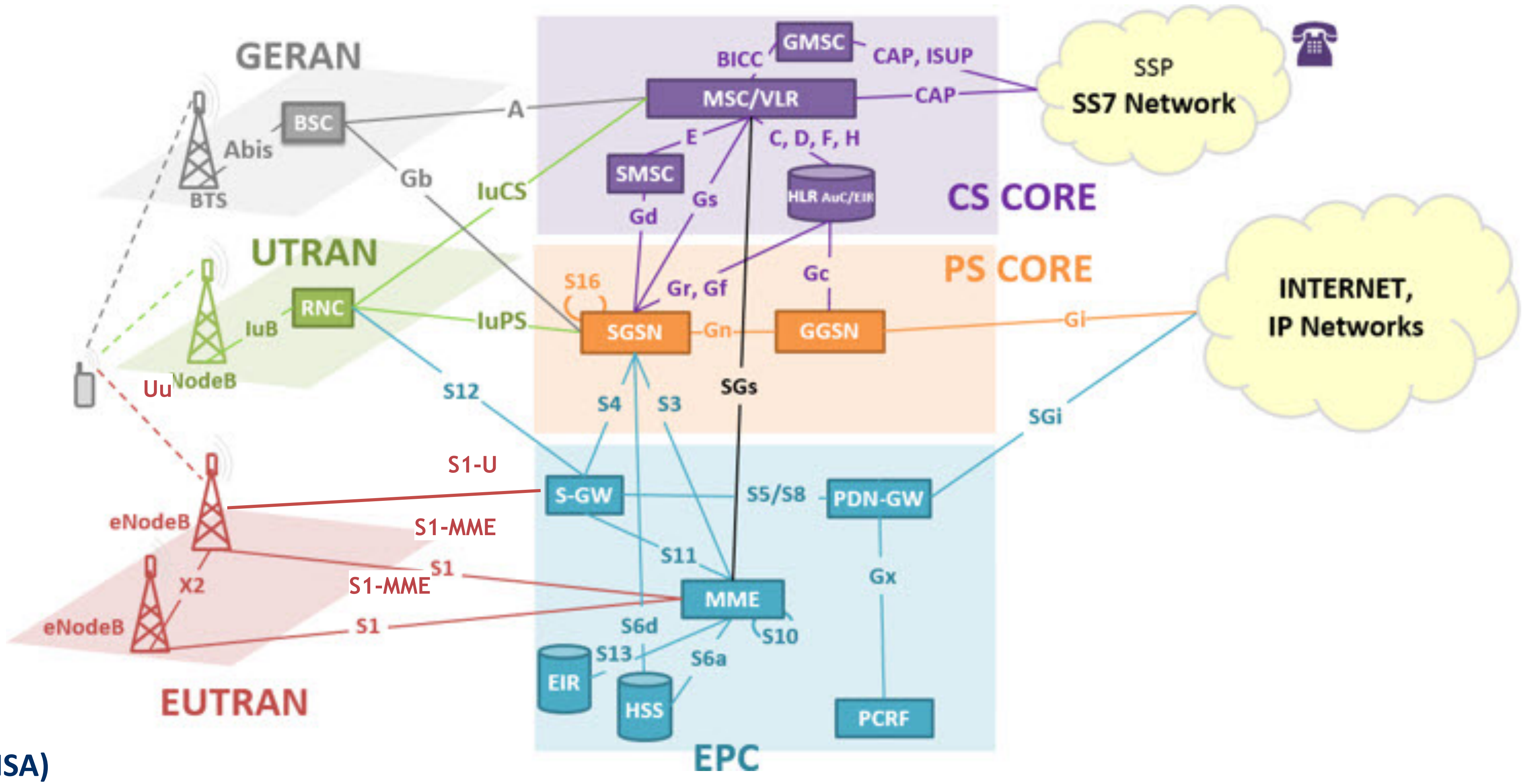
So, how did we get to 4G, and what do we need to know?

2G

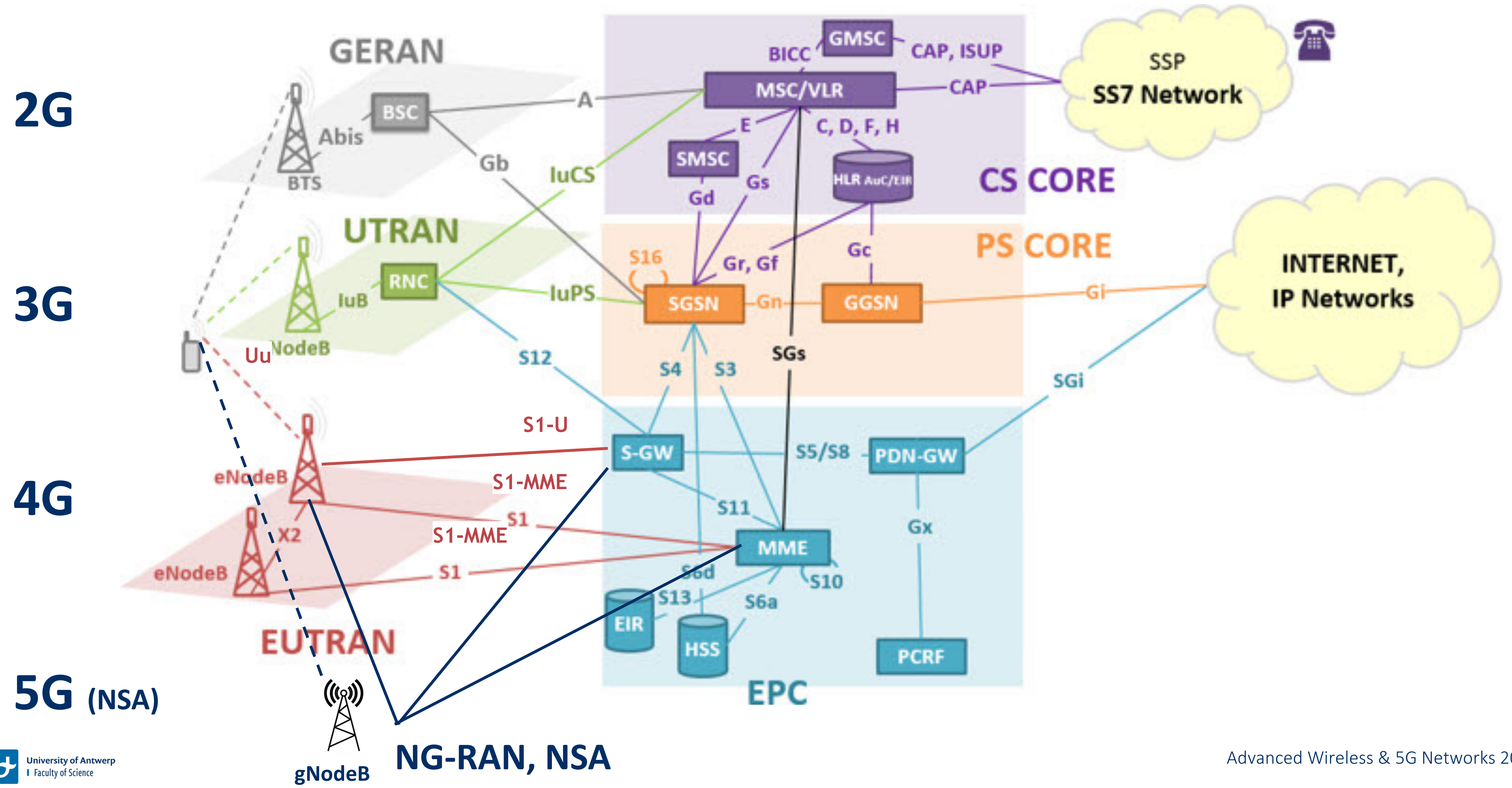
3G

4G

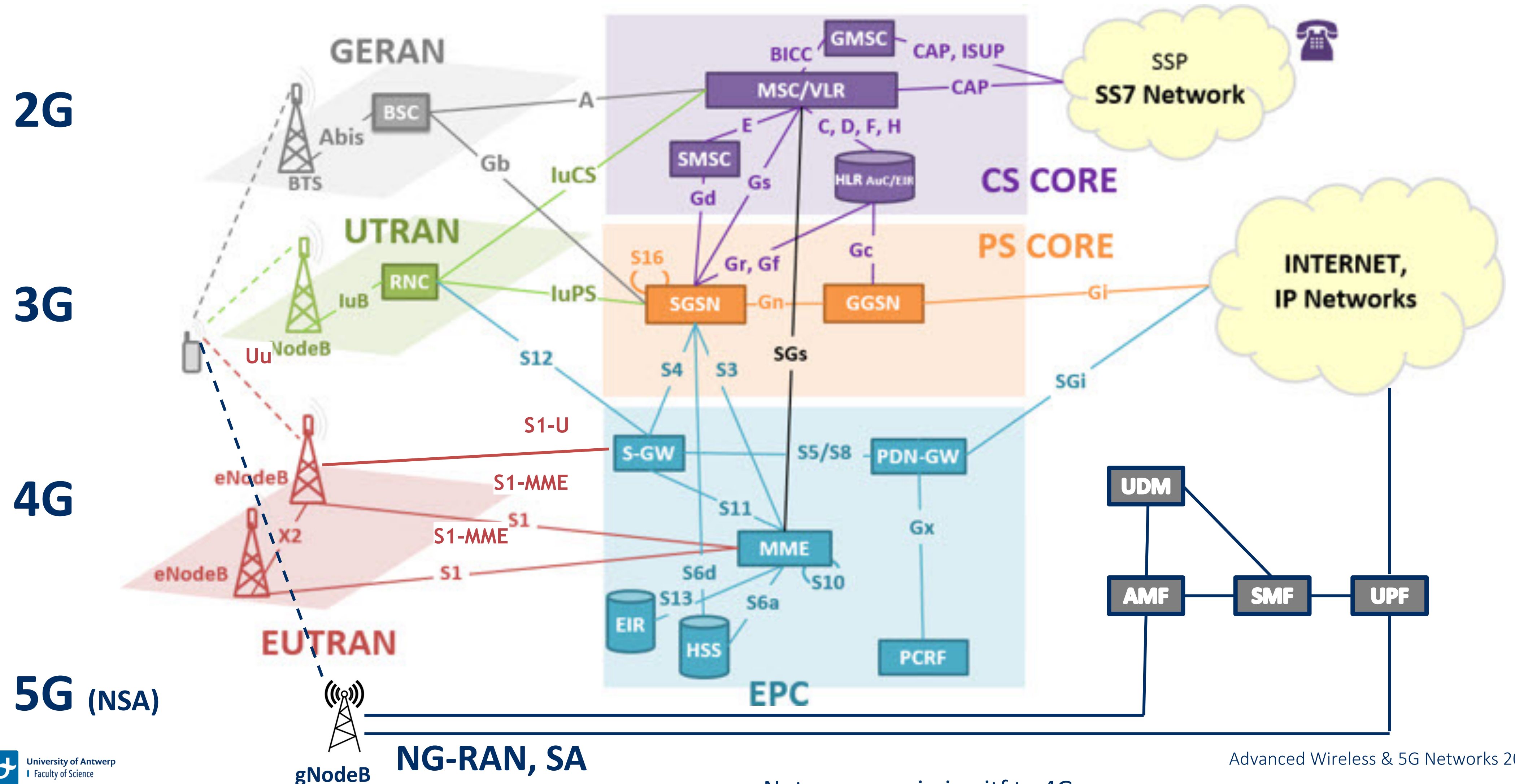
5G (NSA)



So, how did we get to 4G, and what do we need to know?



So, how did we get to 4G, and what do we need to know?



Note: some missing itf to 4G

So, how did we get to 4G, and what do we need to know?

	PHY	RAN	CORE
2G	GSM, GPRS, EDGE	GERAN, BSS: BSC, BTS, MS	NSS: MSC, GMSC, HLR, SGSN, GGSN
3G	UMTS	UTRAN, RNS: NodeB, RNC, UE	”, CS, PS
4G	LTE, LTE-A, LTE-A Pro	E-UTRAN: eNodeB, UE	EPC, CN: MME, S-GW, P-GW, HSS
5G (NSA)	NR	NG-RAN: gNodeB, UE	"
5G (SA)	NR	NG-RAN: gNodeB, UE	5GC: AMF, SMF, UPF, UDM, UDR, NRF

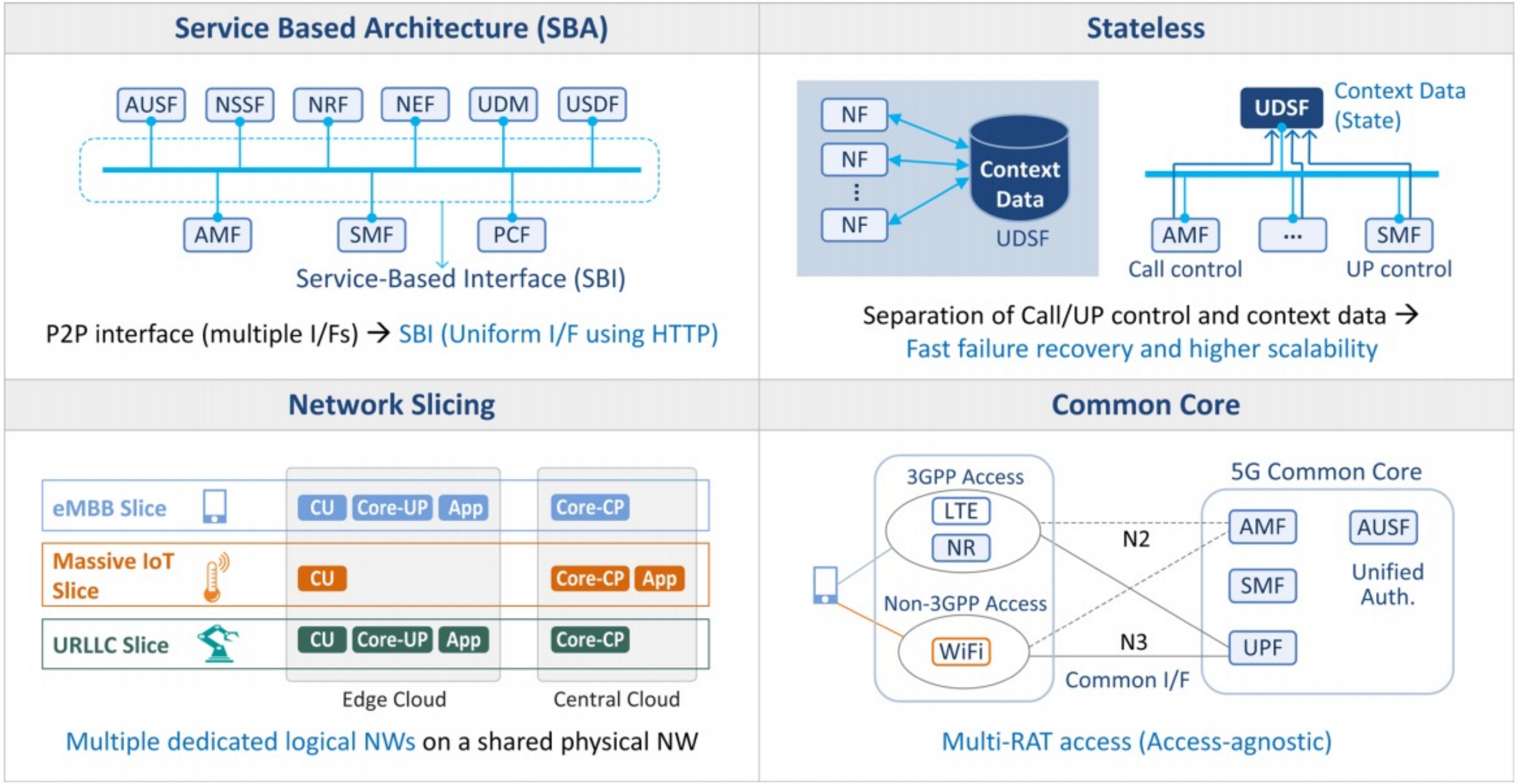
Lots of drawing on the blackboard…

Acronymitis

- GSM – Global System for Mobile communication (orig. Groupe Speciale Mobile)
- GPRS – General Packet Radio Services
- EDGE – Enhanced Data rates for GSM Evolution
- GERAN – GSM/EDGE Radio Access Network
- BSS – Basestaion Subsystem
- BSC – Basestation Controller
- BTS – Basestation Transceiver Station
- MS – Mobile Station
- NSS – Network Switching Subsystem
- MSC – Mobile Switching Center
- GMSC – Gateway Mobile Switching Centre
- HLR – Home Location Register
- SGSN – Serving GPRS Support Node
- GGSN – Gateway GPRS Support Node
- UMTS – Universal Mobile Telecommunications System
- UTRAN – UMTS Terrestrial Radio Access Network
- RNS – Radio Network Subsystem
- NodeB – a basestation :-)
- RNC – Radio Network Controller
- CS, PS Domain – Circuit, Packet Switching Domain
- UE – User Equipment
- LTE – Long Term Evolution
- LTE-A – LTE Advanced
- E-UTRAN – Evolved UTRAN
- eNodeB – Evolved nodeB
- EPC – Evolved Packet Core
- CN – Core Network
- MME – Mobility Management Entity
- S-GW – Serving Gateway
- P-GW – Packet Data Network Gateway
- HSS – Home Subscriber Server
- NR – New Radio
- NG-RAN – Next Generation Radio Access Network
- gNodeB – (Next-)Generation nodeB, also gNB
- 5GC – 5G Core
- AMF – Access and Mobility Management Function
- SMF – Session Management Function
- UPF – User Plane Function
- UDM – Unified Data Management
- UDR – Unified Data Repository
- NRF – Network Repository Function

Infrastructure: 5G CN and SA

Design goals



- **UPF (User Plane Function): It performs operations like maintaining PDU Session, Packet routing & forwarding, Packet inspection, Policy enforcement for User plane, QoS handling, etc. When compared with 4G EPC, it's functionalities resembles with SGW-U (Serving Gateway User Plane function) and PGW-U (PDN Gateway User Plane function) of 4G Network.**

- **AMF (Access and Mobility Management Function): It performs operations like Mobility Management, Registration Management, Connection Management, etc. It acts as a single-entry point for the UE connection. Based on the Service requested by Consumer, AMF selects the respective SMF for managing the user session context. When compared with 4G EPC, it's functionalities resembles with MME of 4G Network.**

- **AUSF (Authentication Server Function): It allows the AMF to authenticate the UE. When compared with 4G EPC, it's functionalities resembles with HSS/AAA Server of 4G Network.**

- **PCF (Policy ControlFunction): governs the Control plane functions via Policy rules defined and User plane functions via Policy enforcement. It works very closely with CHF (Charging Function) for Usage Monitoring. Through PCF, Operators can manage & govern network behavior.**

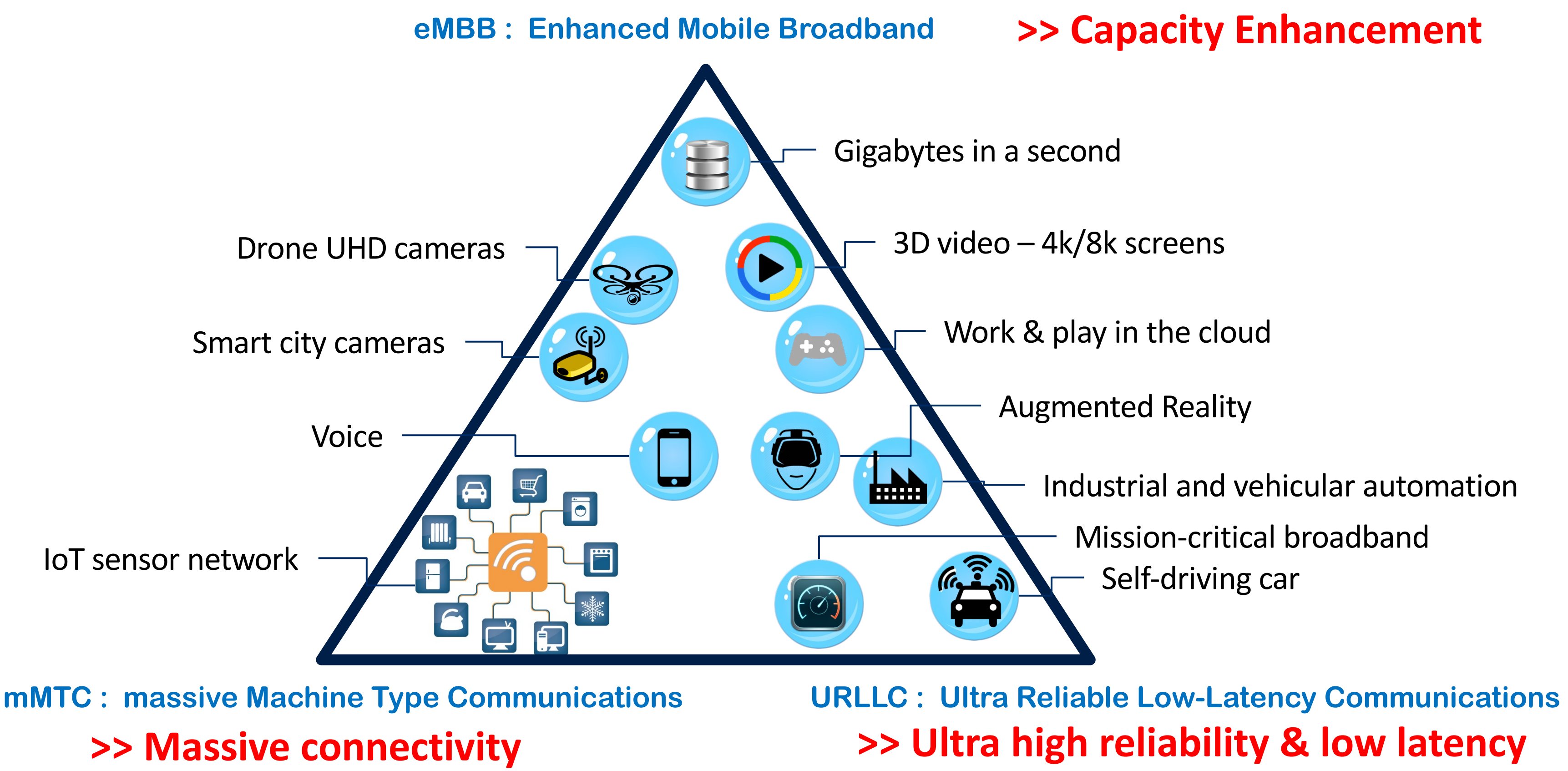
- SMF (Session Management Function): Performs operations like Session Management, IP Address allocation & management for UE, User plane selection, QoS & Policy enforcement for Control Plane, used for Service registration/discovery/establishment, etc. When compared with 4G EPC, it's functionalities resemble with MME, SGW-C (Control Plane) and PGW-C (Control Plane) of 4G Network.

- NRF (NF Repository Function): It maintains the list of available Network Functions instances and their profiles. It also performs Service registration & discovery so that different Network functions can find each other via APIs. As an example, SMF which is registered to NRF; gets discoverable by AMF when UE tries to access a Service type served by the SMF. Since Network functions are connected via Service Message Bus in SBA, any authorized Consumers can access the services offered via registered Network functions (Producers).

- Unified Data Management (UDM): It performs operations like User identification handling, Subscription Management, User Authentication, Access Authorization for operations like Roaming, etc. When compared with 4G EPC, it's functionalities resemble with HSS/AAA Server of 4G Network.

- Unified Data Repository (UDR): (note: database, apart from interfaces: proprietary)
- Subscription Data
- Policy Data
- Structured Data for Exposure
- Application Data

5G use cases defined by ITU under IMT-2020



IRG Heads' Workshop 2018, Brussels, 18 October, 2018

eBOS Technologies

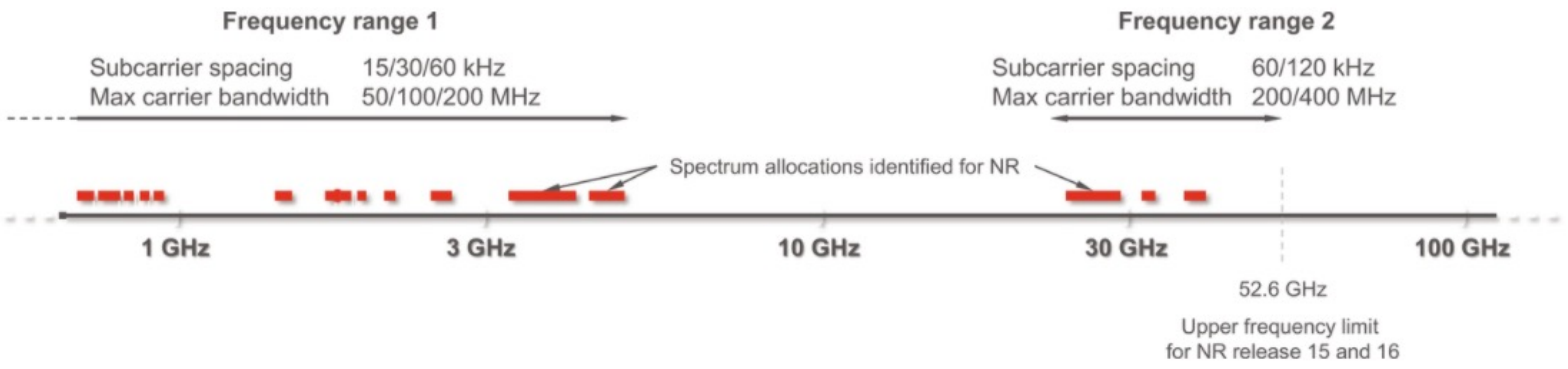
Requirements for reference

Parameter	Minimum Technical Performance Requirement
Peak data rate	Downlink: 20 Gbit/s Uplink: 10 Gbit/s
Peak spectral efficiency	Downlink: 30 bit/s/Hz Uplink: 10 bit/s/Hz
User-experienced data rate	Downlink: 100 Mbit/s Uplink: 50 Mbit/s
Fifth percentile user spectral efficiency	3 × IMT-Advanced
Average spectral efficiency	3 × IMT-Advanced
Area traffic capacity	10 Mbit/s/m^2 (Indoor hotspot for eMBB)
User plane latency	4 ms for eMBB 1 ms for URLLC
Control plane latency	20 ms
Connection density	1,000,000 devices per km^2
Energy efficiency	Related to two aspects for eMBB: (a) Efficient data transmission in a loaded case (b) Low energy consumption when there are no data The technology shall have the capability to support a high sleep ratio and long sleep duration.
Reliability	1–10^{-5} success probability of transmitting a layer 2 PDU (Protocol Data Unit) of 32 bytes within 1 ms, at coverage edge in Urban Macro for URLLC
Mobility	Normalized traffic channel data rates defined for 10, 30, and 120 km/h at ~ 1.5 × IMT-Advanced numbers. Requirement for High-speed vehicular defined for 500 km/h (compared to 350 km/h for IMT-Advanced).
Mobility interruption time	0 ms
Bandwidth	At least 100 MHz and up to 1 GHz in higher-frequency bands. Scalable bandwidth shall be supported.

What are the steps?

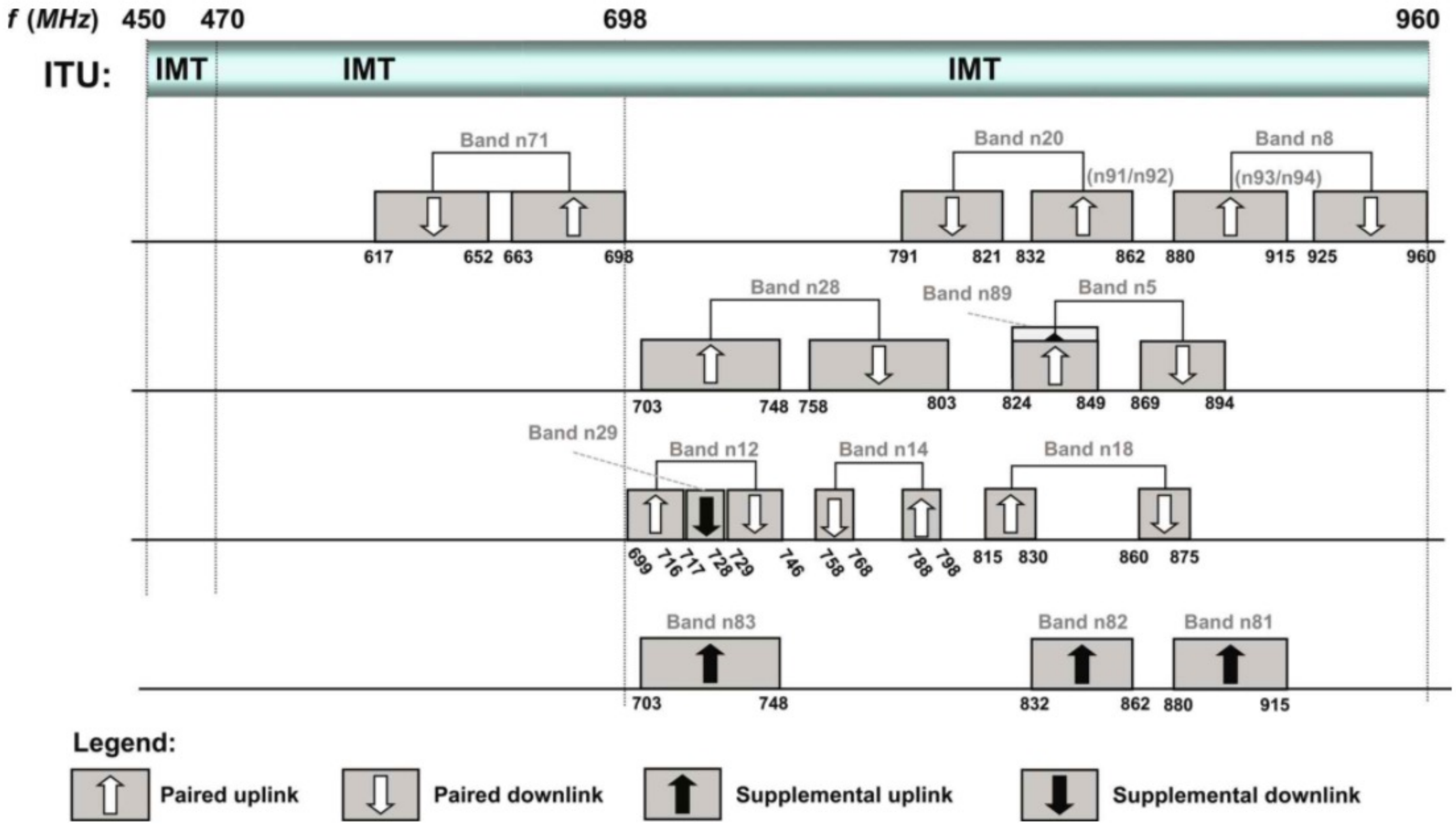
1. ~~Switch on the mobile (& infrastructure)~~
2. Select a frequency band to receive & send
3. Pick a way to send and receive digital bits
4. Define how we are going to organize the bits for multiple users
5. Listen to synchronize and get system information
6. Random Access
7. Get a channel
8. Authenticate
9. Ask to send data (or get some data)
10. Ask to make a call
11. Move around
12. … (location update, release call, handover, etc …)

Frequency Ranges for NR

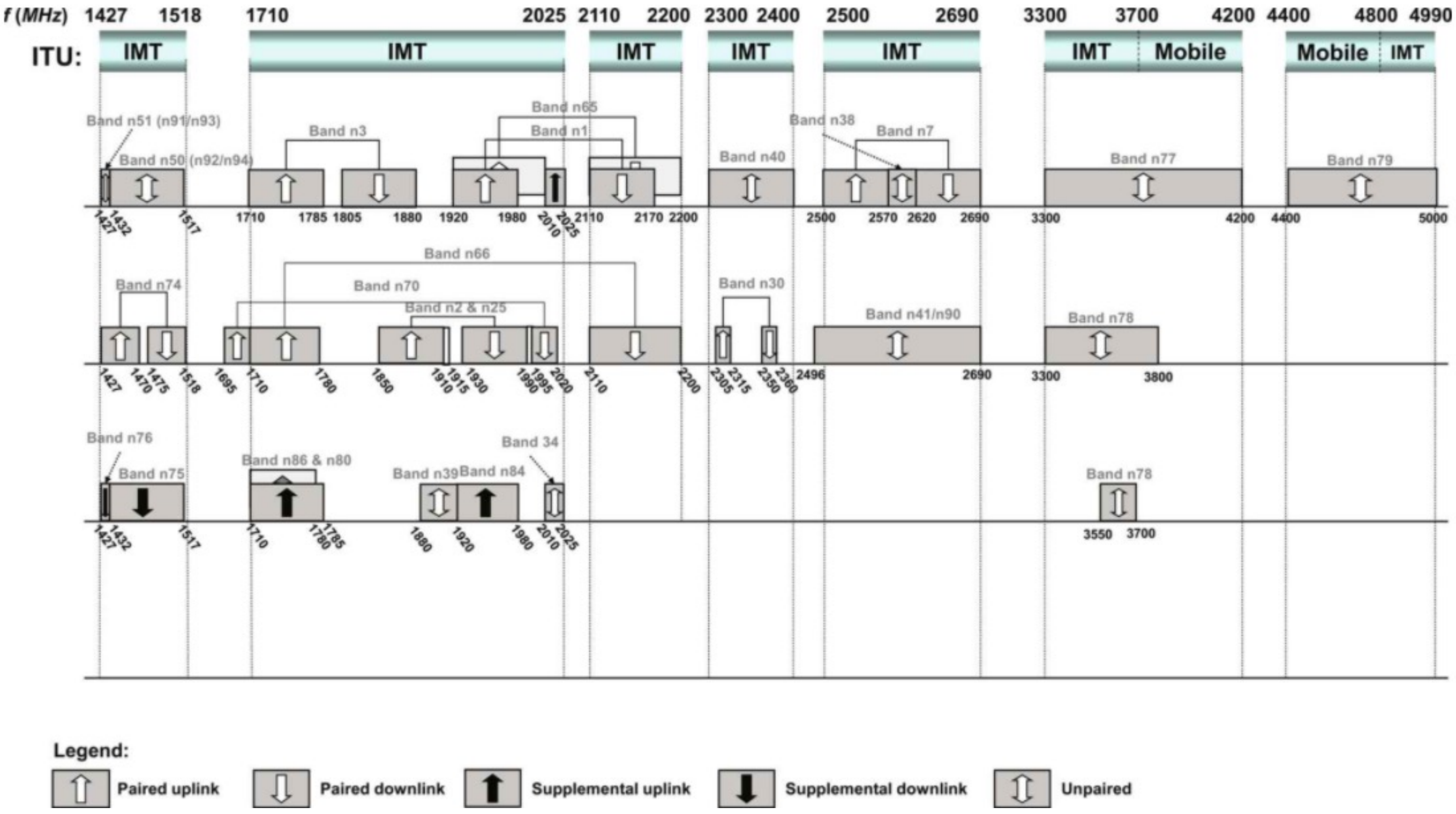


Both TDD and FDD are used to separate uplink and downlink.

FR1 below 1 GHz

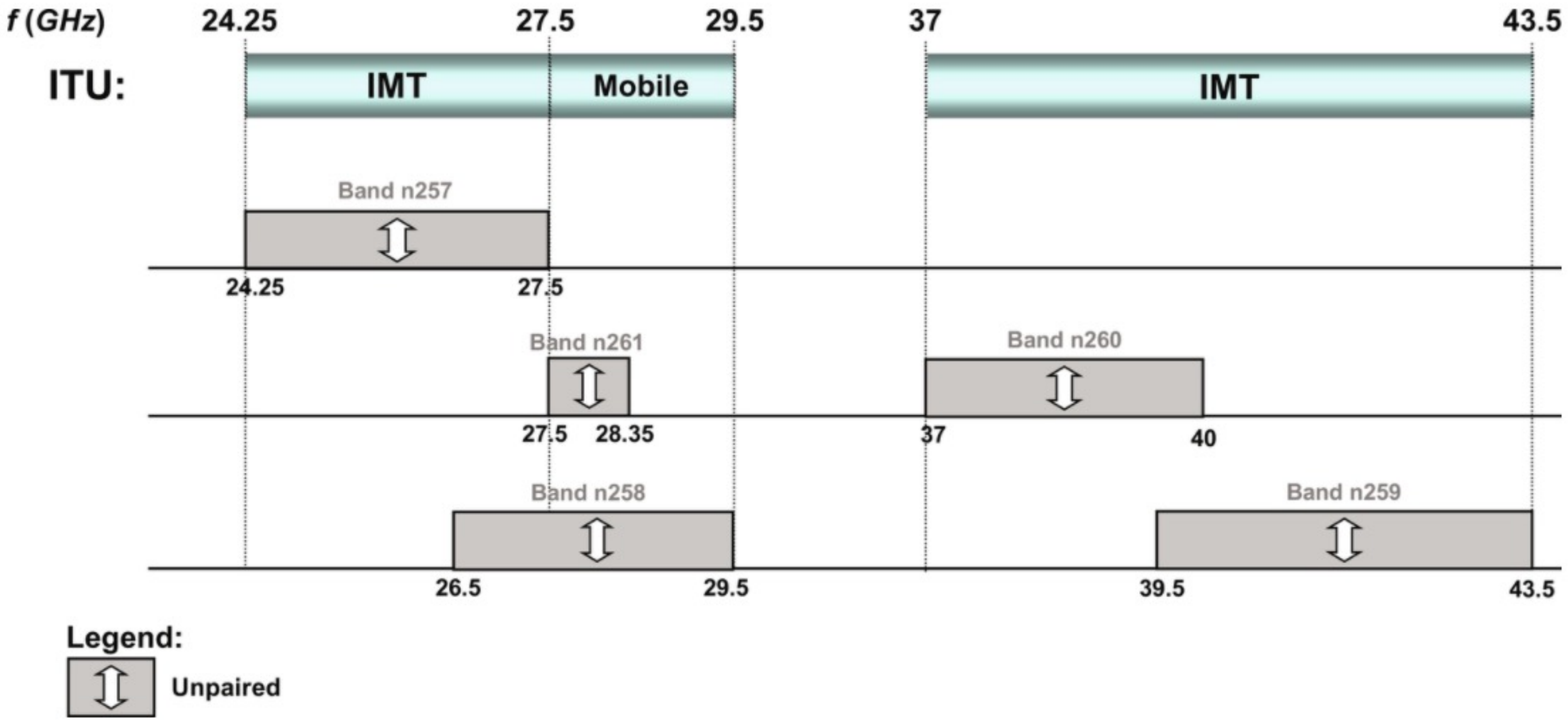


FR1 up to 6 GHz



Unpaired = TDD

FR2 from 26GHz to 52GHz



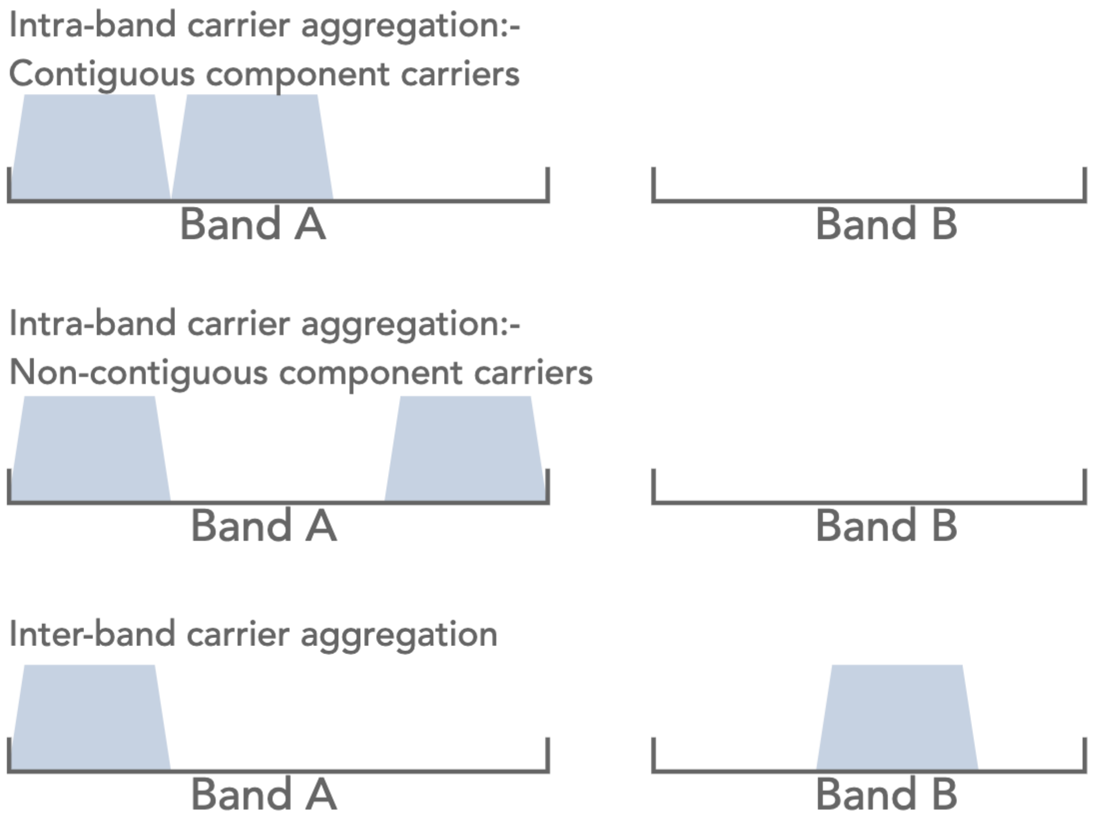
4G: E-ARFCN; 5G: NR-ARFCN

- **E-UTRA Absolute Radio Frequency Channel Number.**
- **carrier frequency in the uplink and downlink is designated by EARFCN, which ranges between 0-65535.**
- **EARFCN uniquely identify the LTE band and carrier frequency.**
  - for example Band-1 and Band-4 can have same Rx frequency 2110-2170 MHz, but their EARFCN are different.
  - EARFCN is independent of channel bandwidth.

Table 5.7.3-1 E-UTRA channel numbers

E-UTRA operating band	Downlink			Uplink		
	F_{DL_low} [MHz]	$N_{Offs\text{-}DL}$	Range of N_{DL}	F_{UL_low} [MHz]	$N_{Offs\text{-}UL}$	Range of N_{UL}
1	2110	0	0 – 599	1920	18000	18000 – 18599
2	1930	600	600 – 1199	1850	18600	18600 – 19199
3	1805	1200	1200 – 1949	1710	19200	19200 – 19949
4	2110	1950	1950 – 2399	1710	19950	19950 – 20399
5	869	2400	2400 – 2649	824	20400	20400 – 20649
6	875	2650	2650 – 2749	830	20650	20650 – 20749
7	2620	2750	2750 – 3449	2500	20750	20750 – 21449

Carrier Aggregation



When carriers are aggregated, each carrier is referred to as a component carrier. There are two categories:

- Primary component carrier (PCC): This is the main carrier in any group. There will be a primary downlink carrier and an associated uplink primary component carrier.
- Secondary component carrier (SCC): There may be one or more secondary component carriers.

The UE first connects to one carrier for both uplink (UL) and downlink (DL). This is the primary cell (PCell).

- Thereafter, secondary DL carriers) can be added. These are secondary cells (SCells).
- Please note, secondary carriers are DL only, UL is not used on these carriers.

What are the steps?

1. ~~Switch on the mobile (& infrastructure)~~
2. ~~Select a frequency band to receive & send~~
3. Pick a way to send and receive digital bits
4. Define how we are going to organize the bits for multiple users
5. Listen to synchronize and get system information
6. Random Access
7. Get a channel
8. Authenticate
9. Ask to send data (or get some data)
10. Ask to make a call
11. Move around
12. … (location update, release call, handover, etc …)

Orthogonal Frequency Division Multiplexing

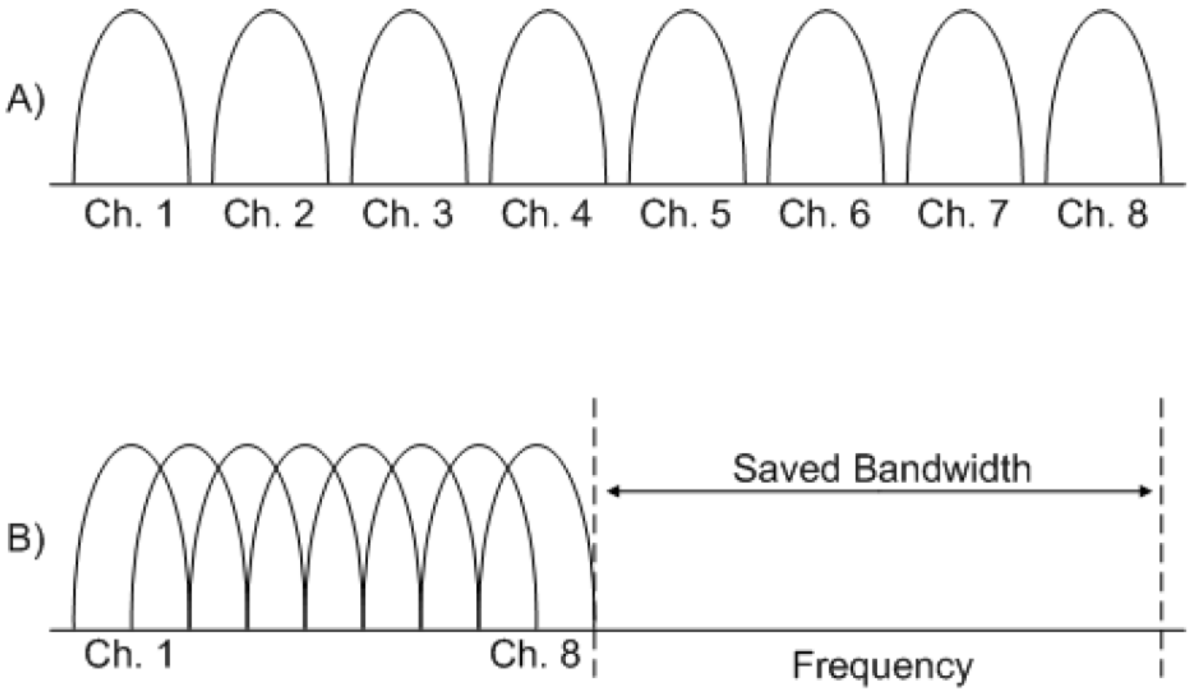


Figure 1: A) The frequency spectrum of eight channels shown utilizing frequency division multiplexing. Parallel transmitters are employed in which guard bands are placed between sub-carriers. B) The frequency spectrum of OFDM is shown where sub-channels are orthogonal to the adjacent channels. The percentage of bandwidth used to transmit the same data is reduced by 50%.

Data Transmission by Frequency-Division Multiplexing Using the Discrete Fourier Transform

S. B. WEINSTEIN, MEMBER, IEEE, AND PAUL M. EBERT, MEMBER, IEEE

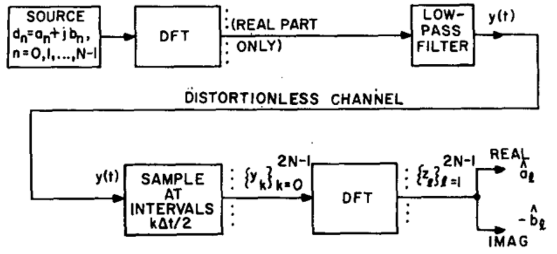


Fig. 2. Fourier transform communication system in absence of channel distortion.

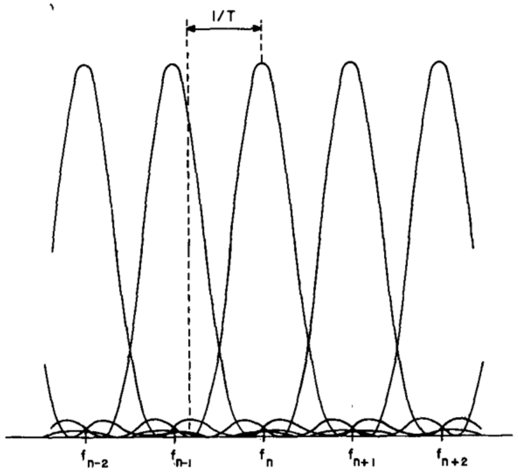


Fig. 3. Power density spectra of subchannel components of $y(t)$.

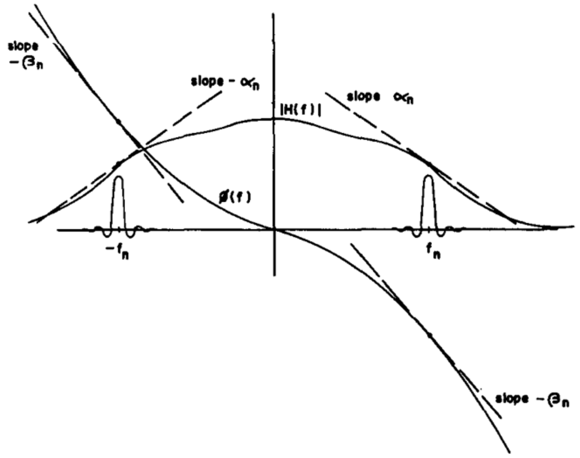


Fig. 6. Linear approximations to amplitude and phase of $H(f)$ in relation to spectra $G_a(f - f_n)$ and $G_a(f + f_n)$.

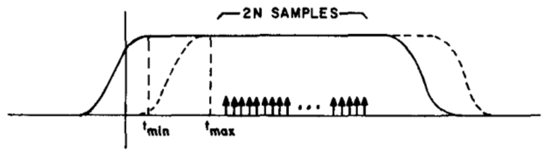
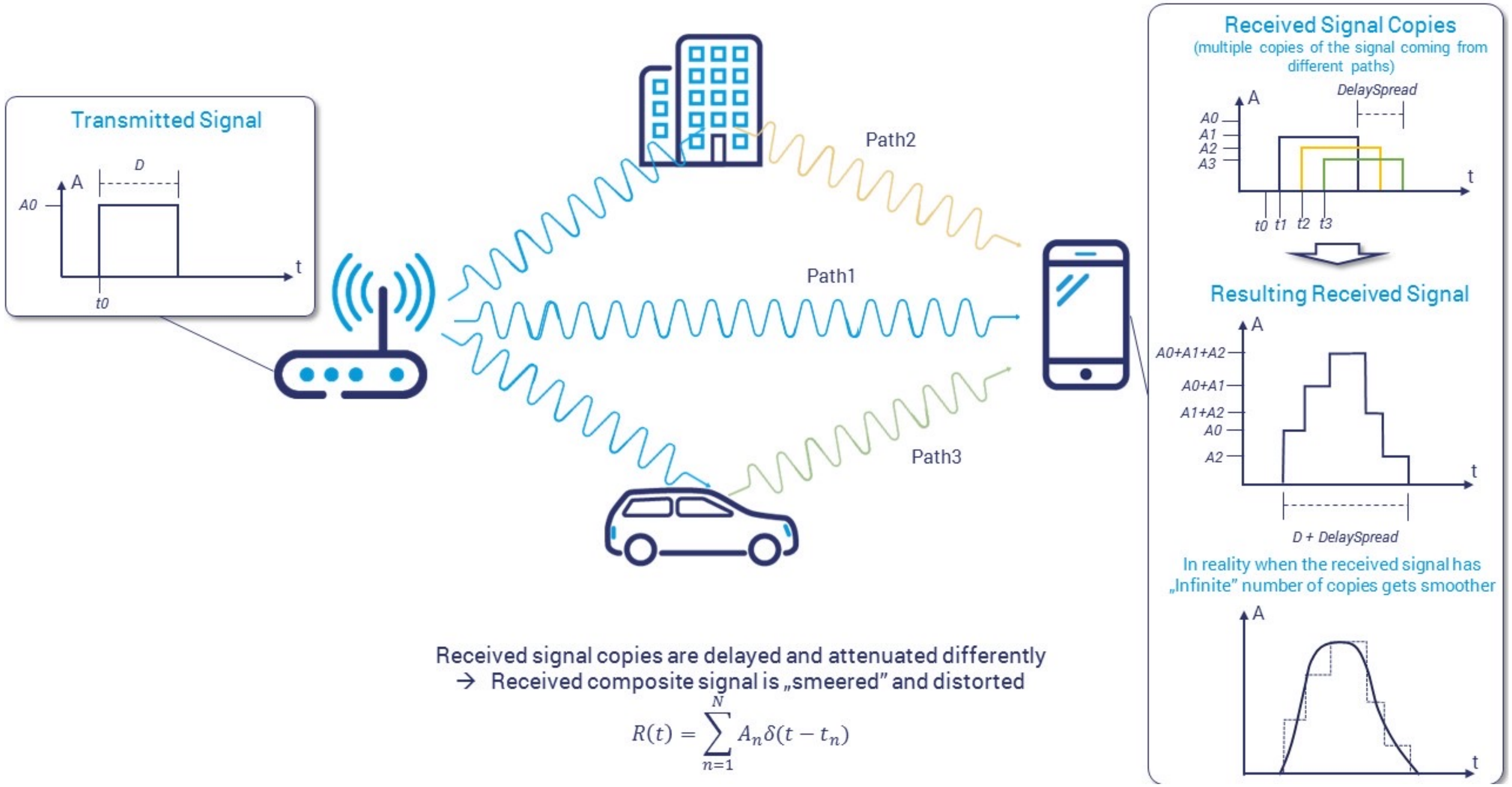


Fig. 7. Shifted versions of $g_a(t)$ corresponding to subchannels with minimum and maximum delay and locations of samples taken by receiver. Here $t_{min} = \min_n \beta_n$, $t_{max} = \max_n \beta_n$.

But why ?

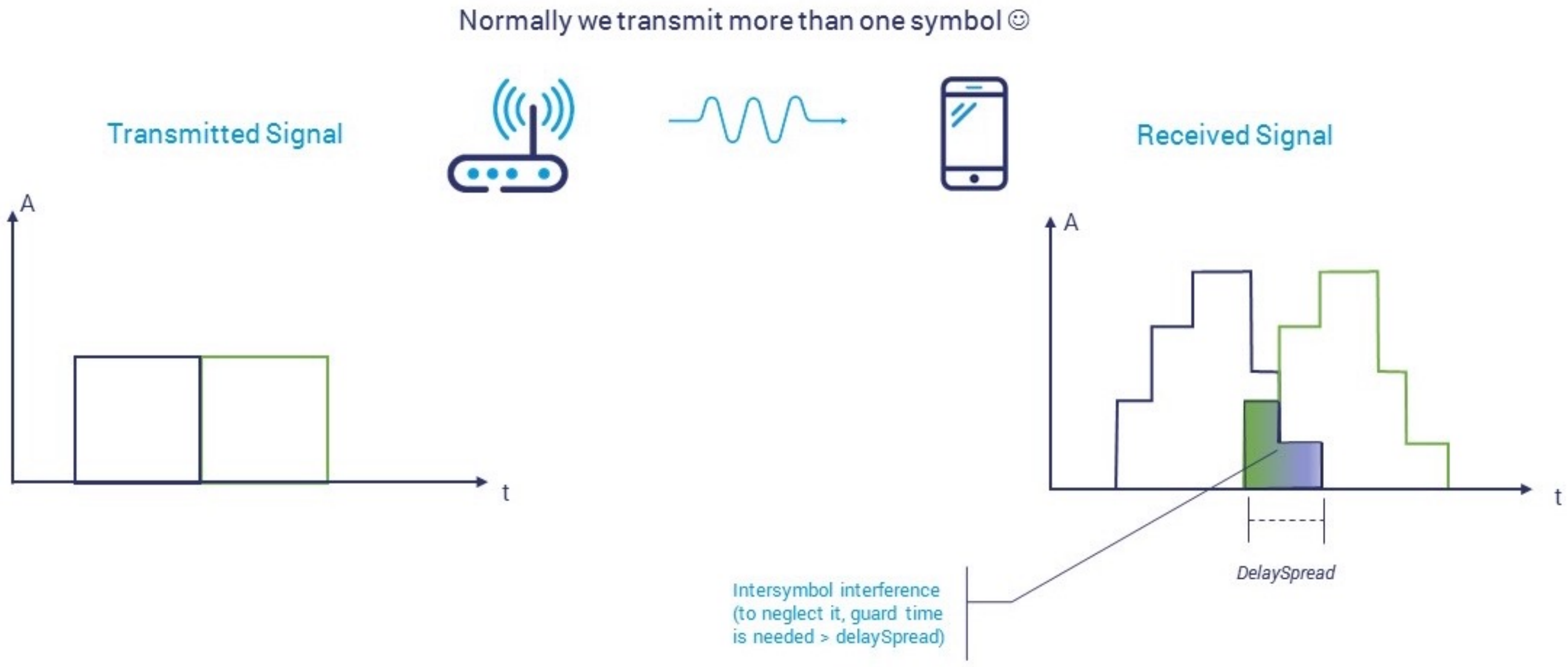
Delay spread and multipath



Received signal copies are delayed and attenuated differently
→ Received composite signal is „smeered" and distorted

$$R(t) = \sum_{n=1}^{N} A_n \delta(t - t_n)$$

Delay spread and multipath

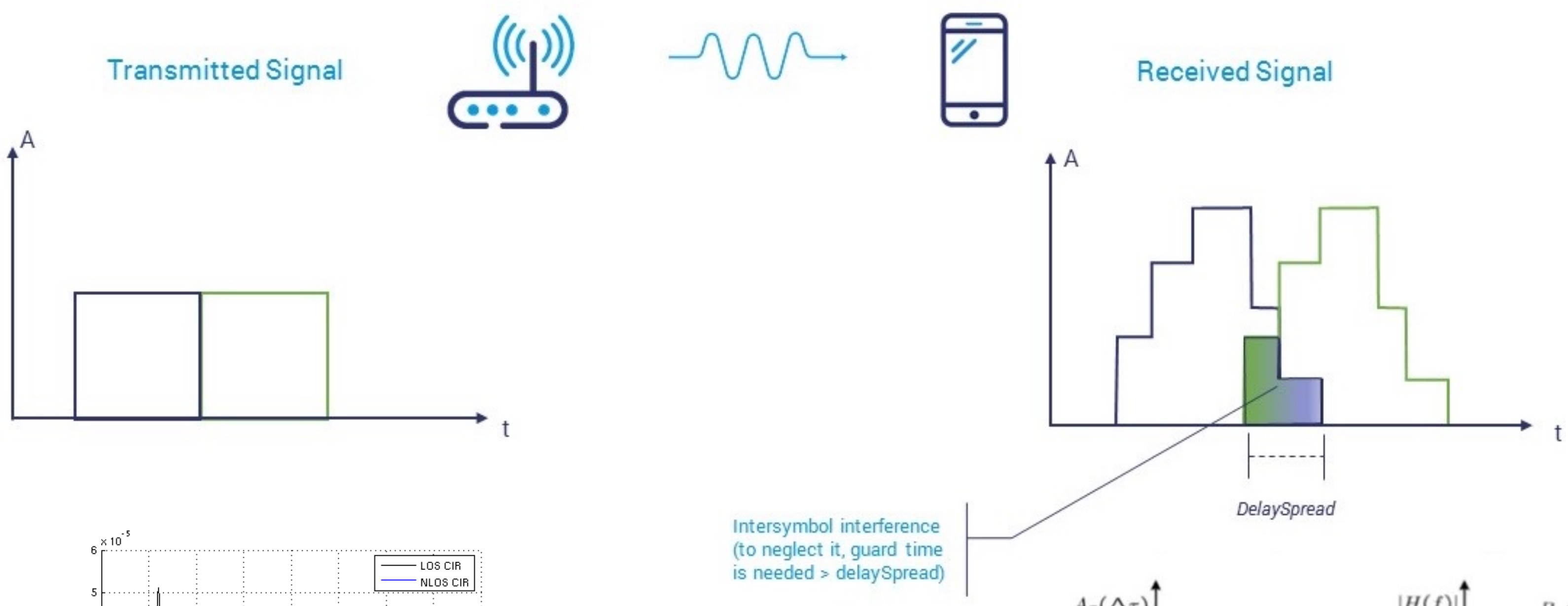


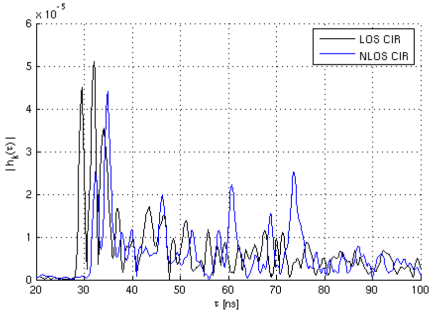
Example delay spreads

Environment	Delay spread (μs)
Rural	10-20
Urban	1-2
Small Office/Home	0.02-0.05

Delay spread and multipath

Normally we transmit more than one symbol ☺

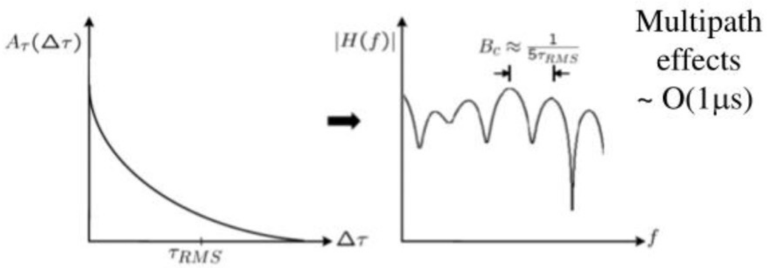




Channel impulse response (CIR)

Example delay spreads

Environment	Delay spread (μs)
Rural	10-20
Urban	1-2
Small Office/Home	0.02-0.05



CIR

Dual in frequency

Need a way to combat intersymbol interference
frequency selective channels (e.g. hopping?)

OFDM(A)

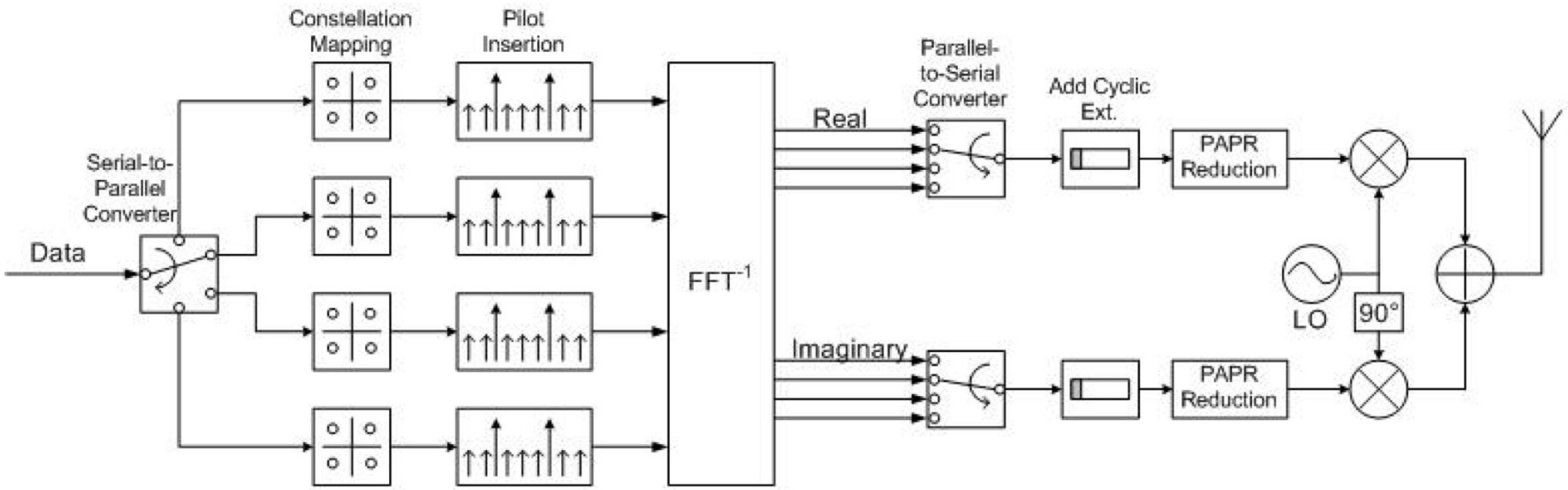
- For high rate data streams: symbol period Ts is smaller than the channel delay spread Td (difference between the time of arrival of the earliest significant multipath component (typically the line-of-sight component) and the arrival time of the latest multipath component if transmitted serially.
- Consequence: Inter-Symbol Interference (ISI)
- Equalization procedures to solve this are very complex
- Therefore: the use of OFDMA (Orthogonal Frequency Division Multiple Access) → splitting up high rate stream in parallel lower rate streams
- Disadvantage of OFDMA: high Peak-to-Average Power Ratio (in particular a problem for uplink communications: limited battery life of UE handheld device)

OFDMA (cont.)

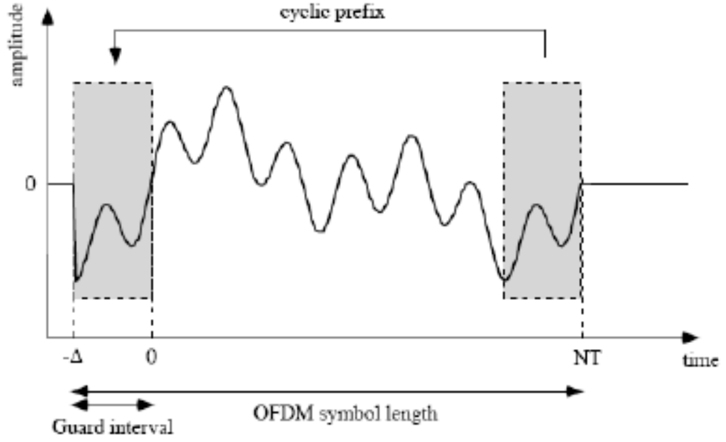
- **Downlink: OFDMA**
  - High robustness against frequency selective fading
  - Spectrum flexibility: #subcarriers scales with bandwidth
  - Large variation in the instantaneous transmit power → low power-amplifier efficiency
  - In spite of orthogonality of subcarriers, interference may still occur; use of cyclic prefix (CP): last part of the OFDM symbol is copied and inserted at the beginning of the symbol
- **Why the A**
  - Multiple streams, but each can **go to a different user.**
- **Note: Uplink can use SC-FDMA (Single Carrier – FDMA)**
  - Better PAPR (Peak-to-Average Power Ratio) than OFDM
    (i.e. small variations in transmit power – more appropriate for handheld devices)

Beautiful implementation with FFT butterfly
http://www.fftw.org – O(N log N).

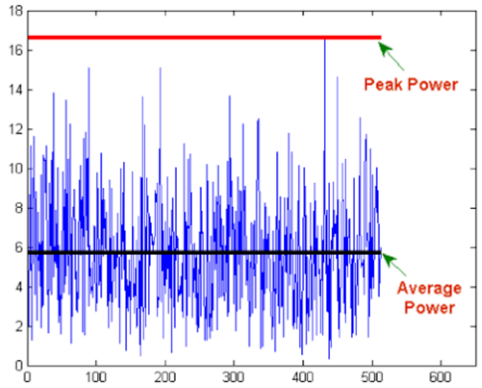
OFDM (cont.)

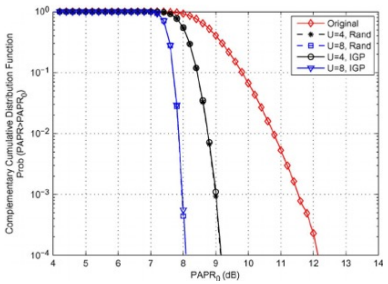


Cyclic Prefix



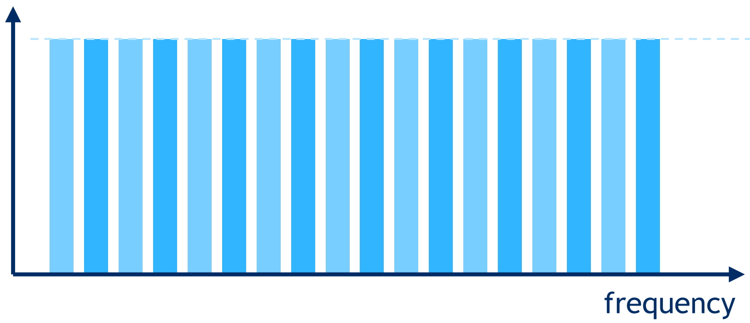
Peak-to-Average Power



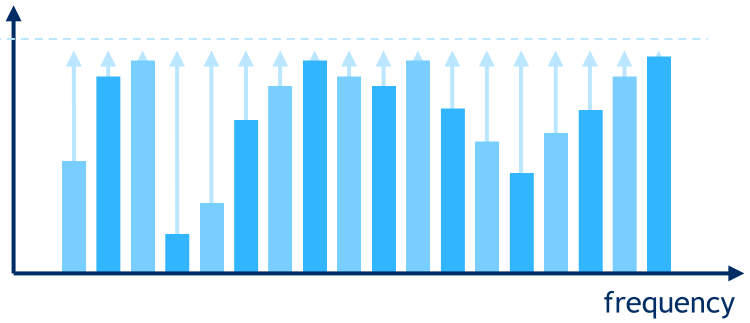


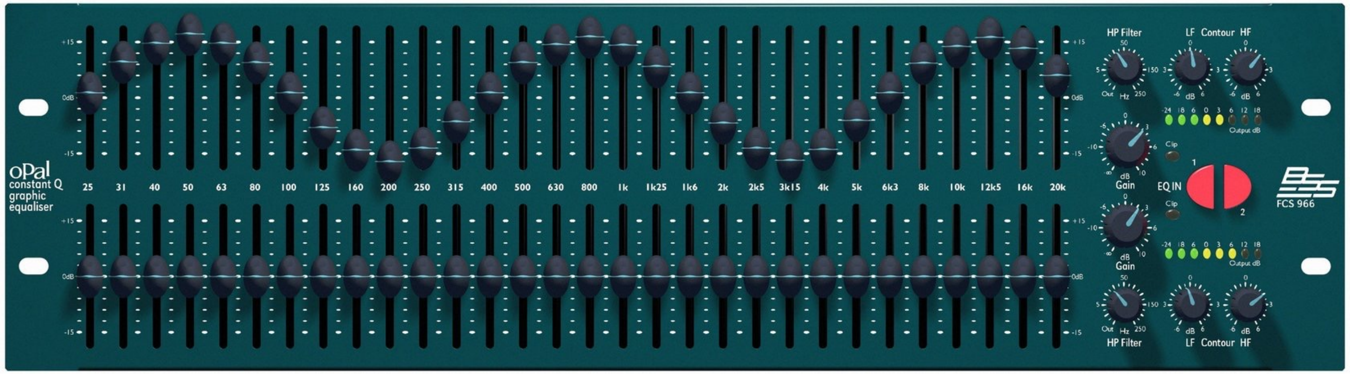
Equalization in OFDM

Tx (amplitude)



Rx (amplitude)



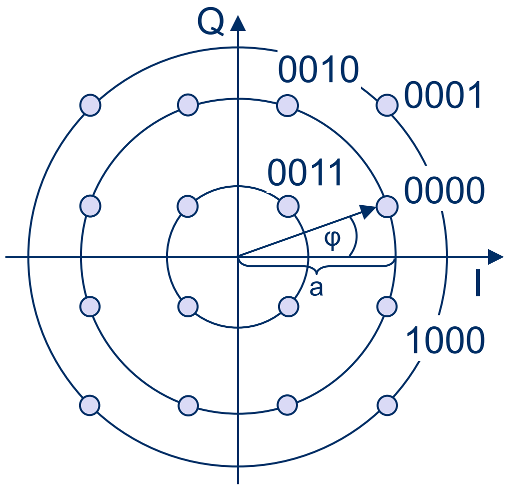


You likely have a simpler version of this one in your living room.

But we do it for amplitude and phase.

Quadrature Amplitude Modulation

- **Quadrature Amplitude Modulation (QAM): combines amplitude and phase modulation**
- **It is possible to code n bits using one symbol**
- **2n discrete levels, n=2 identical to QPSK**
- **Bit error rate increases with n, but less errors compared to comparable PSK schemes**



Example: 16-QAM (4 bits = 1 symbol)

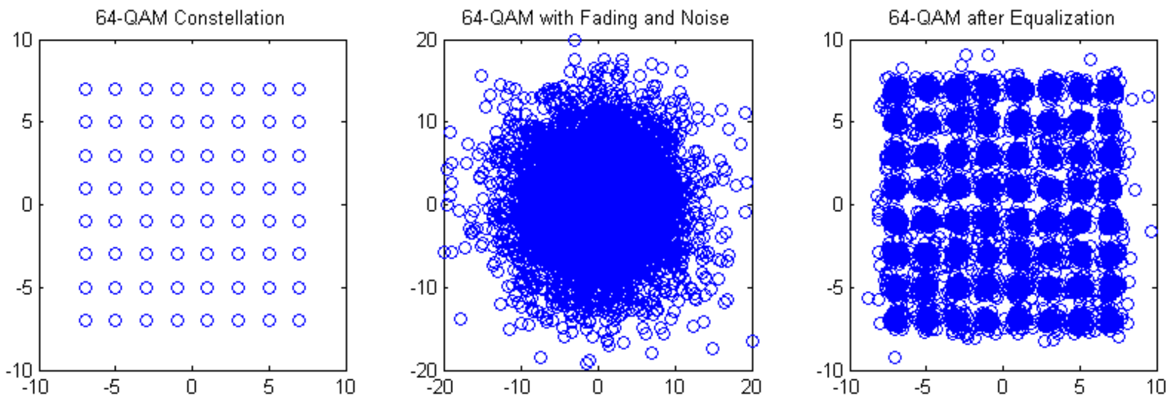
Symbols 0011 and 0001 have the same phase ϕ, but different amplitude

Symbols 0000 and 1000 have different phase, but same amplitude.

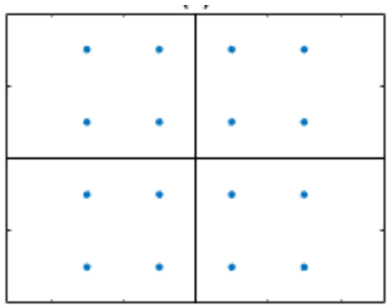
https://www.dspreated.com/showarticle/1312.php

Examples

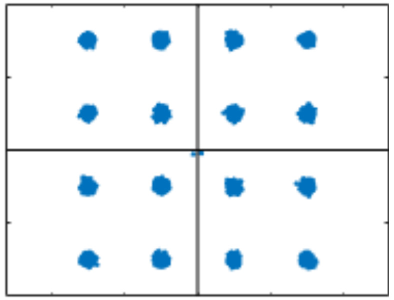
Full equalization magic



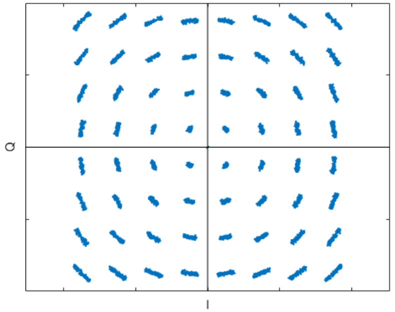
Ideal



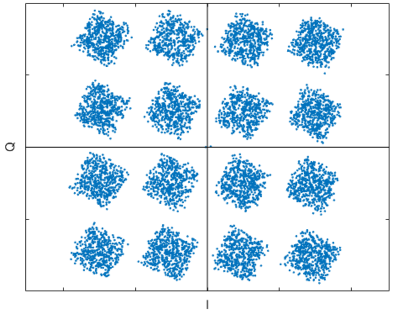
Gaussian noise



Phase noise



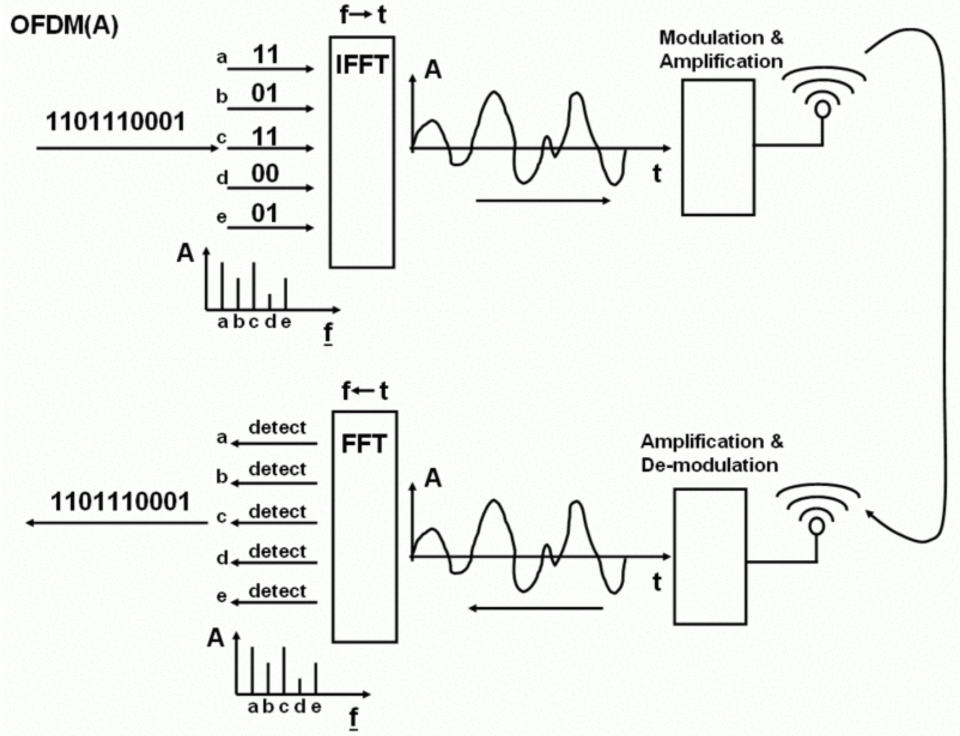
2-path channel

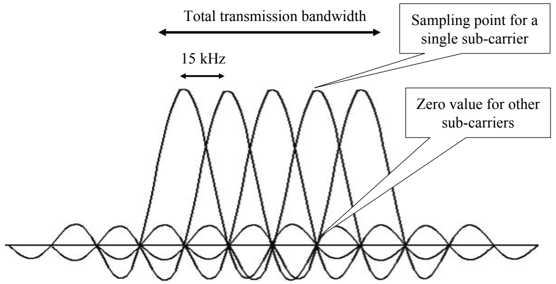


Interferer

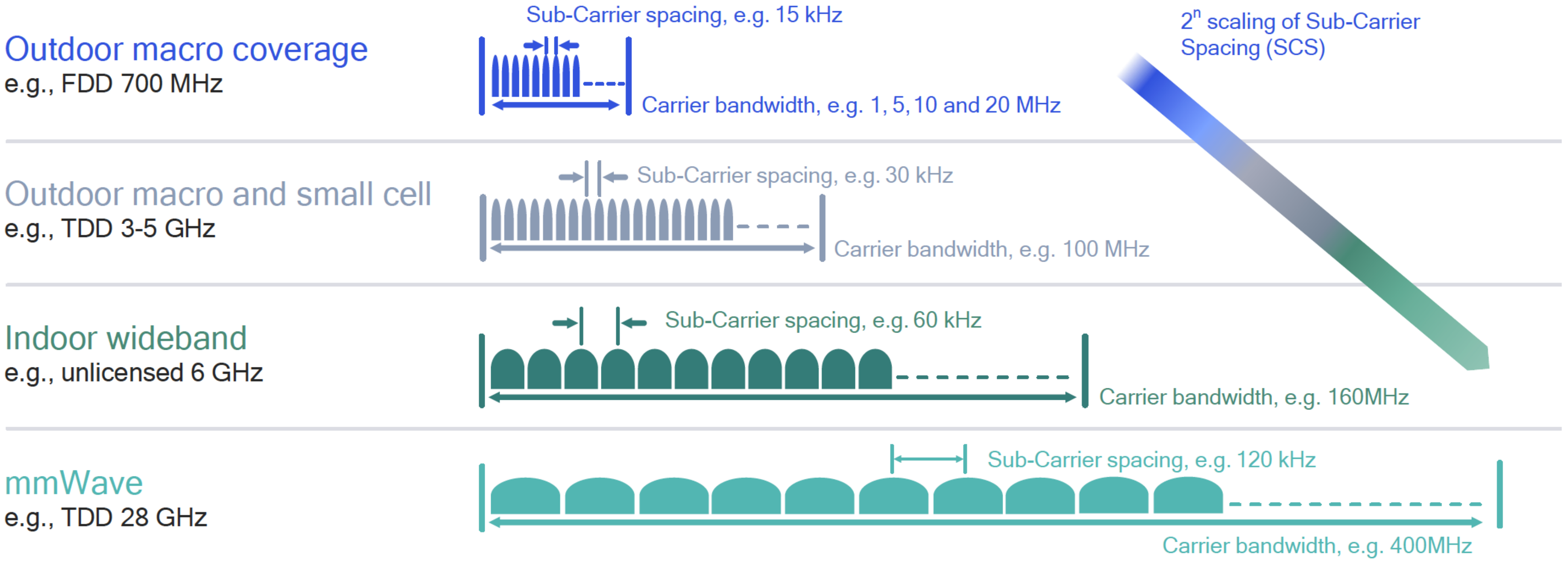
OFDMA Summary

- 5G DL modulations: QPSK, 16QAM, 64QAM, 256 QAM
- OFDMA transmits a data stream by using several narrow band sub-carriers simultaneously
- When e.g. 16QAM is used for a sub-carrier, 4 bits form the signal for one sub-carrier
- In theory, each sub-carrier signal could be generated by a separate transmission chain hardware block
- One sub-carrier spacing in 5G is 15kHz. Thus for a bandwidth of 10MHz, the number of sub-carriers is in the order of 600
- The sub-carriers are orthogonal, i.e. at the sampling instant of a sub-carrier, the other sub-carriers have a zero value.





OFDMA in DL and UL, multiple spacings



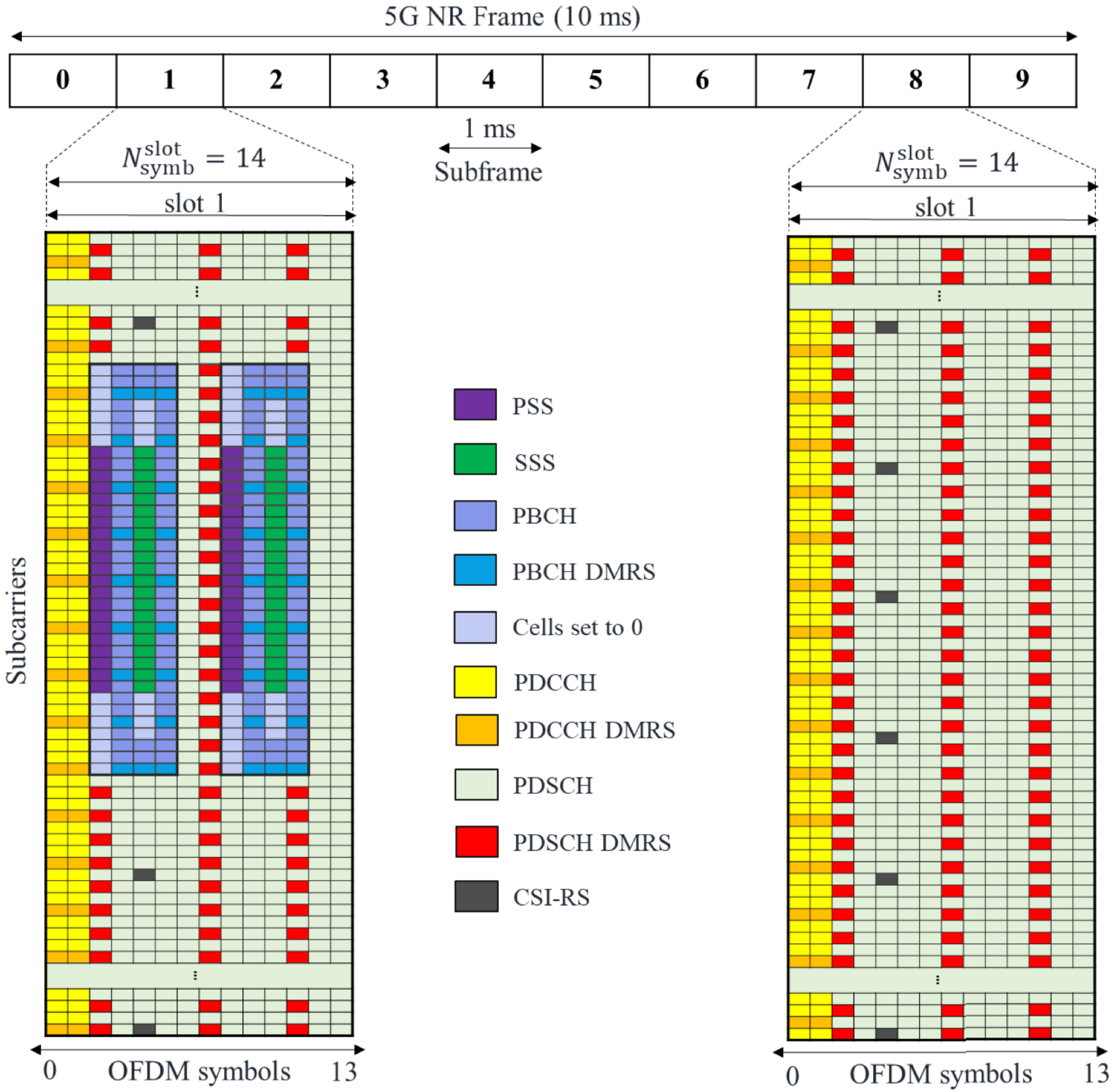
5G uses same sub-carrier spacing as 4G, but allows for scaling

What are the steps?

1. ~~Switch on the mobile (& infrastructure)~~
2. ~~Select a frequency band to receive & send~~
3. ~~Pick a way to send and receive digital bits~~
4. Define how we are going to organize the bits for multiple users
5. Listen to synchronize and get system information
6. Random Access
7. Get a channel
8. Authenticate
9. Ask to send data (or get some data)
10. Ask to make a call
11. Move around
12. … (location update, release call, handover, etc …)

We create a time-frequency grid (like in GSM)

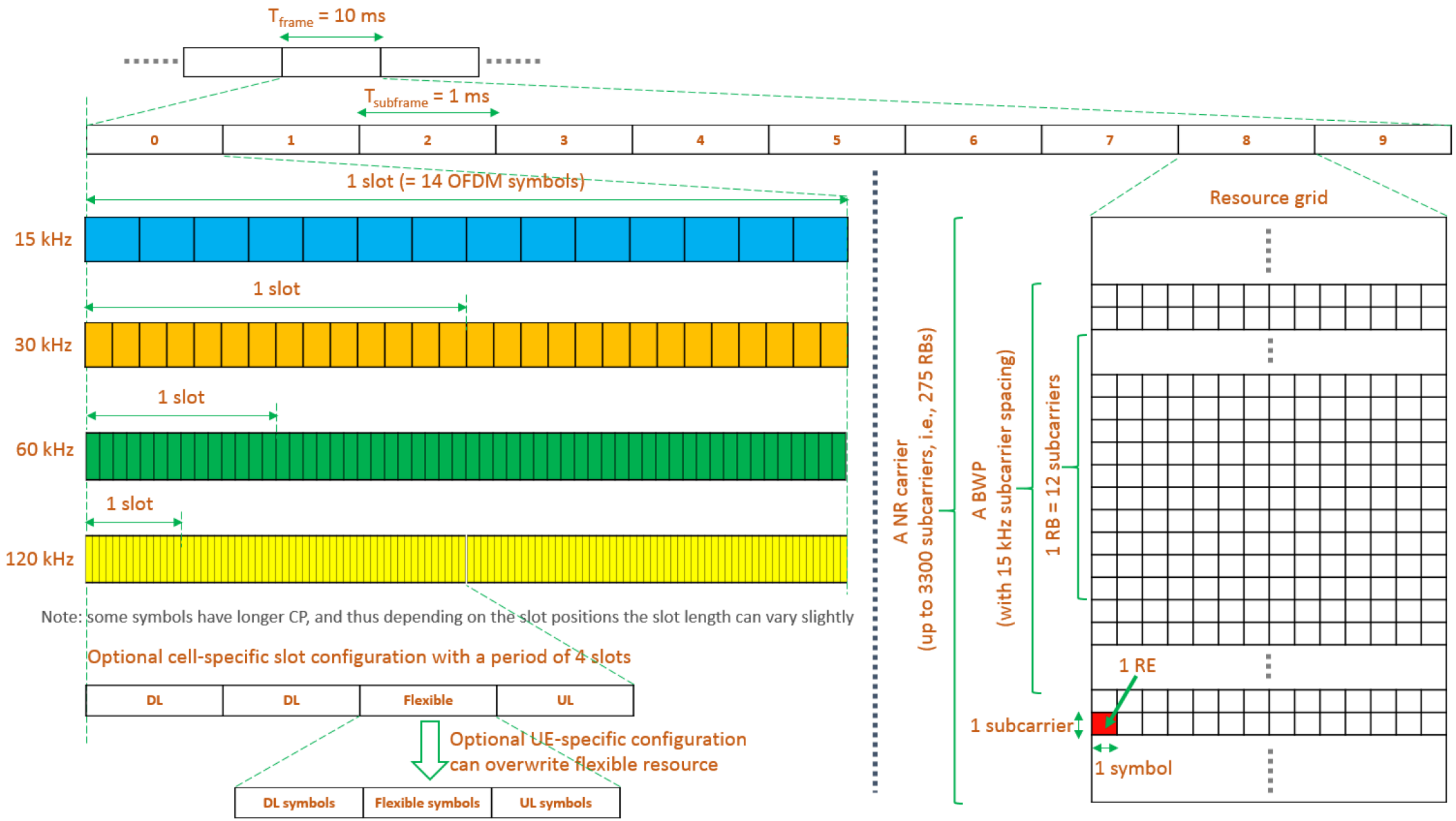
And we can distribute this to every user at the same time.



https://www.sharetechnote.com/html/5G/5G_FrameStructure.html

5G time-frequency grid

μ	Δ_f (kHz)	FR1	FR2	T_S (μs)	T_{CP} (μs)	$T_S + T_{CP}$ (μs)	N_{Slot}^{Frame}	T_{Slot} (ms)
0	15	✓	x	66.67	4.69	71.35	10	1
1	30	✓	x	33.33	2.34	35.68	20	0.5
2	60	✓	✓	16.67	1.17	17.84	40	0.25
3	120	x	✓	8.33	0.57	8.92	80	0.125
4	240	x	✓	4.17	0.29	4.46	160	0.0625



University of Antwerp
Faculty of Science

5G slot types = flexibility

DL-heavy transmission with UL part

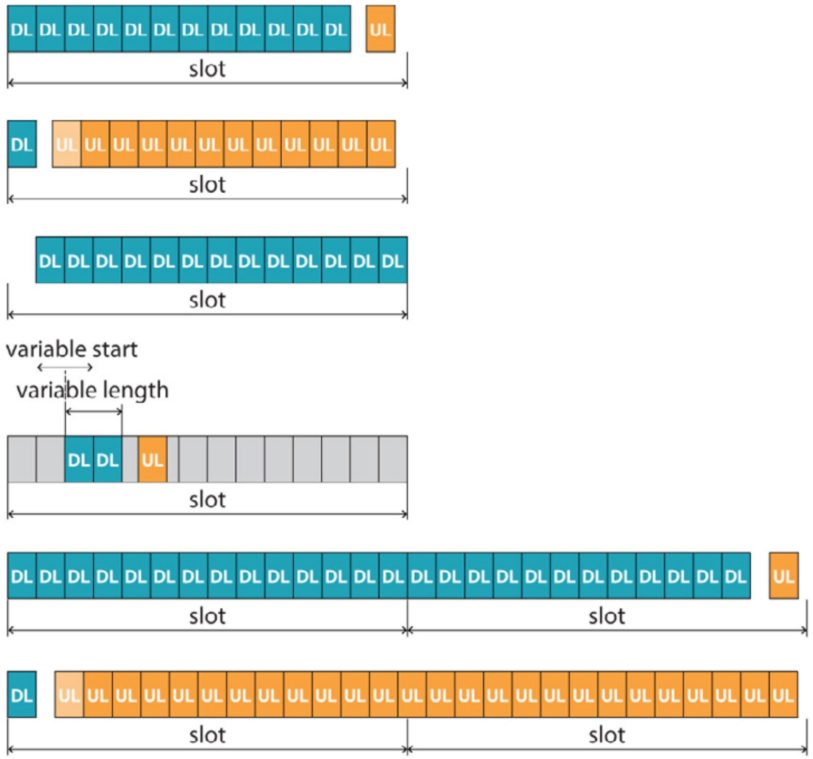
UL-heavy transmission with DL control

DL-only transmission with late start due to LBT or relaxed base station synchronization requirements

Utilizing mini-slots for URLLC transmission

Slot aggregation for DL-heavy transmission (for example, for eMBB)

Slot aggregation for UL-heavy transmission (for example, for eMBB)

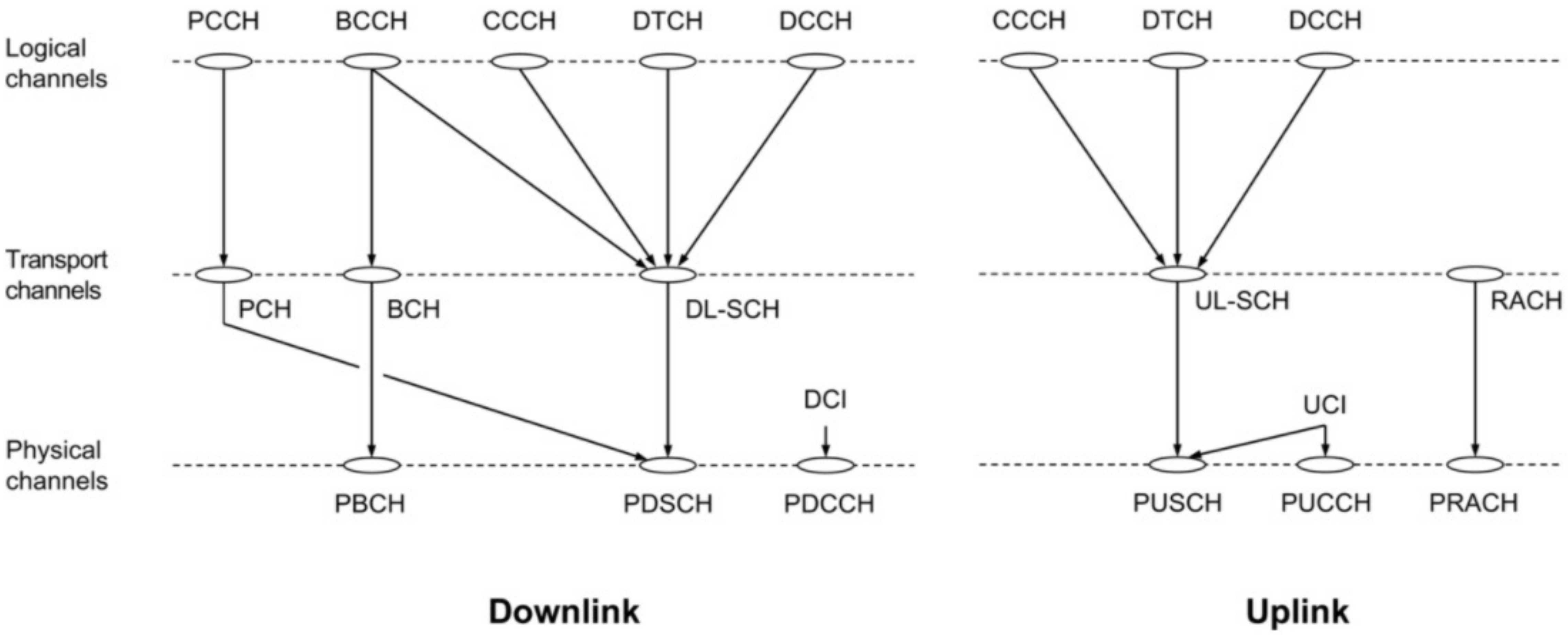


<38.213 v15.7 -Table 11.1.1-1: Slot formats for normal cyclic prefix>
D : Downlink, U : Uplink, F : Flexible

	Symbol Number in a slot													
Format	0	1	2	3	4	5	6	7	8	9	10	11	12	13
0	D	D	D	D	D	D	D	D	D	D	D	D	D	D
1	U	U	U	U	U	U	U	U	U	U	U	U	U	U
2	F	F	F	F	F	F	F	F	F	F	F	F	F	F
3	D	D	D	D	D	D	D	D	D	D	D	D	D	F
4	D	D	D	D	D	D	D	D	D	D	D	D	F	F
5	D	D	D	D	D	D	D	D	D	D	D	F	F	F
6	D	D	D	D	D	D	D	D	D	D	F	F	F	F
7	D	D	D	D	D	D	D	D	D	F	F	F	F	F
8	F	F	F	F	F	F	F	F	F	F	F	F	F	U
9	F	F	F	F	F	F	F	F	F	F	F	F	U	U
10	F	U	U	U	U	U	U	U	U	U	U	U	U	U
11	F	F	U	U	U	U	U	U	U	U	U	U	U	U
12	F	F	F	U	U	U	U	U	U	U	U	U	U	U
13	F	F	F	F	U	U	U	U	U	U	U	U	U	U
14	F	F	F	F	F	U	U	U	U	U	U	U	U	U
15	F	F	F	F	F	F	U	U	U	U	U	U	U	U
16	D	F	F	F	F	F	F	F	F	F	F	F	F	F
17	D	D	F	F	F	F	F	F	F	F	F	F	F	F
18	D	D	D	F	F	F	F	F	F	F	F	F	F	F
19	D	F	F	F	F	F	F	F	F	F	F	F	F	U
20	D	D	F	F	F	F	F	F	F	F	F	F	F	U
21	D	D	D	F	F	F	F	F	F	F	F	F	F	U
22	D	F	F	F	F	F	F	F	F	F	F	F	U	U
23	D	D	F	F	F	F	F	F	F	F	F	F	U	U
24	D	D	D	F	F	F	F	F	F	F	F	F	U	U
25	D	F	F	F	F	F	F	F	F	F	F	U	U	U
26	D	D	F	F	F	F	F	F	F	F	F	U	U	U
27	D	D	D	F	F	F	F	F	F	F	F	U	U	U
28	D	D	D	D	D	D	D	D	D	D	D	D	F	U
29	D	D	D	D	D	D	D	D	D	D	D	F	F	U
30	D	D	D	D	D	D	D	D	D	D	F	F	F	U
31	D	D	D	D	D	D	D	D	D	D	D	F	U	U
32	D	D	D	D	D	D	D	D	D	D	F	F	U	U
33	D	D	D	D	D	D	D	D	D	F	F	F	U	U
34	D	F	U	U	U	U	U	U	U	U	U	U	U	U
35	D	D	F	U	U	U	U	U	U	U	U	U	U	U
36	D	D	D	F	U	U	U	U	U	U	U	U	U	U
37	D	F	F	U	U	U	U	U	U	U	U	U	U	U
38	D	D	F	F	U	U	U	U	U	U	U	U	U	U
39	D	D	D	F	F	U	U	U	U	U	U	U	U	U
40	D	F	F	F	U	U	U	U	U	U	U	U	U	U
41	D	D	F	F	F	U	U	U	U	U	U	U	U	U
42	D	D	D	F	F	F	U	U	U	U	U	U	U	U
43	D	D	D	D	D	D	D	D	D	F	F	F	F	U
44	D	D	D	D	D	D	F	F	F	F	F	F	U	U
45	D	D	D	D	D	D	F	F	U	U	U	U	U	U
46	D	D	D	D	D	F	U	D	D	D	D	D	F	U

LBT=listen-before-talk for operation in unlicensed (wifi) spectrum

Approach: physical, transport and logical channels



Note: same concept as in 2G, and almost identical to 4G

Why so many?

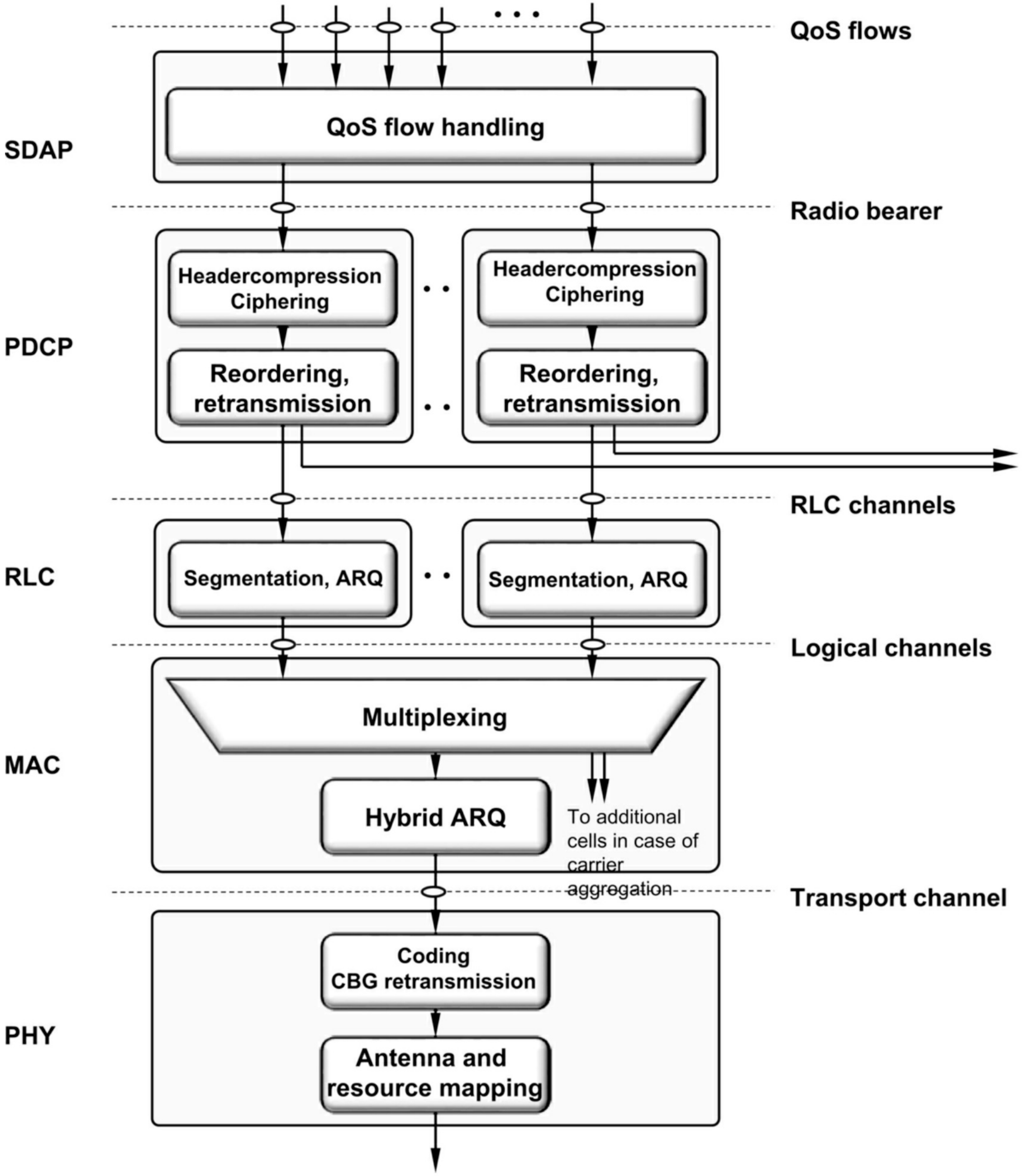


FIG. 6.7 NR downlink user-plane protocol architecture as seen from the device.

- Service Data Application Protocol (SDAP) is responsible for mapping QoS bearers to radio bearers according to their quality-of-service requirements. This protocol layer is not present in LTE but introduced in NR when connecting to the 5G core network due to the new quality-of-service handling.
- Packet Data Convergence Protocol (PDCP) performs IP header compression, ciphering, and integrity protection. It also handles retransmissions, in-sequence delivery, and duplicate removal3 in the case of handover. For dual connectivity with split bearers, PDCP can provide routing and duplication. Duplication and transmission from different cells can be used to provide diversity for services requiring very high reliability. There is one PDCP entity per radio bearer configured for a device.
- Radio-Link Control (RLC) is responsible for segmentation and retransmission handling. The RLC provides services to the PDCP in the form of RLC channels. There is one RLC entity per RLC channel (and hence per radio bearer) configured for a device. Compared to LTE, the NR RLC does not support in-sequence delivery of data to higher protocol layers, a change motivated by the reduced delays as discussed below.
- Medium-Access Control (MAC) handles multiplexing of logical channels, hybrid-ARQ retransmissions, and scheduling and scheduling-related functions. The scheduling functionality is located in the gNB for both uplink and downlink. The MAC provides services to the RLC in the form of logical channels. The header structure in the MAC layer has been changed in NR to allow for more efficient support of low-latency processing than in LTE.
- Physical Layer (PHY) handles coding/decoding, modulation/demodulation, multiantenna mapping, and other typical physical-layer functions. The physical layer offers services to the MAC layer in the form of transport channels.

Why so many?

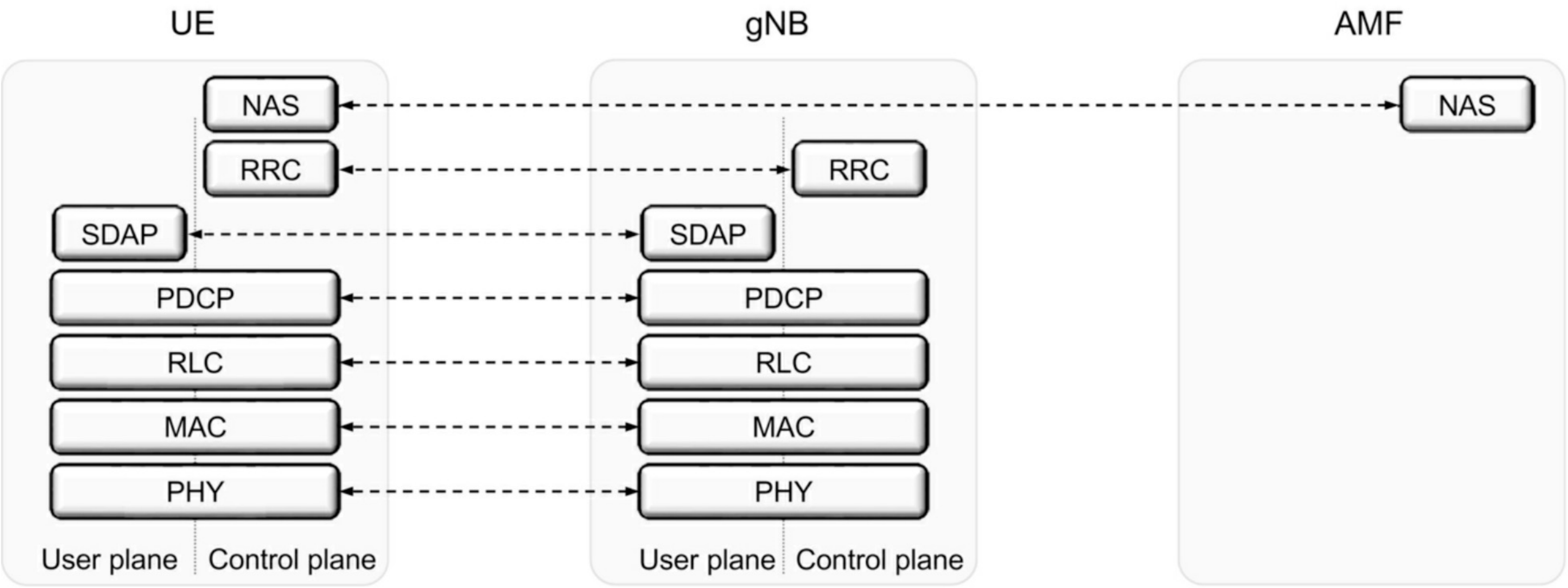


FIG. 6.6 User-plane and control-plane protocol stack.