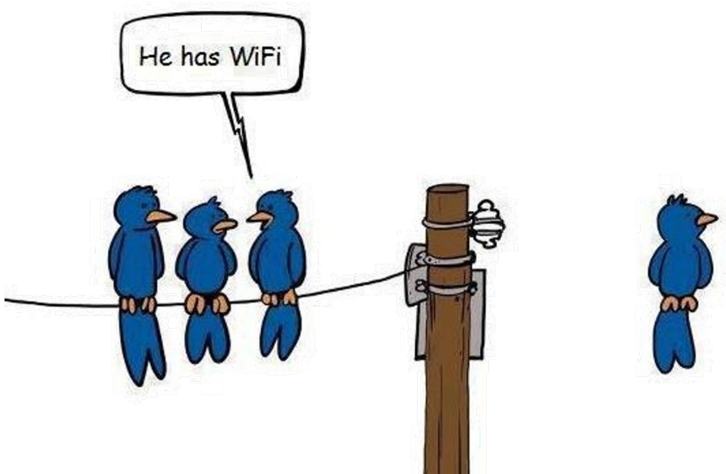
COM-405: Mobile Networks

Lecture 8.0: Cellular Networks II
Haitham Hassanieh

slides shamelessly stolen from Prof. JP Hubaux & others



EPFL

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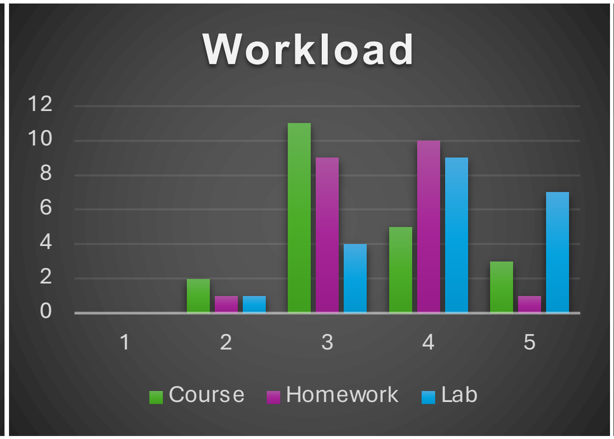
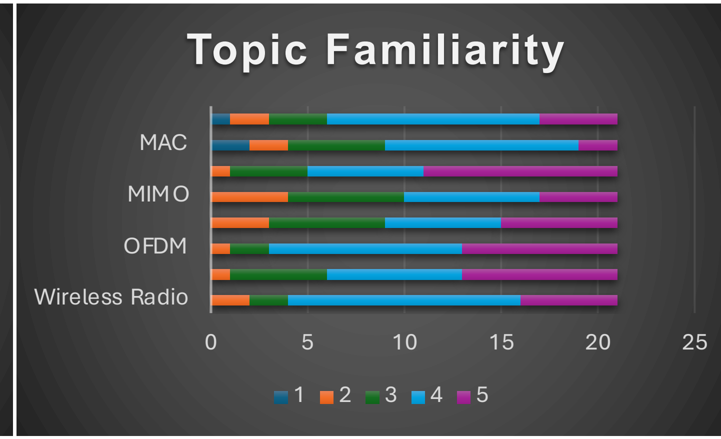
Feedback Survey Results





Highlights of constructive critism from verbal feedback:

- 3 hour lectures are mentally tiring
- Labs are not straightforward and require extra clarification by attending lab sessions
- Consistency of terminology and equations between labs/homeworks/lectures
- More background and extra material to look back at (eg. more detailed slides)
- More concrete examples shown in class
- Labs should be in Matlab 🤨

However, overall, it seems like most people enjoy the material presented in class! ☺

Cellular Networks Modeling

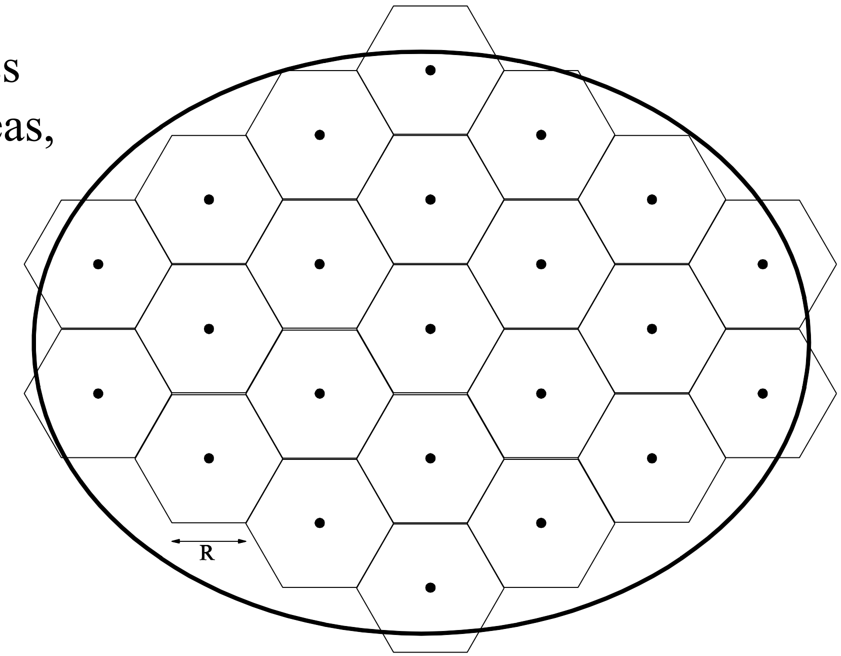
- Infrastructure
  - Base Station (BS)
  - Fixed network

- The most common model used for wireless networks is uniform hexagonal shaped areas, called cells.

- Uniform cells with radius R.

- Omnidirectional antennas
  - radiate radio wave power uniformly in all directions in one plane

- Base station with an omnidirectional antenna is positioned in the middle of each cell



Area Coverage Planning

- The received Signal-to-Noise (SNR) power by a receiver can be written as follows:

$$\Gamma = \frac{c_t P_t}{r^{\alpha} N}$$

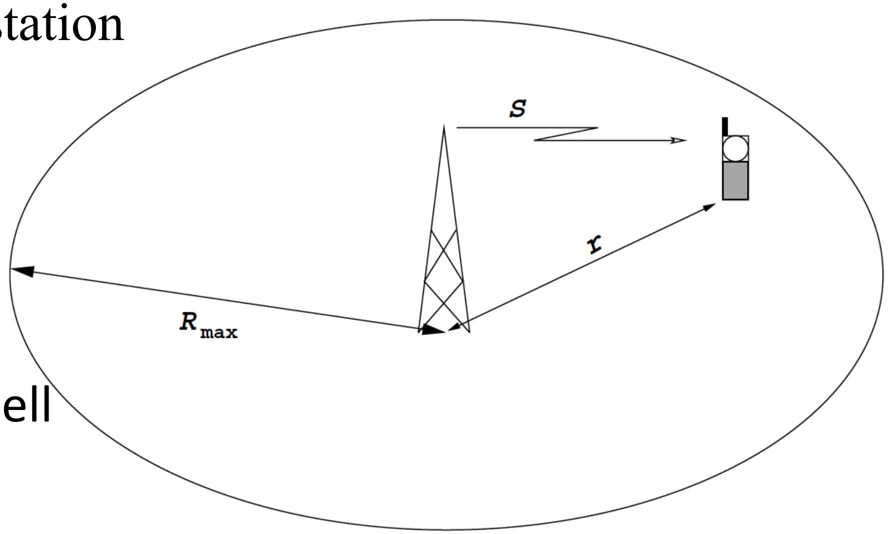
  r – distance from receiver to base station

  P_t – transmitted power

  N – noise power

  c_t – constant = $G_{TX} G_{RX} / (4\pi\lambda)^2$

  α – propagation constant



- The minimum received SNR within the cell
  - is the SNR at the cell border
  - is given by $\gamma_0 = \dfrac{c_t P_t}{R^{\alpha} N}$
- The radius of the coverage area (maximum range) is obtained as

$$R_{max} = \left(\frac{c_t P_t}{\gamma_0 N}\right)^{1/\alpha}$$

Cellular Networks Modeling

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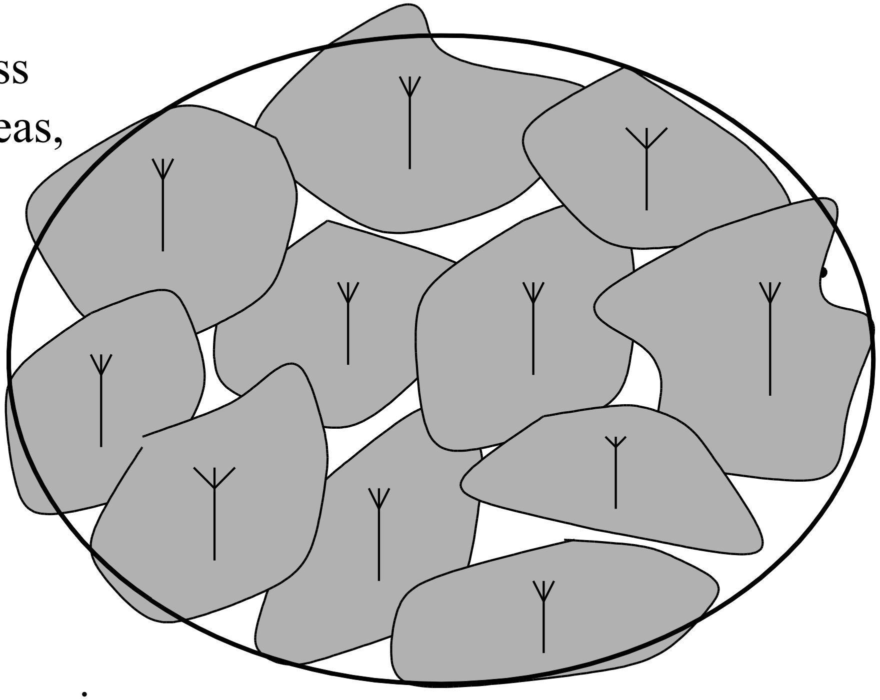


Area Coverage Planning – Effect of Fading

- Considering shadowing and fading, the received SNR becomes random.
- For a time availability of $p_{ta} = 1 - p_{out}$, we have

$$P(\Gamma \le \gamma_0) = P\left(\frac{c_t G P_t}{r^\alpha N} \le \gamma_0\right) \le p_{out}$$

G is assumed to be lognormal distributed with standard deviation σ dB.

p_{out} is the outage probability (probability of failure to provide service)

- To preserve the same cell coverage area, an extra fade margin, M, at the transmitter is needed.

$$P\left(\frac{c_t G P_t M}{r^\alpha N} \le \gamma_0\right) \le p_{out}$$

- The fade margin is then obtained as

$$M_{\ dB} = \sigma Q^{-1}(p_{out})$$

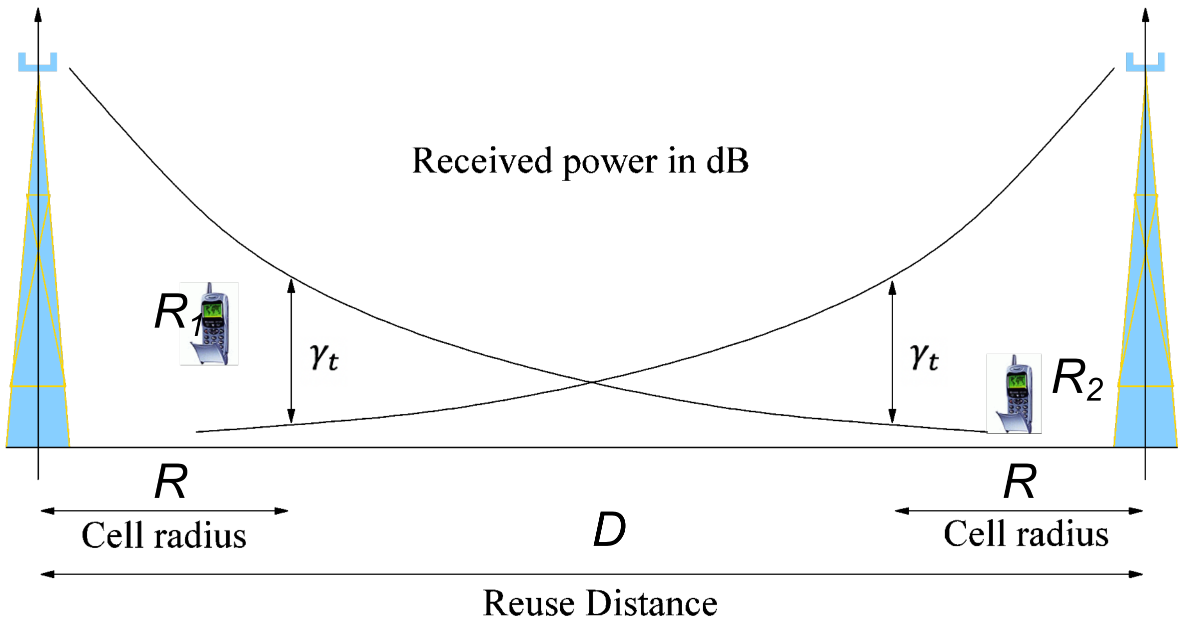
Q is the tail probability of the distribution of G (Q-function)

- Once the radius is known, the number of cells required to cover the service area can be computed as:

$$\text{Number of cells} = \frac{Total\ area}{Cell\ area}$$

Frequency Planning – Frequency Reuse

- An efficient way of managing the radio spectrum is to reuse the same frequency, within the service area, as often as possible.
- Frequency reuse is possible thanks to the propagation properties of radio waves.



- By properly setting the distance D, the same frequency can be used at two cells simultaneously.
- D is called the reuse distance

Frequency Planning – Frequency Reuse: 2 base stations

- The worst SINR (Signal-to-Interference-Noise-Ratio) at the receiving mobile unit R_1 (placed at the border of the cell) can be written as:

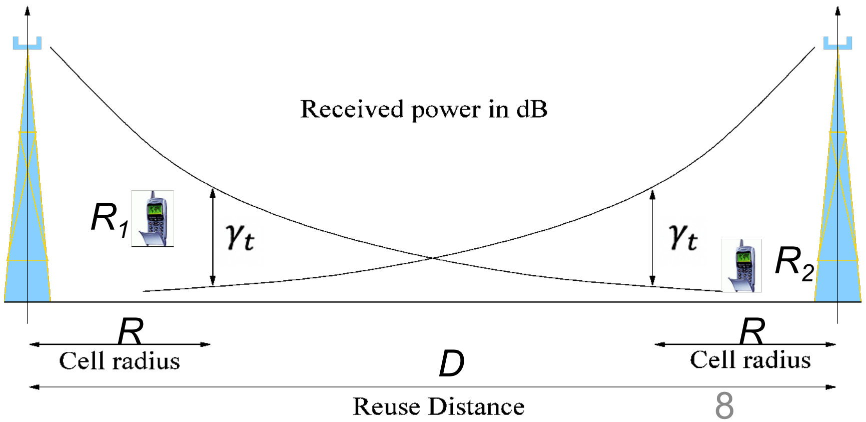
$$\Gamma_1 = \frac{P_\mathrm{R}}{P_\mathrm{R} + N} = \frac{\frac{c_t P_t}{R^\alpha}}{\frac{c_t P_t}{(D-R)^\alpha} + N} = \frac{\gamma_0}{1 + \frac{\gamma_0}{\left(\frac{D}{R} - 1\right)^\alpha}} \qquad \gamma_0 = \frac{c_t P_t}{R^\alpha N}$$

P_t is the transmitted power for both base stations

- With a required SINR minimum threshold of γ_t, we have

$$\Gamma_1 \geq \gamma_t \mapsto D \geq R\left[1 + \left(\frac{\gamma_0 \gamma_t}{\gamma_0 - \gamma_t}\right)^{1/\alpha}\right]$$

R should be selected s.t. $\gamma_0 > \gamma_t$



Frequency Planning – Frequency Reuse: B base stations

- The same frequency can be used at B different cells.

- The SINR at any receiver k (located in cell k) can be written as

$$\Gamma_k = \frac{c\,P_t/r^{\alpha}}{\sum_{\substack{i=1\ldots B\\ i<>k}} \frac{cP_t}{d_i^{\alpha}} + N} \geq \gamma_t$$

d_i - the distance from receiver k to base station i

r - the distance from receiver k to base station k

γ_t - the minimum required threshold of SNR

N - noise power

- With a proper choice of d_i, the minimum desired link quality can be achieved in all the links.

Design of Wireless Networks – Fixed Channel Allocation for Frequency Reuse

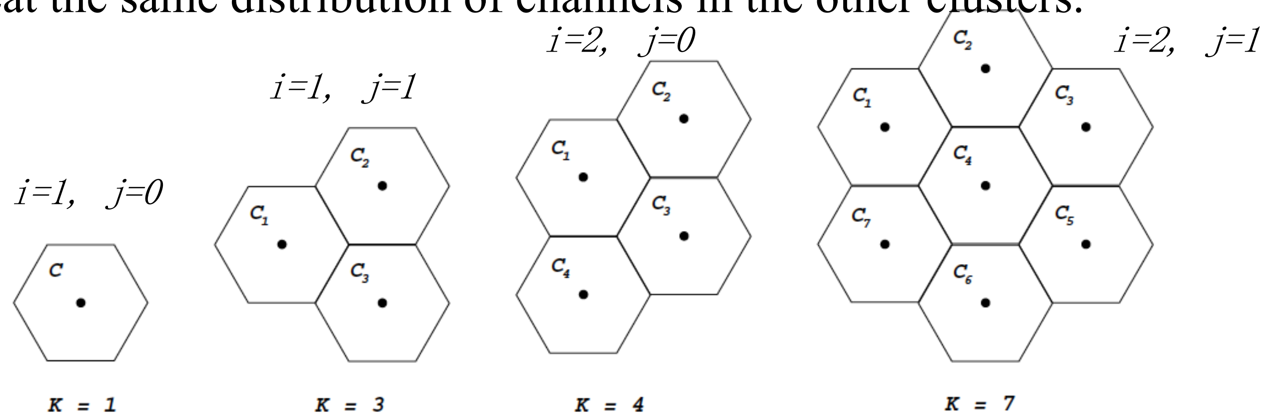
- Goal: for a certain available bandwidth, design a system with the highest possible capacity
- For a hexagonal cell structure, cells are grouped in clusters of K (called the reuse factor) cells. Let R be the radius of the cell and D the distance between 2 base stations using the same frequency band

$$K = \frac{1}{3}\left(\frac{D}{R}\right)^2, or\ D = R\sqrt{3K}, \qquad K = (i+j)^2 - ij, \qquad i, j = 0,1,2,3\ldots$$

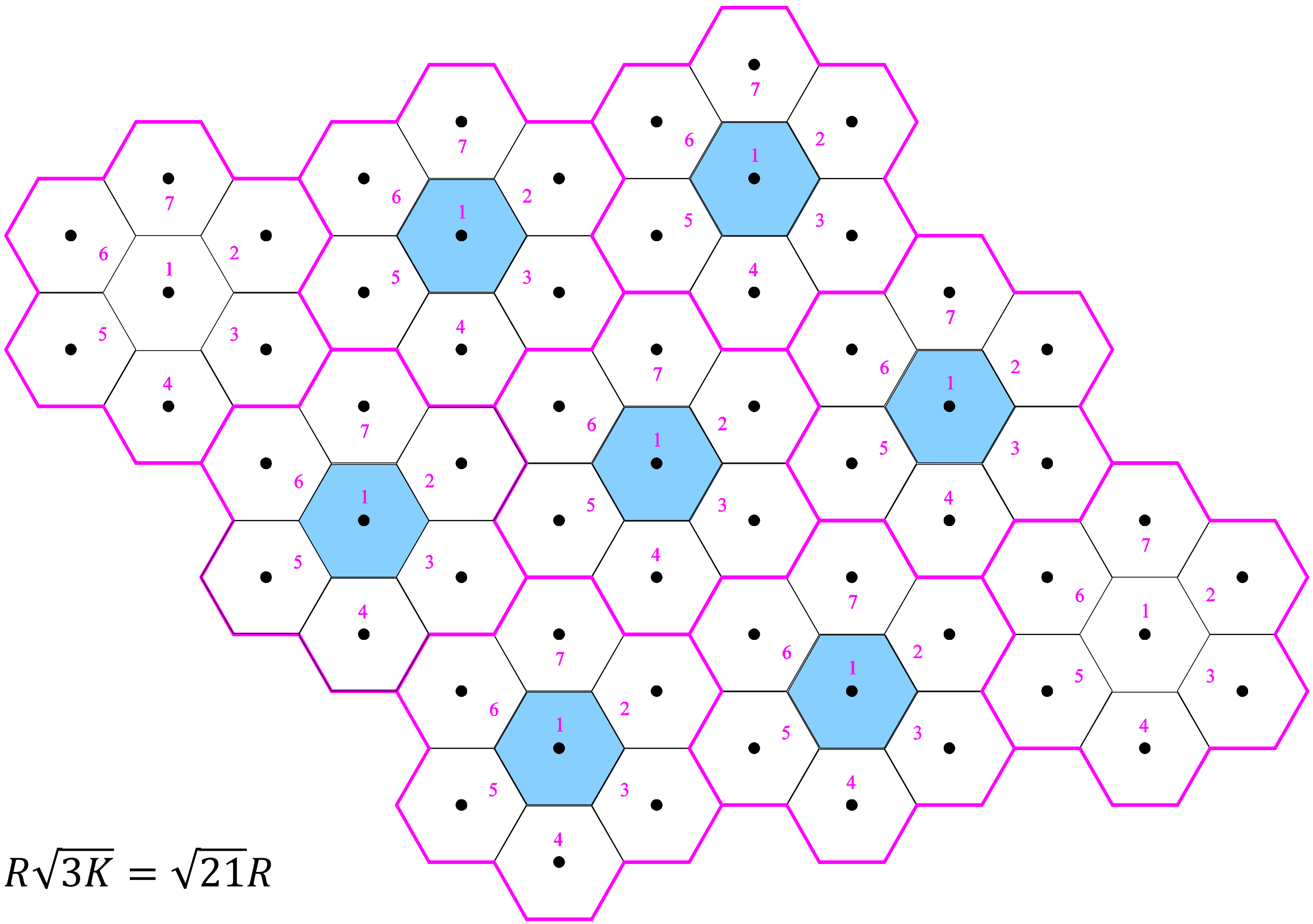
- Let C be the total number of orthogonal channels available.

$$C = \{f_1, f_2, \ldots, f_C\}$$

- Divide C into K disjoint groups $\{C_1, C_2, \ldots C_K\}$
- Assign each group C_i to a different cell of a cell cluster.
- Repeat the same distribution of channels in the other clusters.



Fixed Channel Allocation for Frequency Reuse – Example *K*=7



$$D = R\sqrt{3K} = \sqrt{21}R$$

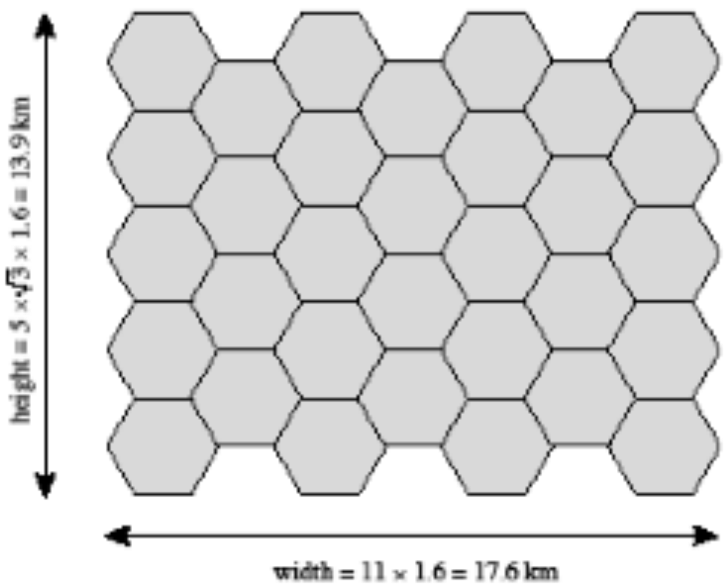
Cells with the same number use the same channel

Example: system of 32 cells with cell radius of 1.6km
Total frequency bandwidth supporting 336 traffic channels
Reuse factor (or cluster size) = 7
What geographic area is covered?
Total number of supported channels?

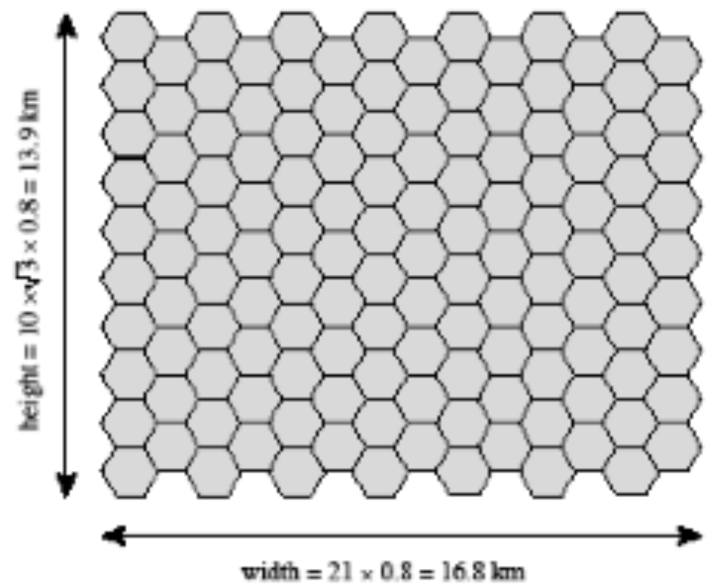
Solution:
Cell area = 6.65 km^2
Covered area: 32*6.65=213 km^2
Channels/cell = 336/7=48
Total channel capacity: 32*48=1536 channels

Same question for a system of 128 cells with cell radius of 0.8km. As before:
- total frequency bandwidth supporting 336 traffic channels
- reuse factor (or cluster size) = 7

Solution:
Cell area: 1.66 km^2
Covered area: 128*1.66=213 km2
Total channel capacity: 128*48=6144



(a) Cell radius = 1.6 km



(b) Cell radius = 0.8 km

Area of the hexagon: $1.5R^2\sqrt{3}$

Capacity of Wireless Networks

- The capacity of a wireless network is measured as the average number of simultaneous radio links supported by the system

$$\eta = \left\lfloor \frac{C}{K} \right\rfloor \text{ users/cell}$$

C – total number of channels available
K – reuse factor

- η indicates the maximum number of simultaneous connections in each cell

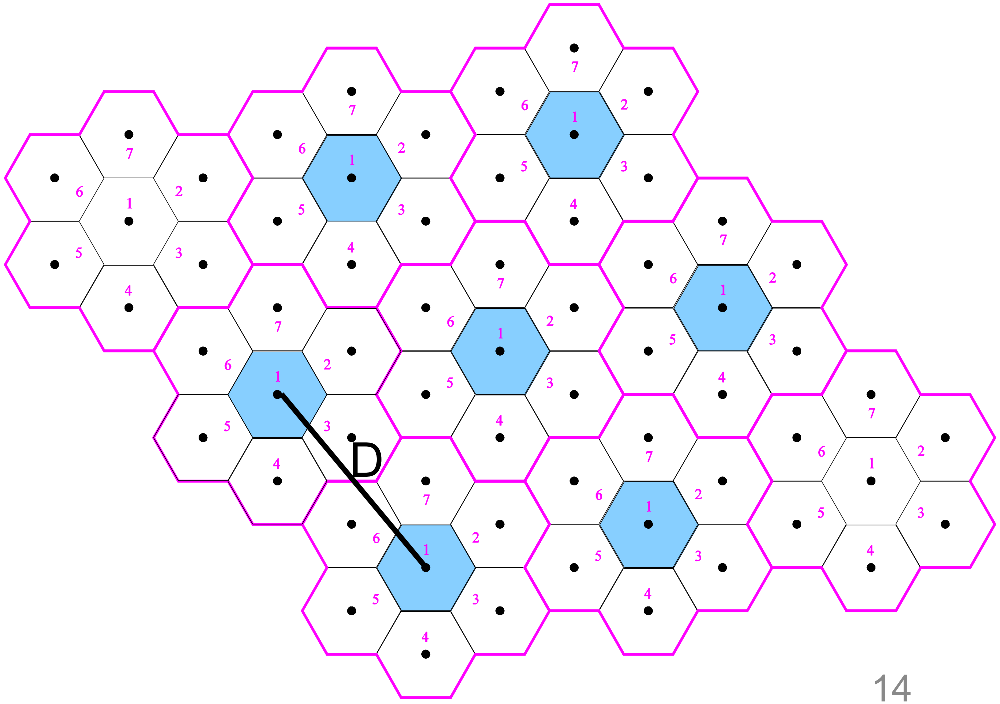
- The area capacity is defined as follows:

$$\text{area capacity} = \frac{C}{K\, A_{cell}} \text{ users/cell/unit area}$$

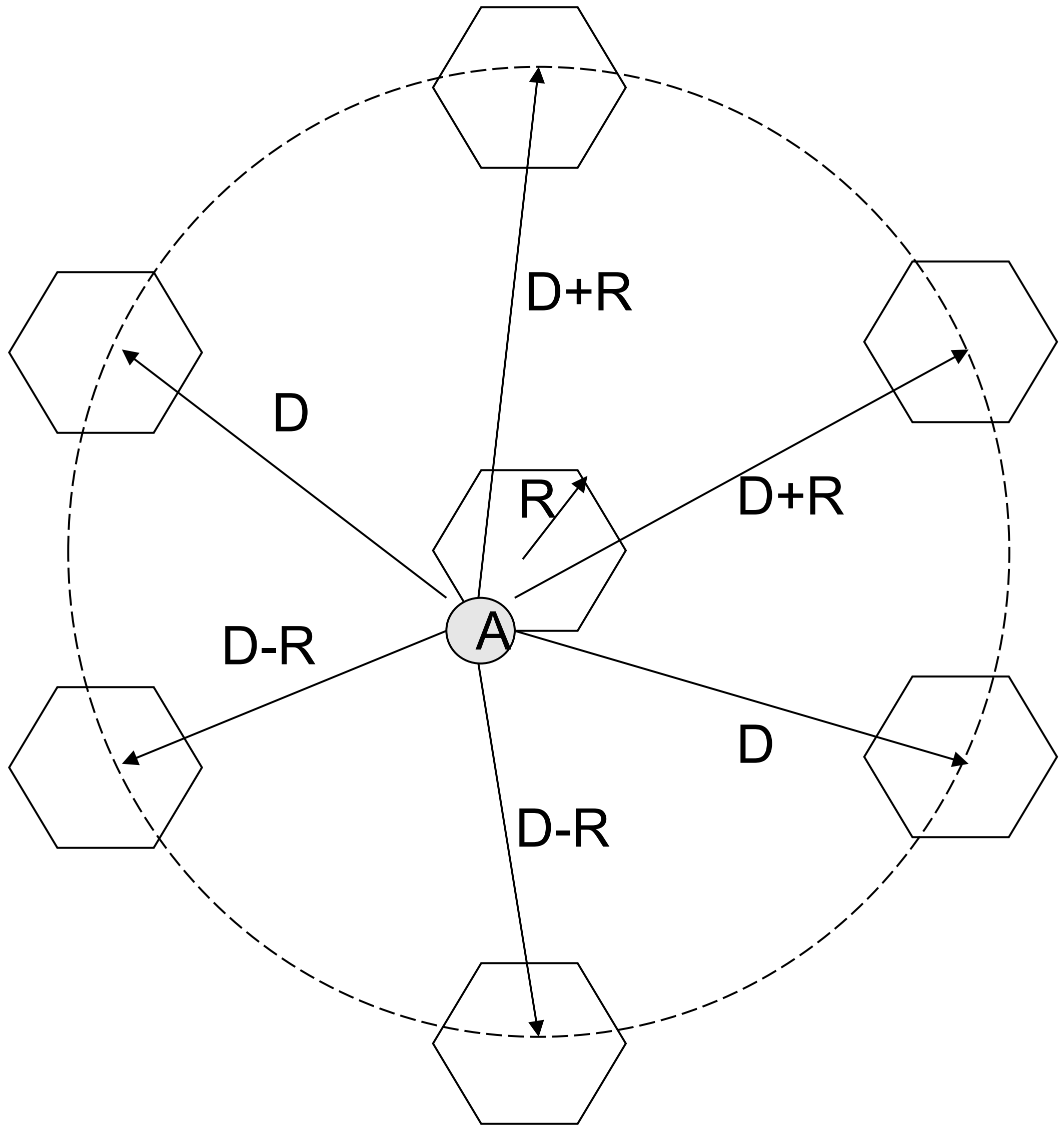
A_{cell} is the cell area, e.g., the area of the hexagon is $1.5R^2\sqrt{3}$

Quality(SINR) vs. Capacity(η) Tradeoff

- Ideal case: high SINR and high η
- But the interference cause by frequency reuse is proportional with the reuse distance (distance between cells using the same channel, D)
  - Large K
    -> large D -> High SINR
    -> Low η
  - Small K
    -> Small D -> Low SINR
    -> High η



Co-channel Interference



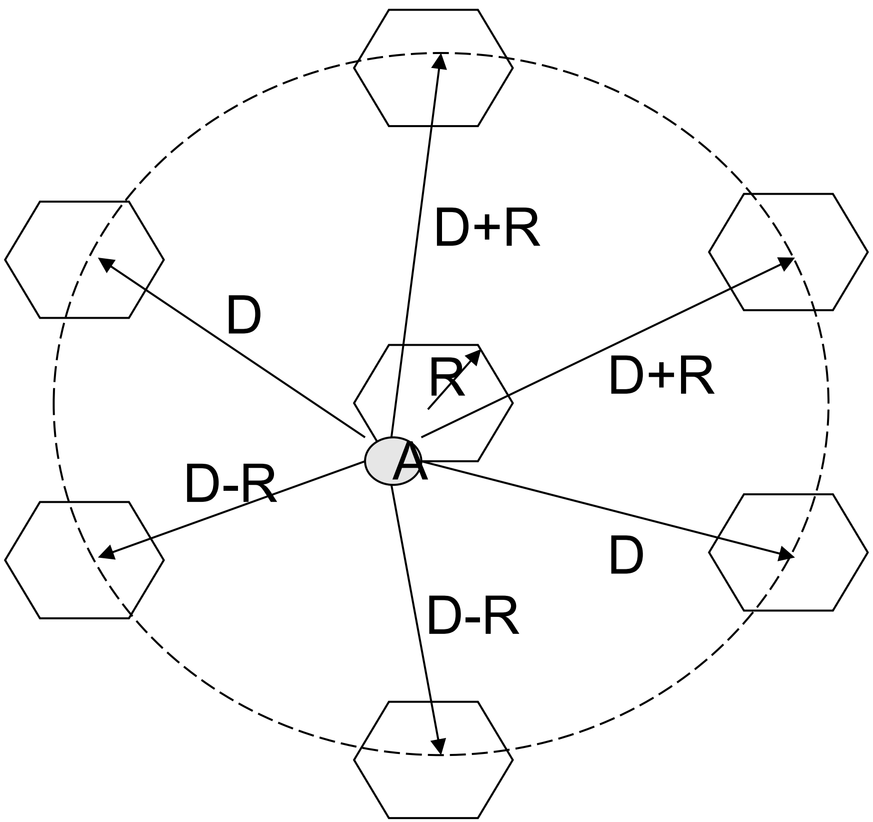
First tier of co-channel cells for a cluster size of K=7
Note: the marked distances are approximations

Co-channel Interference (cont'd)

- If the transmit power of each base station is equal and α is the same throughout the coverage area, in a corner of a cell (most remote place from the base station in the cell) we have:

$$\Gamma_A \sim \frac{R^{-\alpha}}{\sum_{i=1}^{i_0} D_i^{\ -\alpha}}$$

i_0 - number of co-channel interfering cells
D_i - distance from corner A to the center of the interfering co-channel cell i
R - radius of a cell
K - cluster size (or "reuse factor")



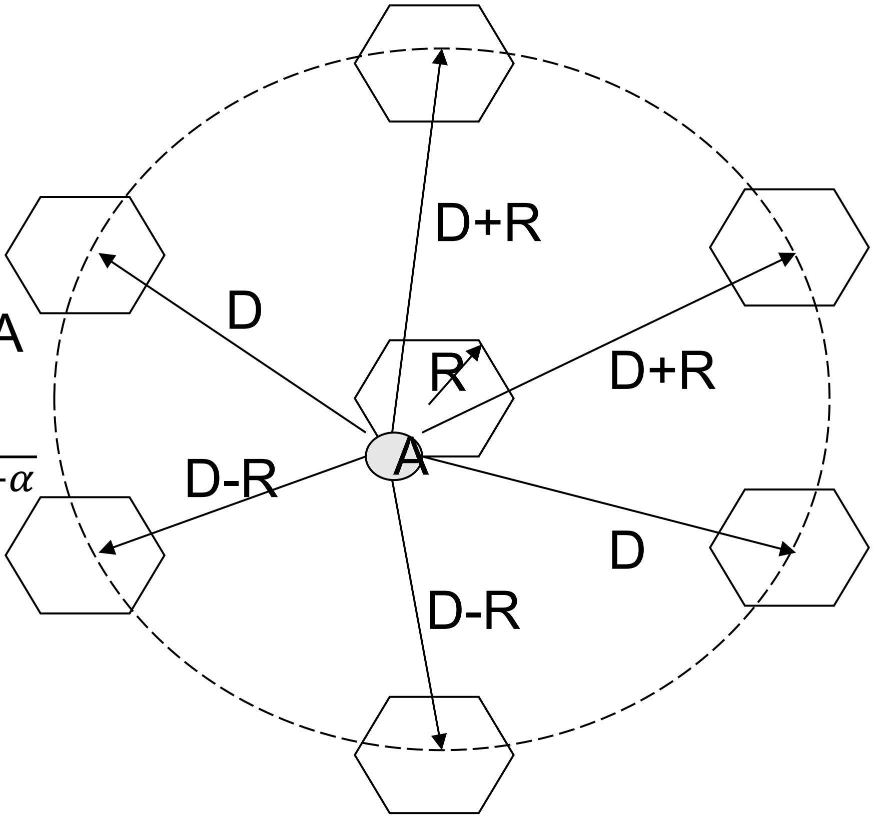
Co-channel Interference (cont'd)

- Considering only the first layer of interfering cells and assuming that they are equidistant from the desired base station (all at distance D):

$$\Gamma \sim \frac{(D/R)^{\alpha}}{i_0} = \frac{\sqrt{3K}^{\alpha}}{i_0}$$

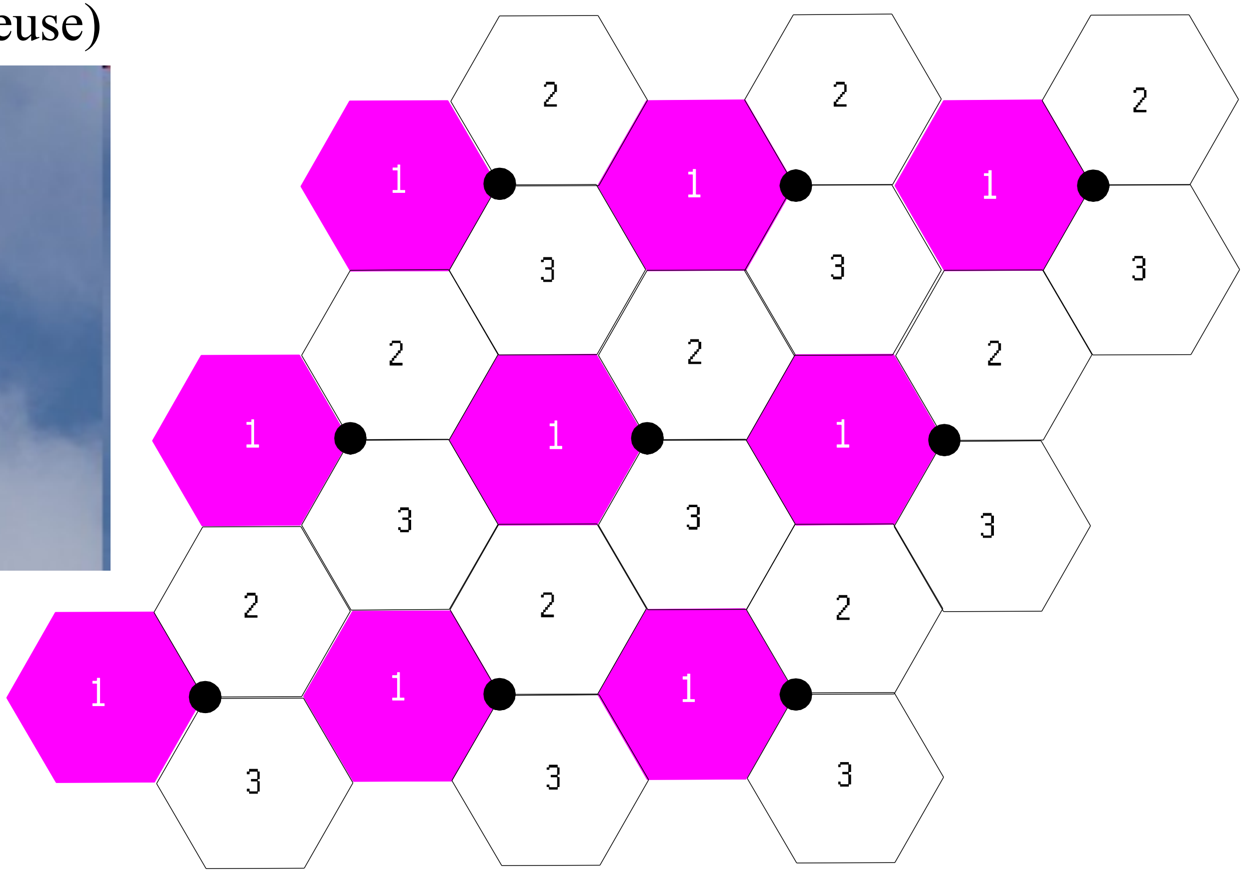
- Approximation of the SINR at point A

$$\Gamma_A \sim \frac{R^{-\alpha}}{2(D-R)^{-\alpha} + 2D^{-\alpha} + 2(D+R)^{-\alpha}}$$



Directional Antennas in Wireless Networks

- Directional antennas in wireless networks reduce the number of sites by allowing multiple BS to share the same site (120 degree site patterns for 1/3 reuse)



Directional Antennas

- The interference received at the mobile or the base station is dependent on the directivity of the antenna.

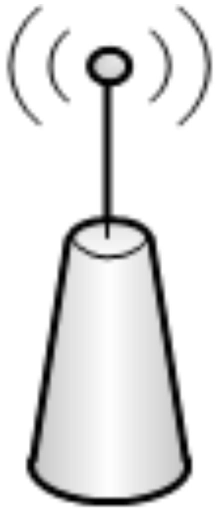
$$\Gamma = \frac{S_b(\Phi_0)\frac{cP_t}{r^\alpha}}{\sum_k S_b(\Phi_k)\frac{cP_t}{D_k^\alpha} + N}$$

$S_b(\phi)$ is the base station antenna gain.

- More reduction in interference can be obtained through the use of narrower sector antennas.

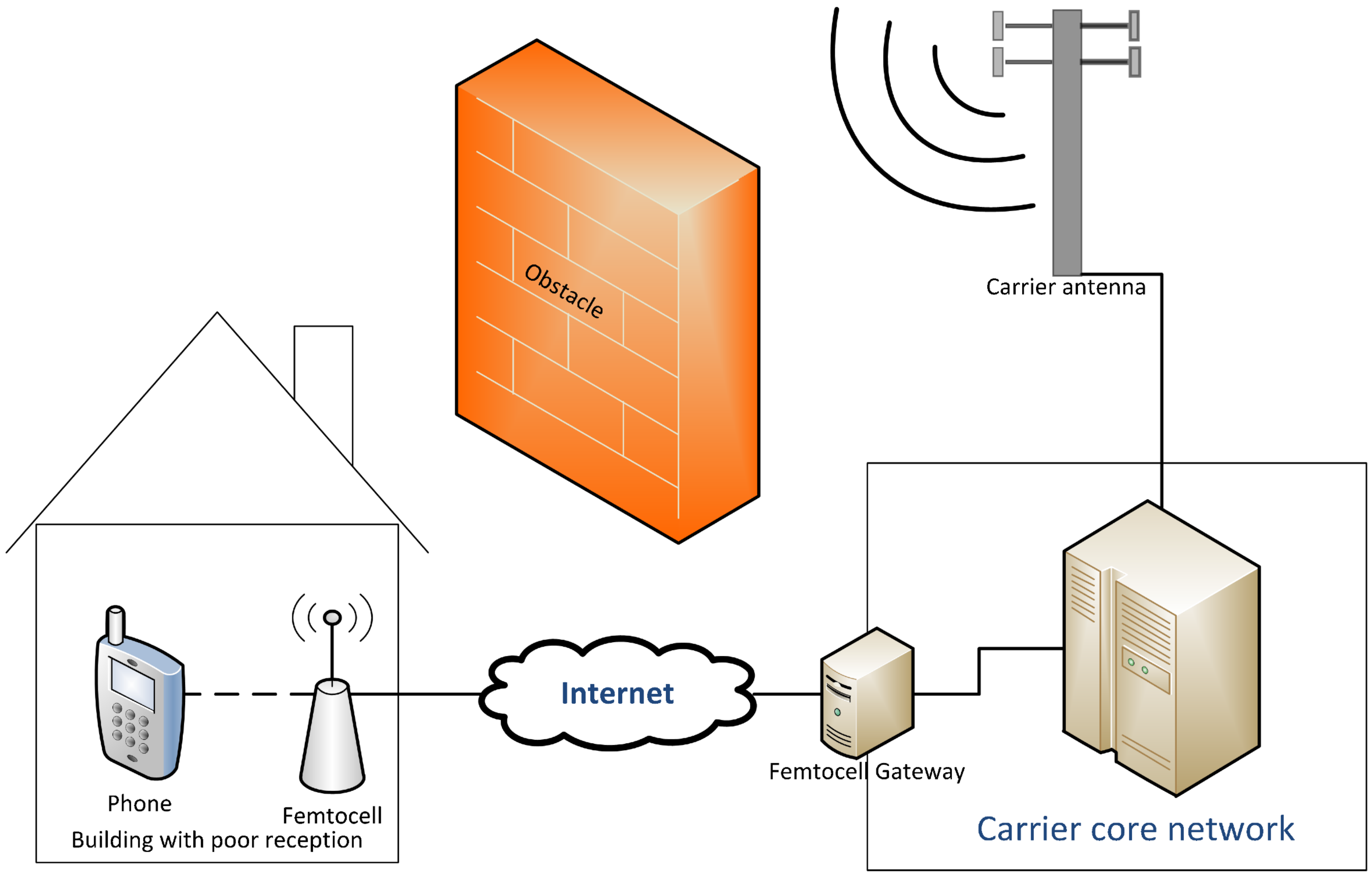
Femtocells

- Home base stations for mobile networks
  - Licensed spectrum
  - Low-power, low-range
  - At user’s premises
  - Cellular access through fixed broadband connection (ADSL,…)



- Why femtocells?
  - Better throughput, coverage, lower prices for users
  - Unload wide area cellular networks, reduce op. costs
- Examples in Switzerland:
  - Sunrise Indoor Box
  - Salt Booster Box

Femtocell Deployment



Frequency Management

- In all countries of the world, the licensed spectrum is managed by the government and (usually) leased to private operators
- Regulation authority
  - In Switzerland: Federal Commission for Communications, or ComCom; assisted by BAKOM
  - In the US: FCC
  - In the EU: each country still has its *national* regulation authority
- Some political willingness (especially in the US) to reduce the role of the FCC → Dynamic Spectrum Allocation (cognitive radios)
  See the IEEE DySPAN conference (ieee-dyspan.org)

Procedure for Frequency Allocation

- 2 main options
  - Auction
  - “Beauty contest”
    - Usually fixed price
    - Based on very detailed dossiers

    + : price pre-determined

    - : temptation/suspicion of bribery; no price discovery

Auctioning of Frequencies

- Goal of auction: *best* possible allocation of frequencies to operators
- Auctions are *not* meant to maximize the revenue for the government
- Splitting of the frequency bands in blocks (e.g., of 2*5Mhz)
- Issue: how to combine the auctioned blocks
- Caps in high-value bands to avoid unfair behavior
- Typical duration of allocation: 10 to 20 years
- Minimal (or starting) price: xxx CHFrs/MHz*Year (defined by law in the case of CH)

The case of Switzerland

- 3 main cellular operators (cellcos)
  - Swisscom (state-controlled) has 60% of the mobile market
  - Failed attempt of merger of Orange and Sunrise (in 2010)
  - Orange → Salt Mobile (2015)
- Good quality of service, but high prices
- Swiss peculiarities: topography, super-tight emission regulations, site acquisitions (to set up base stations) often problematic, expensive manpower, high-revenue and change-averse population
- All licenses already available at that time (800, 900, 1800, 2100 and 2600MHz) (re-)allocated as of 2013 or 2016 until 2028

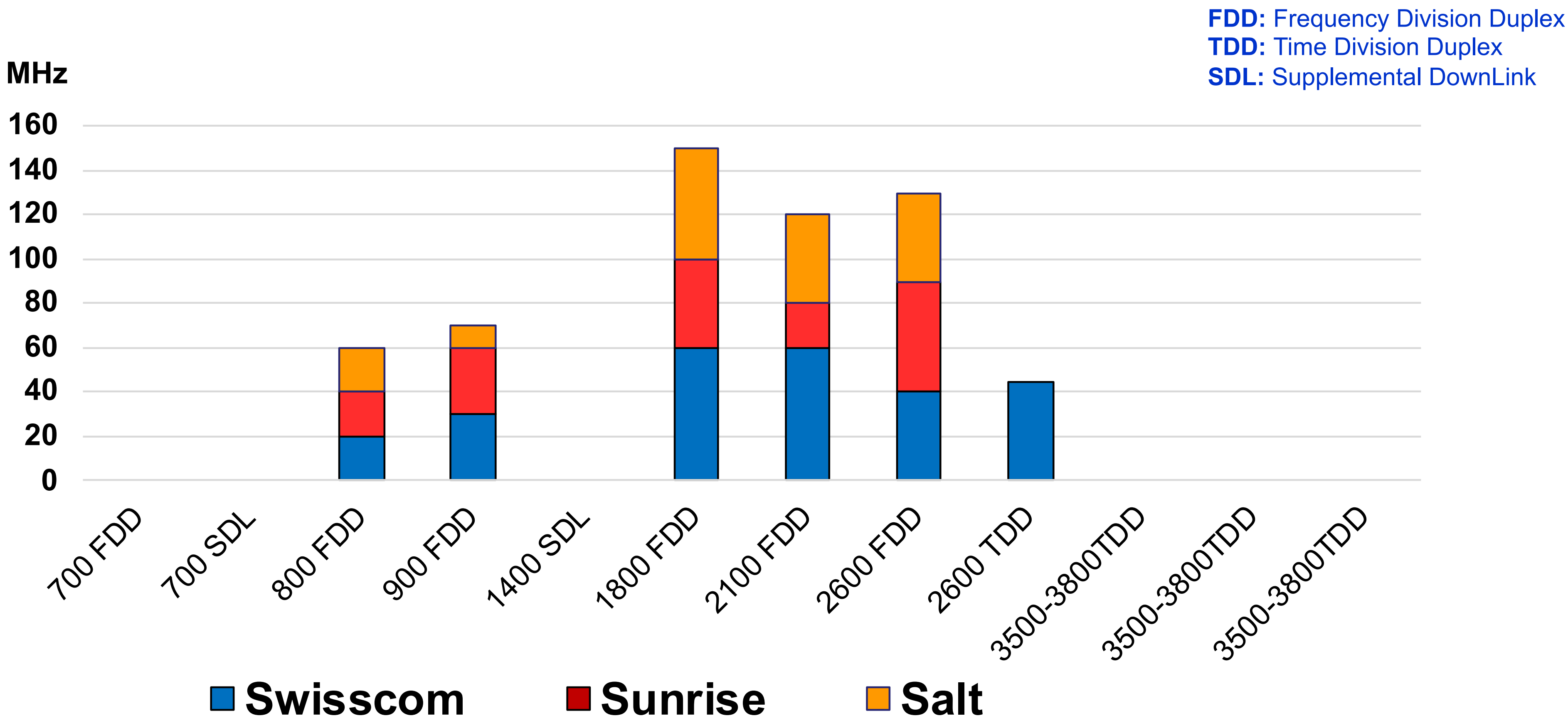
5G Requires Low and High Frequencies

Use of **low frequencies** (e.g., 700, 800 et 900 MHz) in **macrocells** for service across the territory

Source: amta.org.au

Use of **high frequencies** (e.g., 3.5 GHz and higher) in **small cells** located in streets and buildings. This allows very high bandwidths over short distances

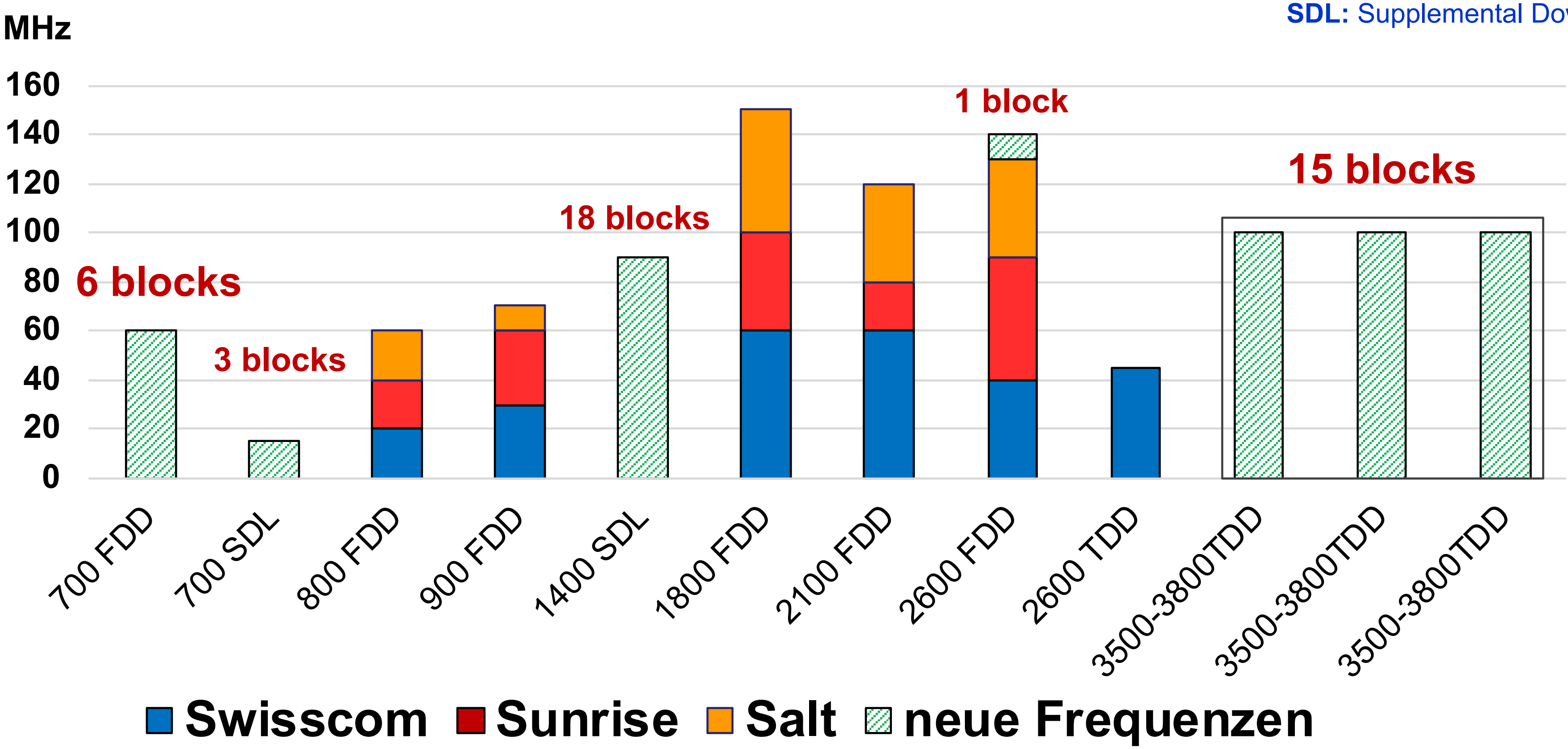
Frequency Allocation for Operators In Switzerland (before 5G)



Note: This slide and some of the following adapted from a slide show kindly provided by Urs von Arx (BAKOM)

5G New Mobile Frequencies

FDD: Frequency Division Duplex
TDD: Time Division Duplex
SDL: Supplemental DownLink



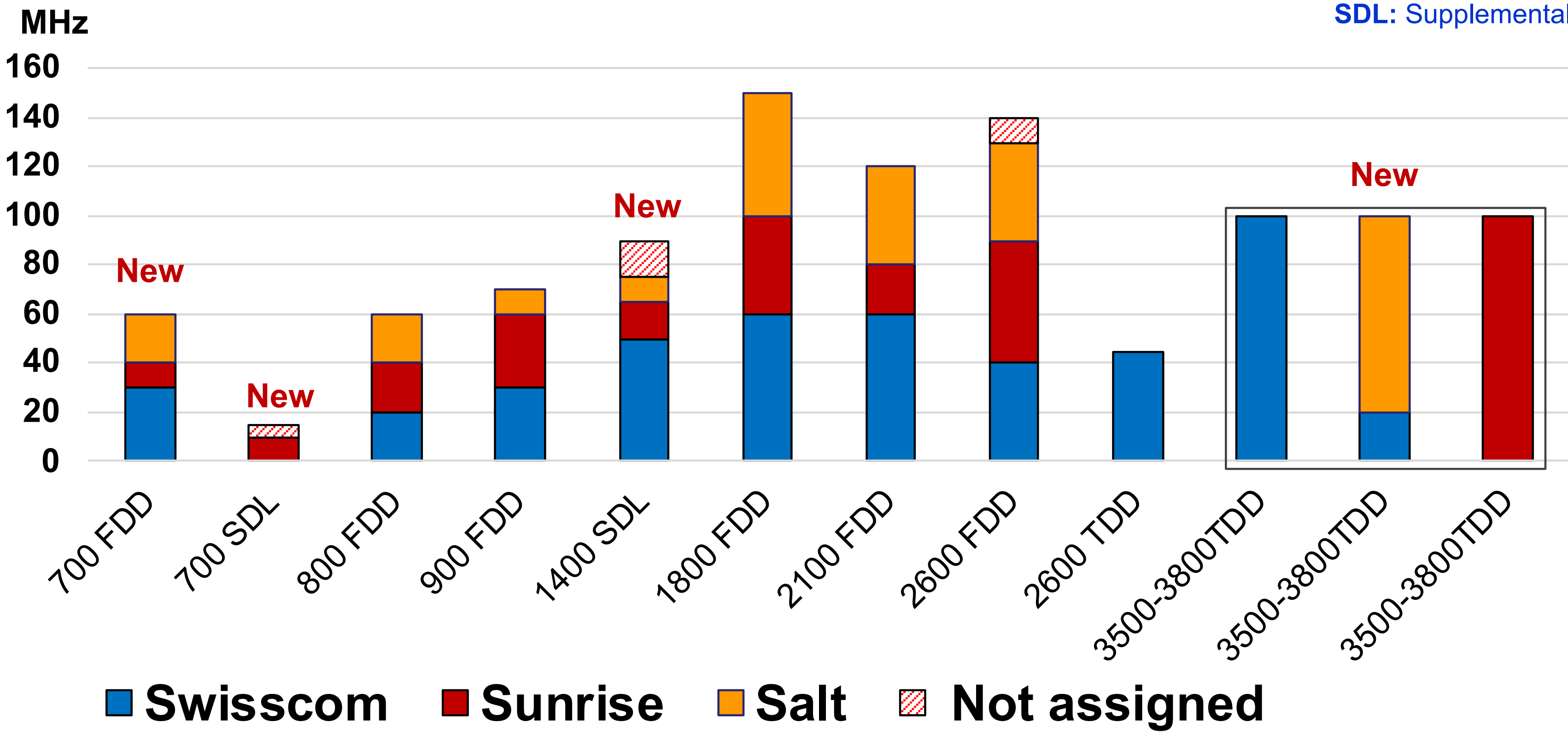
5G Frequencies Auction Results

	DENSE AIR	Salt.	Sunrise	swisscom
700 MHz FDD	0	**20 MHz**	**10 MHz**	**30 MHz**
700 MHz SDL	0	0	**10 MHz**	0
1400 MHz SDL	0	**10 MHz**	**15 MHz**	**50 MHz**
2600 MHz TDD	0	0	0	0
3500 - 3800 MHz TDD	0	**80 MHz**	**100 MHz**	**120 MHz**
Surcharge in CHF	**0**	**94'500’625**	**89'238’101**	**195'554’002**

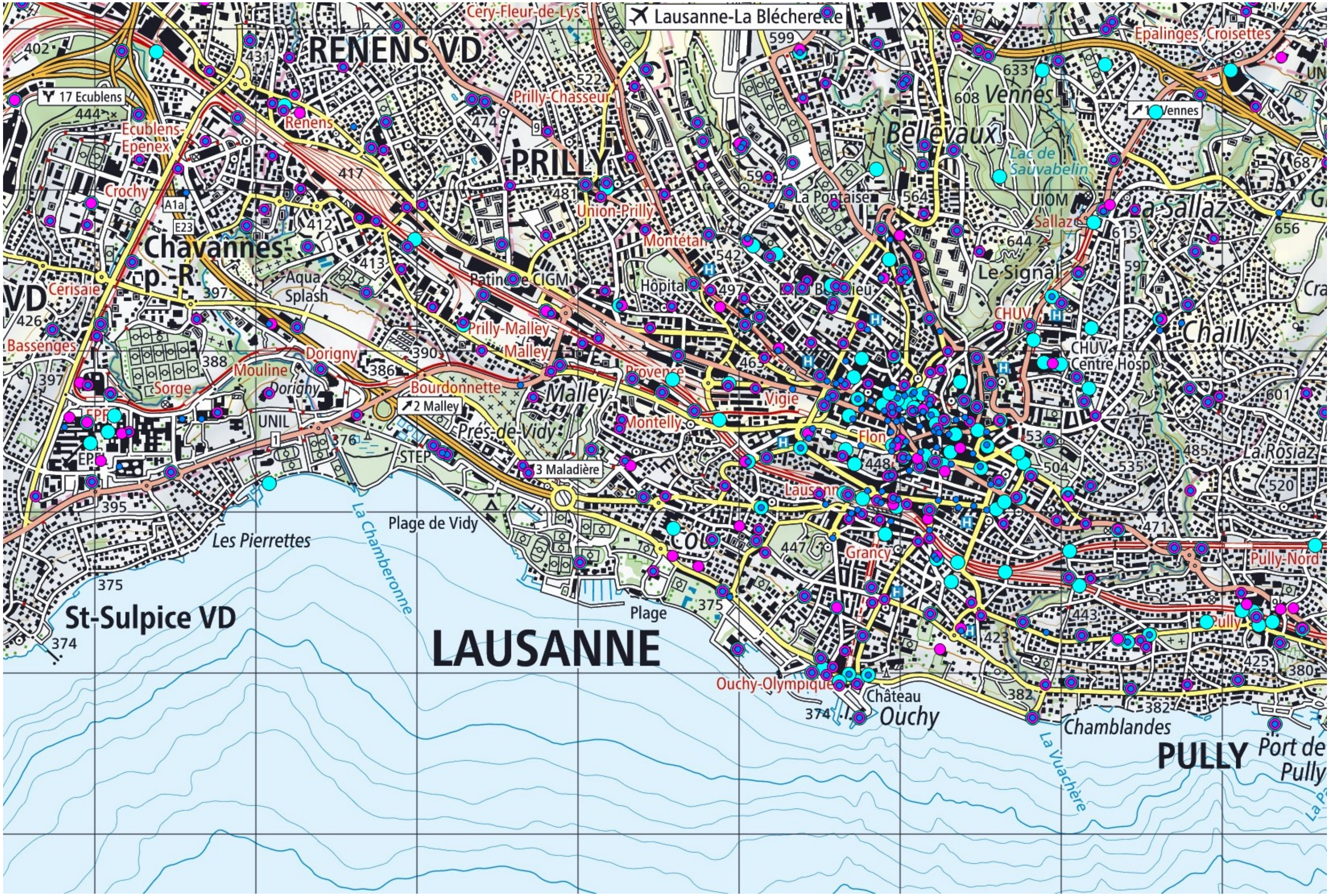
Total Revenue: 379’292’728 CHF

New Frequency Allocation for Operators in Switzerland

FDD: Frequency Division Duplex
TDD: Time Division Duplex
SDL: Supplemental DownLink



https://www.bakom.admin.ch/bakom/en/homepage/frequencies-and-antennas/location-of-radio-transmitters.html

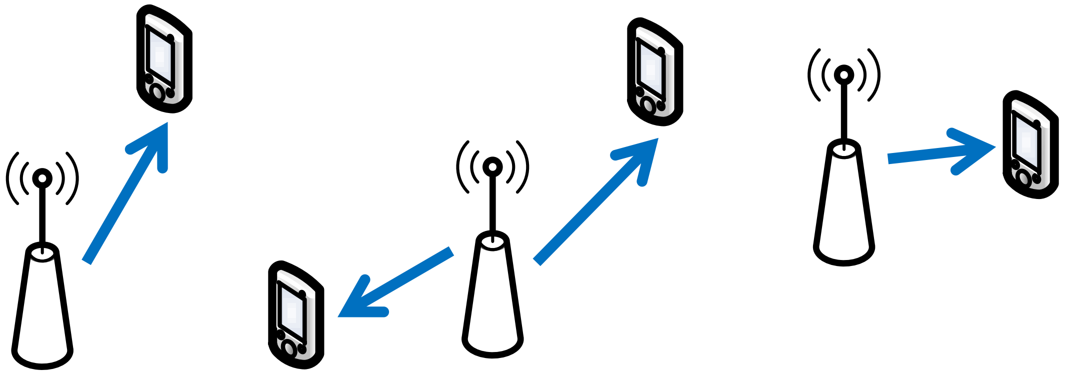


Association: Radio Resource Management problem

To each active terminal, we need to assign:

- Transmit power
- Waveform
- Base station(s)

in order to maximize system utility



Association on the move: **handover**

Mobility management

While inactive

- Tracking location of terminal and waking it up when necessary
  - Location area updates
  - Paging

While connection in progress:

- Handover (or “handoff”, US English): timely selection (transition) of base stations based on signal quality measurements

Handover types

Involved networks

- Horizontal handover
  - Within a single network of homogeneous radio access technology (RAT)
- Vertical handover (or network selection)
  - Between different networks, usually with heterogeneous RATs

2 families of handover

- Hard handover
  - Only one base station serving at a time
- Soft handover
  - Multiple base stations can simultaneously serve a mobile terminal

Handover phases

Handover measurement & decision

- Decides when and where to handover

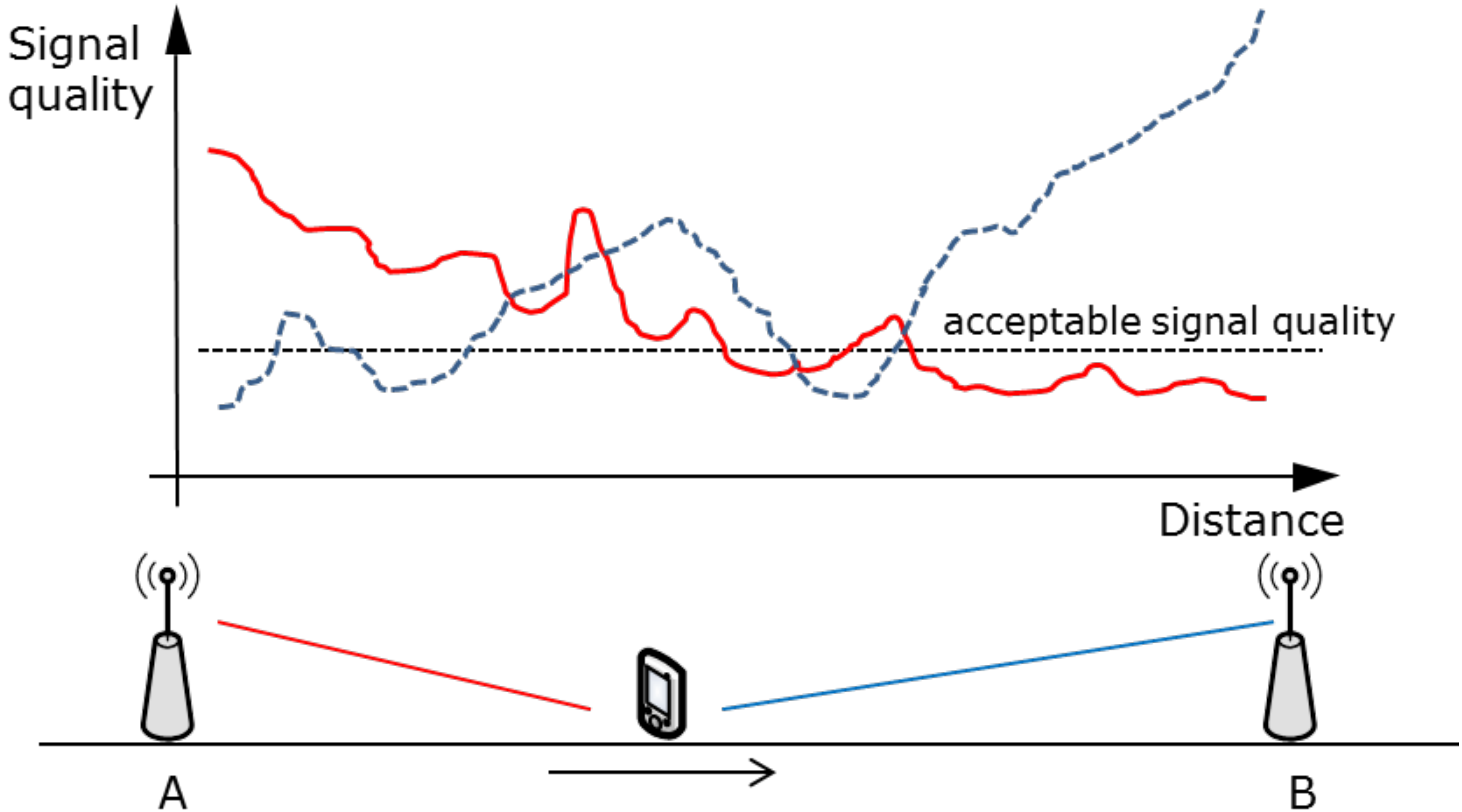
Handover resource management

- Radio resources available in the target base station?
  → allocate them

Handover execution

- Reliable handover signaling (handshaking) procedure

Handover decision



Performance metric

Two main metrics

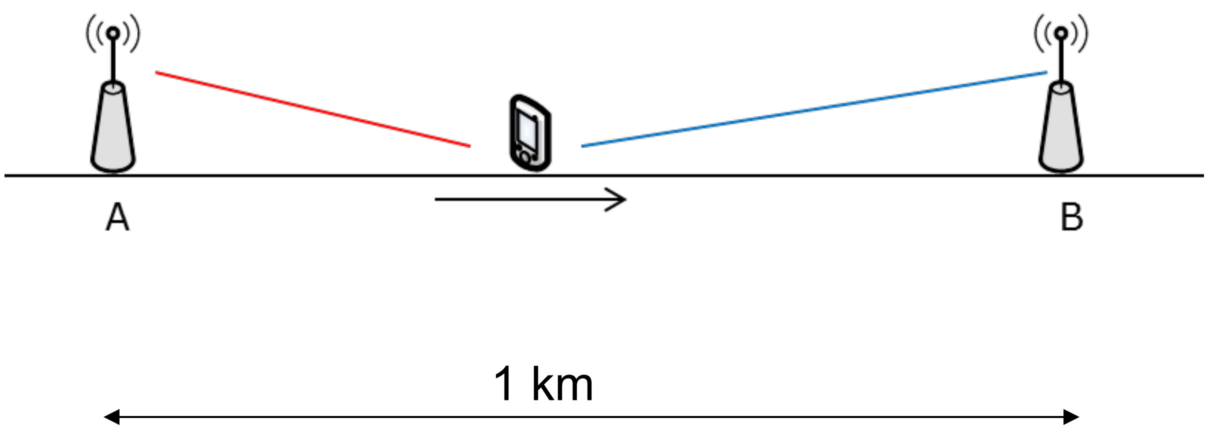
- Handover failure probability
  - Measures how often handover attempts fail
  - Probability that signal quality is below the required value for more than a given time interval
- Handover frequency (or rate)
  - Measure of how frequently handover decisions are made

Tradeoff between handover frequency and failure probability

Handover Decisions

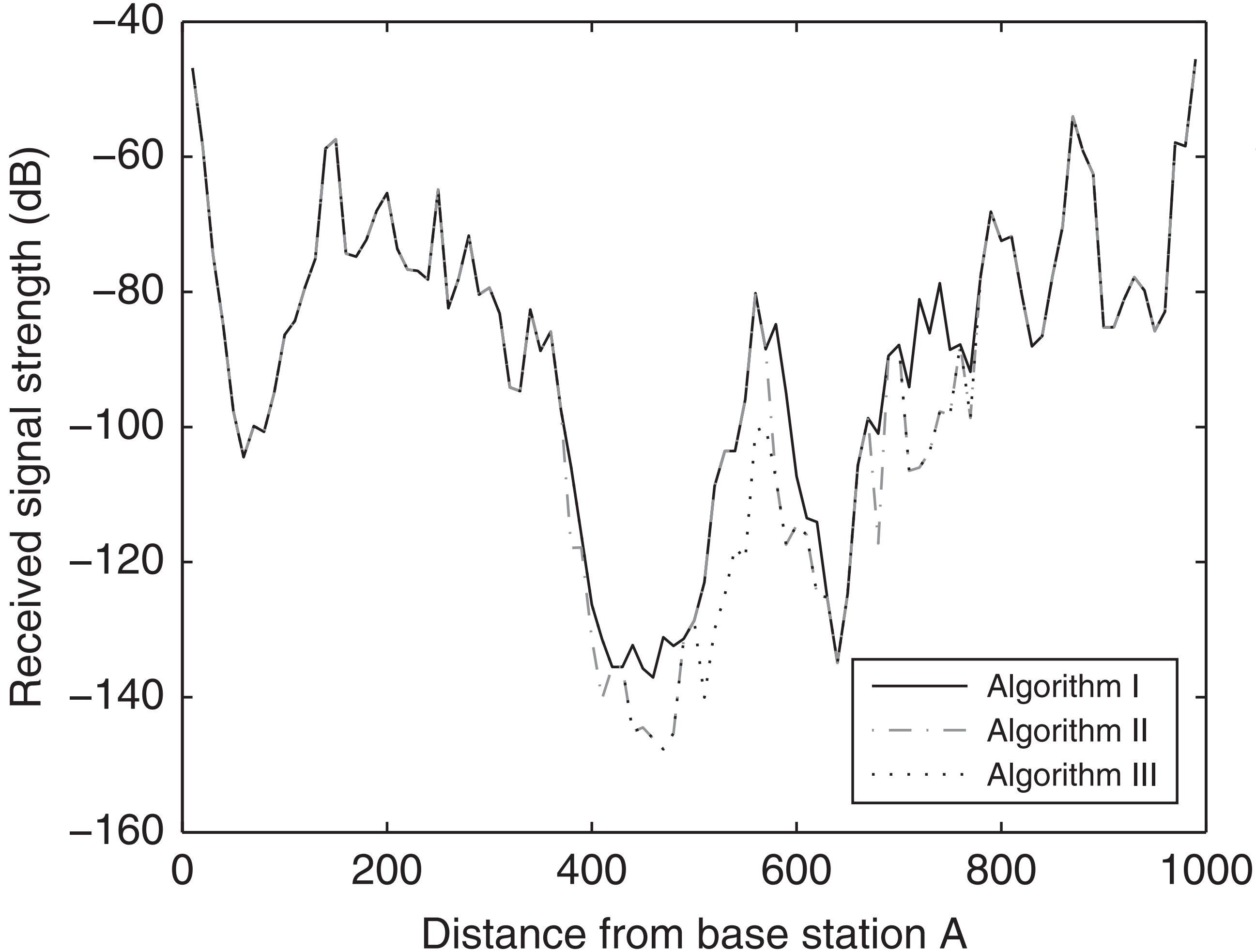
Handover decision algorithms:

- **Algorithm I:** instantaneous decision
  - AP with the highest signal level is chosen at any sample point
- **Algorithm II:** moving average
  - Average over the last 10 samples determines the serving AP
- **Algorithm III:** expected value
  - AP is selected based on expected signal level rather than on measurements



Handover Decisions

Algorithm	N_{HO}	P_{out}
I	7.7	2.4 %
II	1.7	4.9 %
III	1.0	6.1 %



N_{HO}: number of handovers
P_{out}: probability of outage

Handover decision criteria

Received signal strength (RSS)

- Detecting cell boundaries
- Designed for (low capacity) macro-cellular systems (noise-limited)

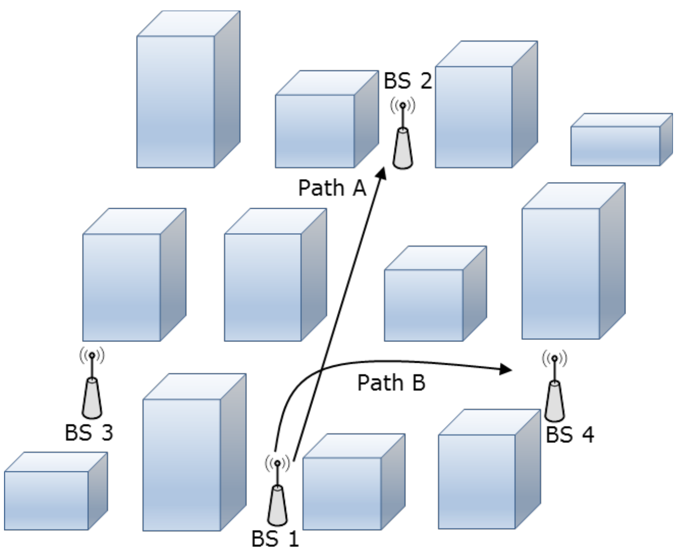
Signal to interference ratio (SIR)

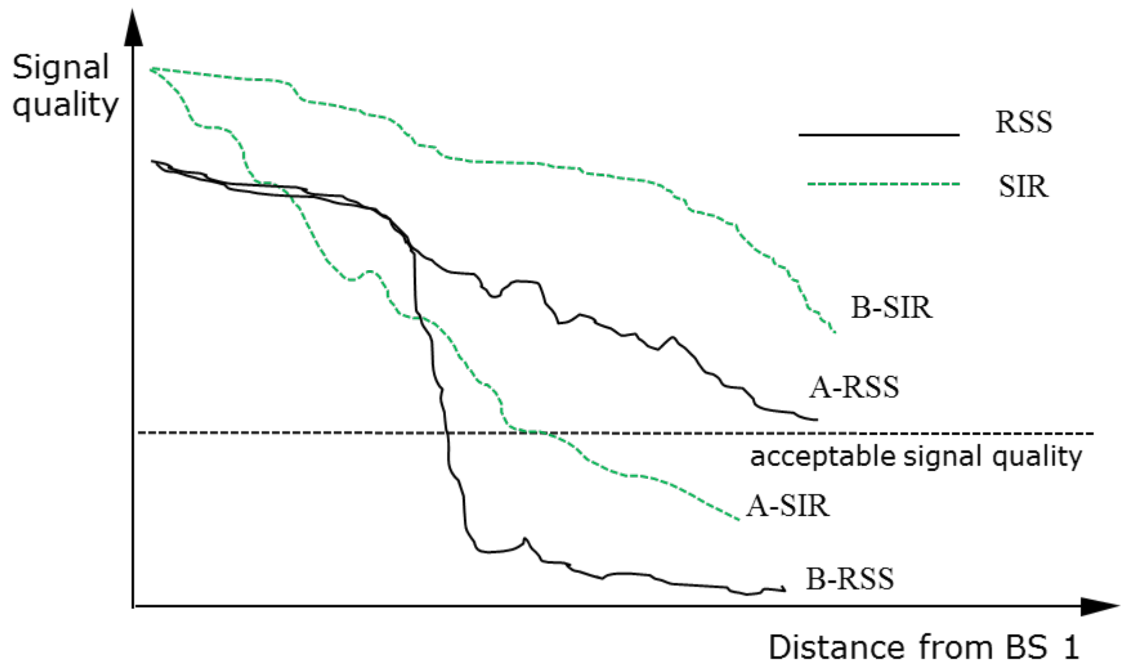
- Efficient in micro-cellular environments (interference-limited)

Example

Limitation of RSS-based handover in microcells

- Rapid RSS level changes at street corners
- RSS is not a good indicator of connection quality in microcells



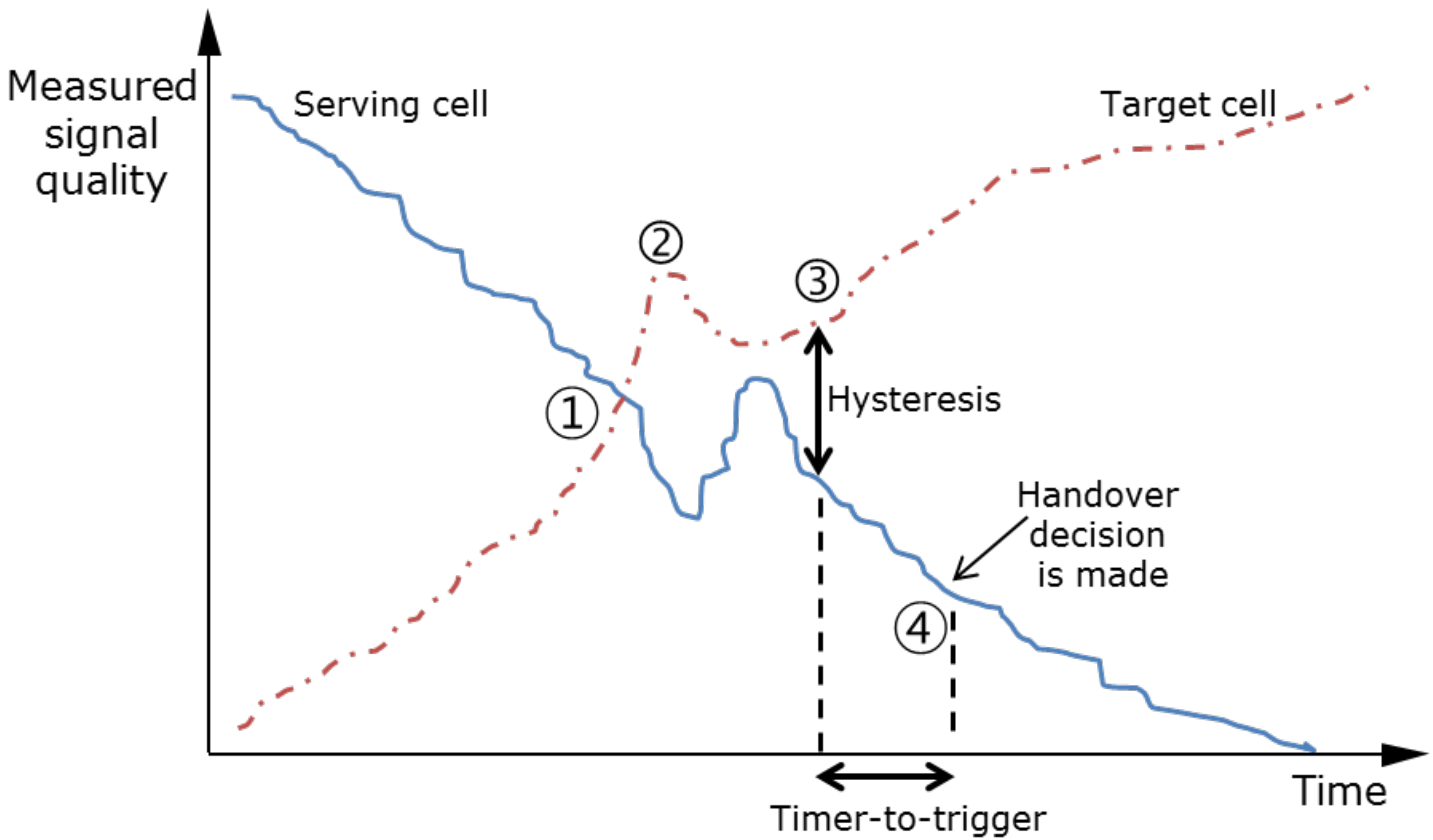


BS1 and BS2 use the same frequency channel, while BS3 and BS4 utilize another one.

Practical handover algorithm

Typical hard handover decision in LTE system

- Hysteresis & time-to-trigger
- This is the very basic handover mode in LTE

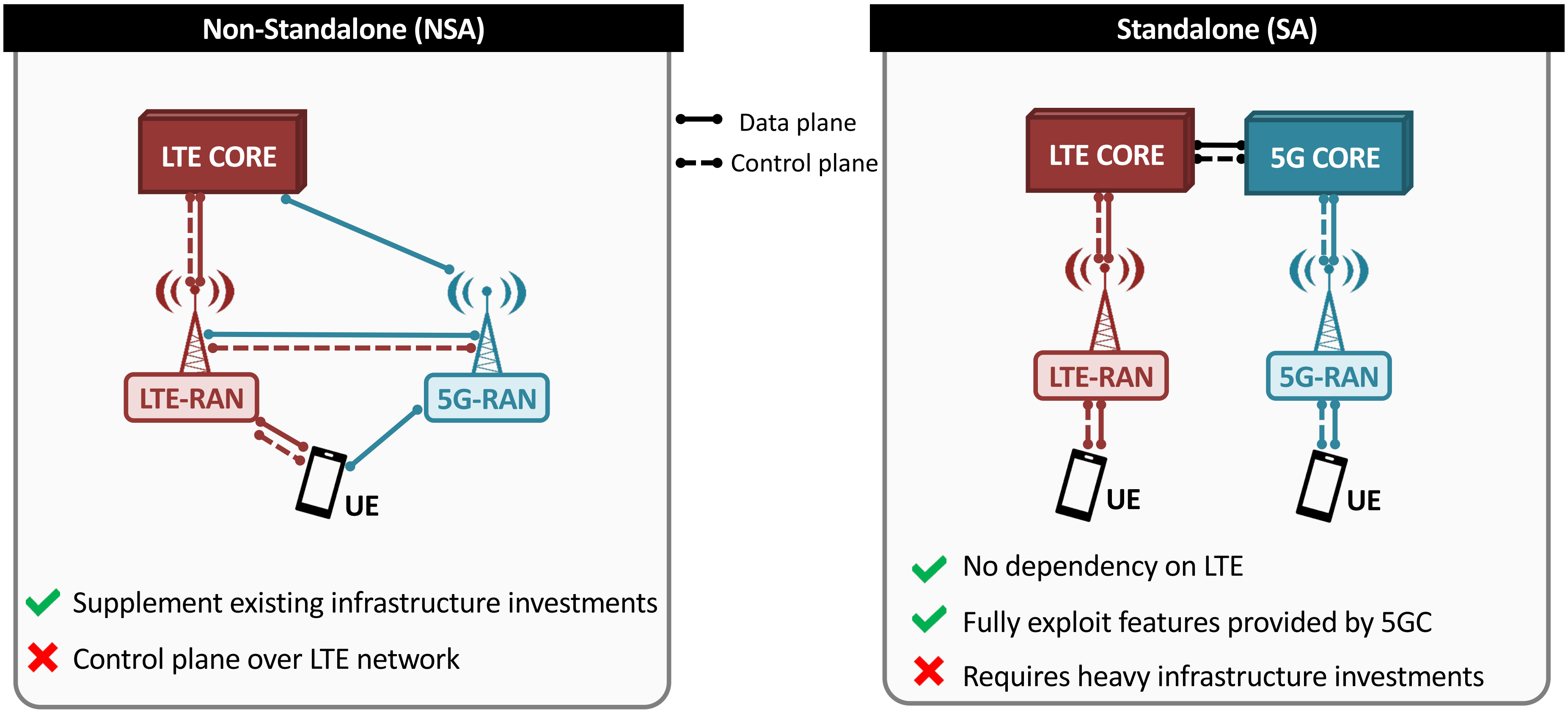


Handover execution

It is mostly about signaling procedure

- The system and mobile should reach agreement on
  - Which Base station?
  - Which waveform? (frequency, timeslot, code, etc.)
  - Authentication
- The signaling should be fast & reliable
  - Handover is performed under difficult SIR conditions

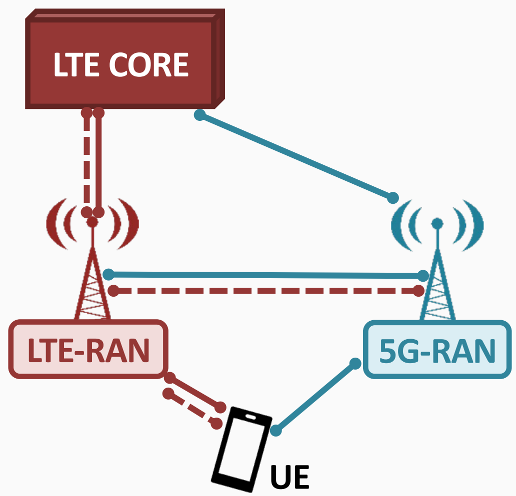
5G Deployment Strategies



https://networking.umn.edu/research-projects/5g-measurements

5G Deployment Strategies

Non-Standalone (NSA)



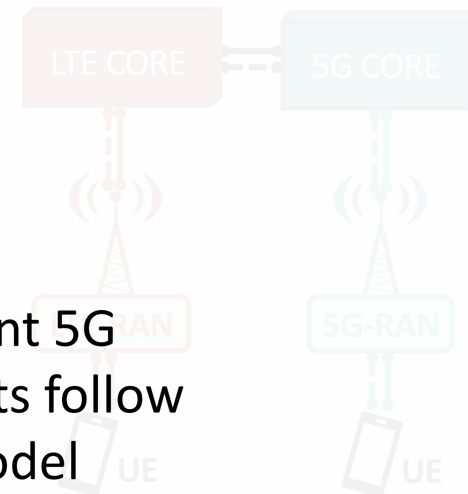
✔ Supplement existing infrastructure investments

✘ Control plane over LTE network

Data plane
Control plane

All current 5G deployments follow this model

Standalone Mode (SA)



✔ No dependency on LTE

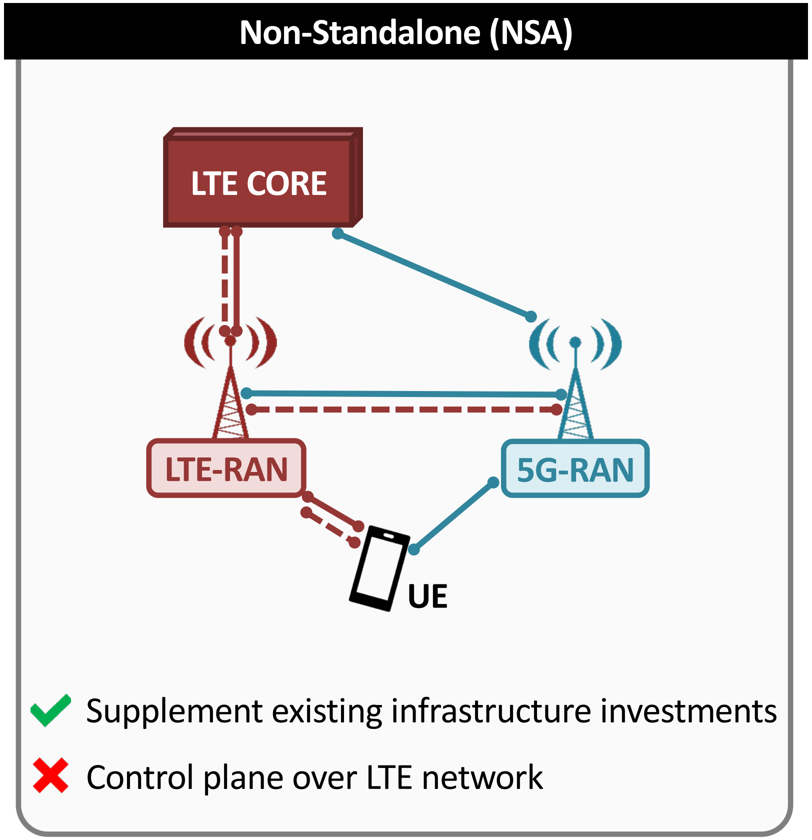
“Main drop”

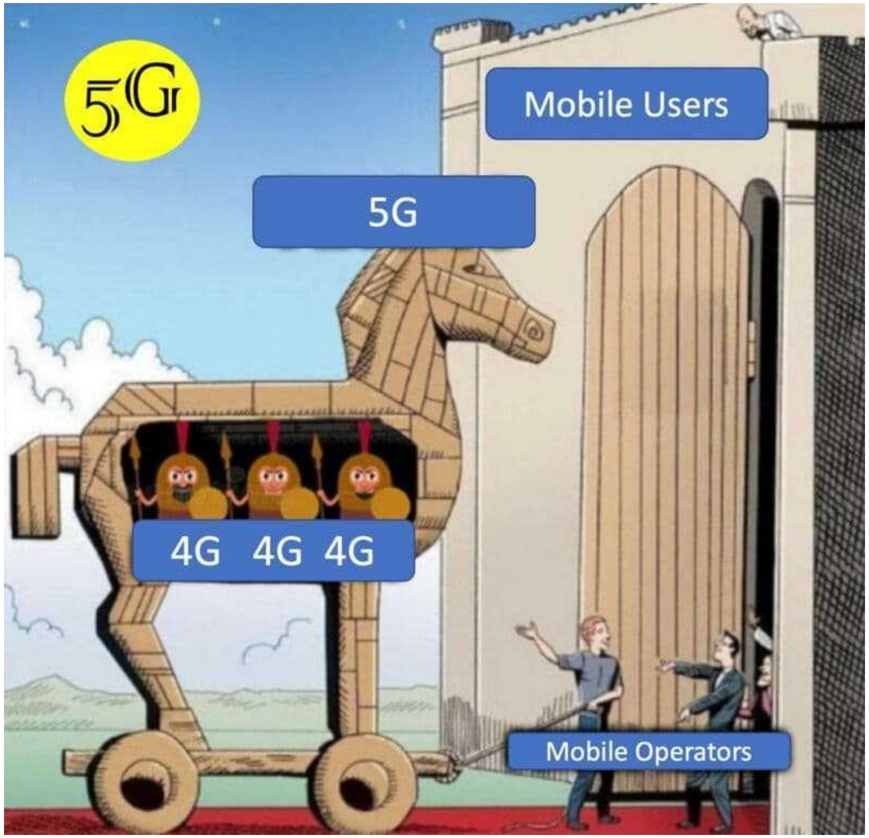
✔ Fully exploit features provided by 5GC

✘ Requires heavy infrastructure investments

https://networking.umn.edu/research-projects/5g-measurements

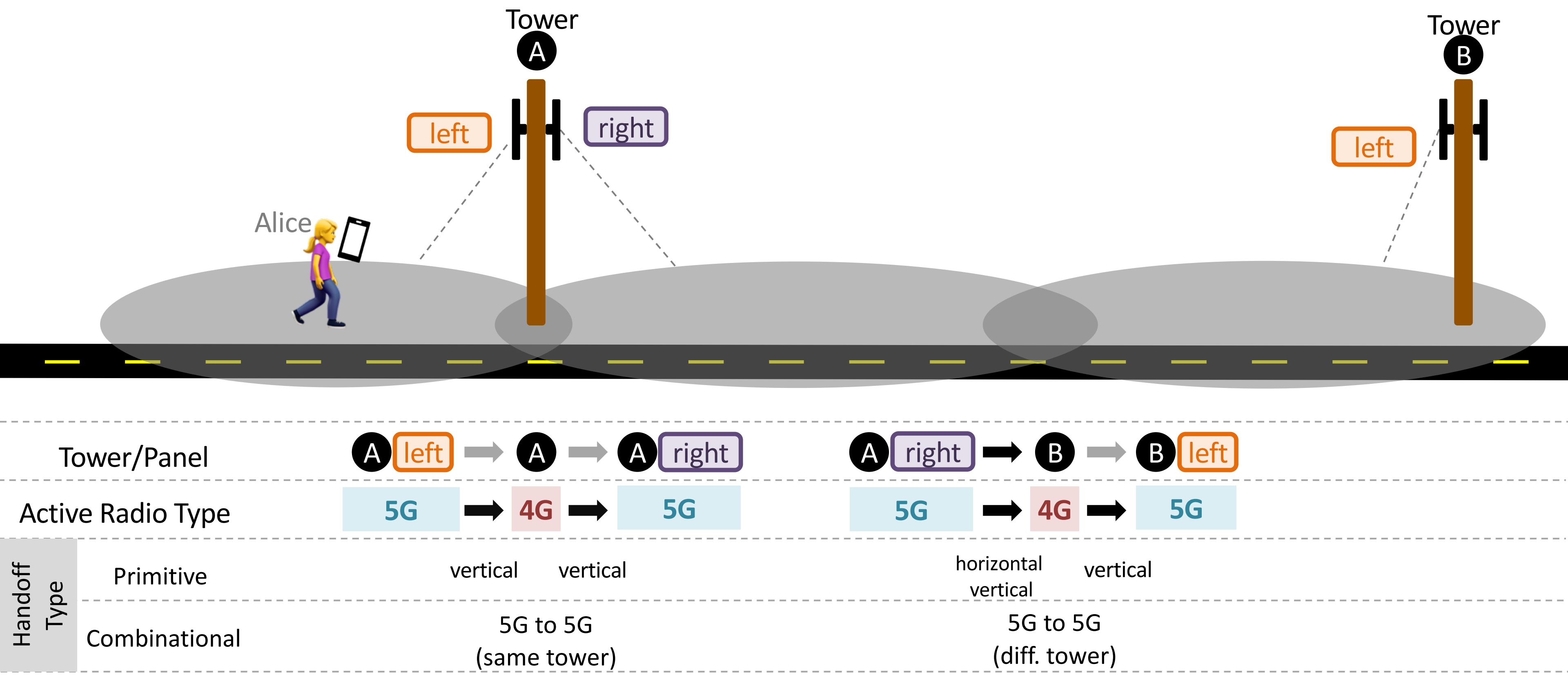
5G Deployment Strategies





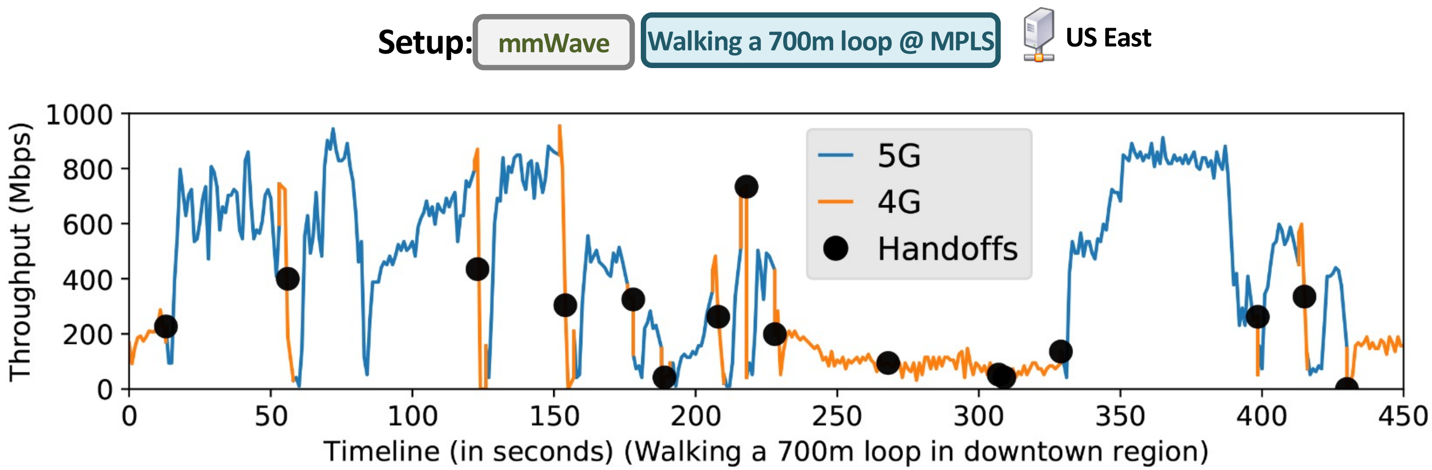
https://networking.umn.edu/research-projects/5g-measurements

Handoffs in NSA 5G



https://networking.umn.edu/research-projects/5g-measurements

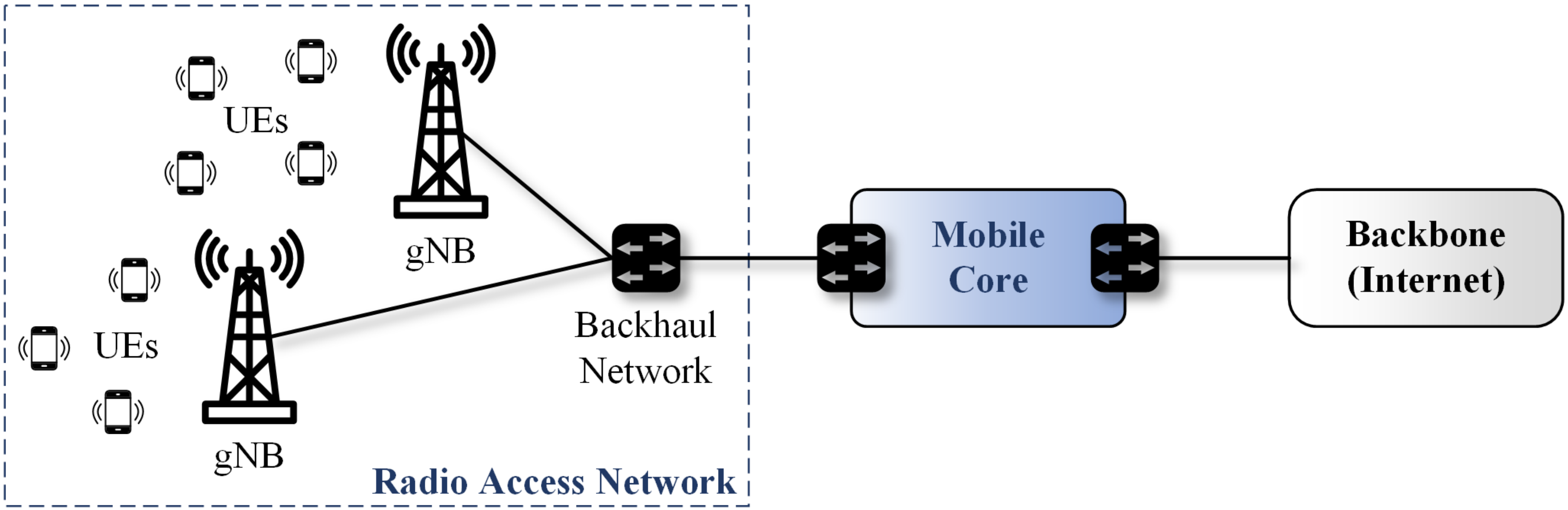
Handoff Analysis



- UE experiences a total of **31 primitive handoffs** **(16 combinational)** within 8 minutes!
- Frequent handoffs causes **frequent throughput fluctuations**

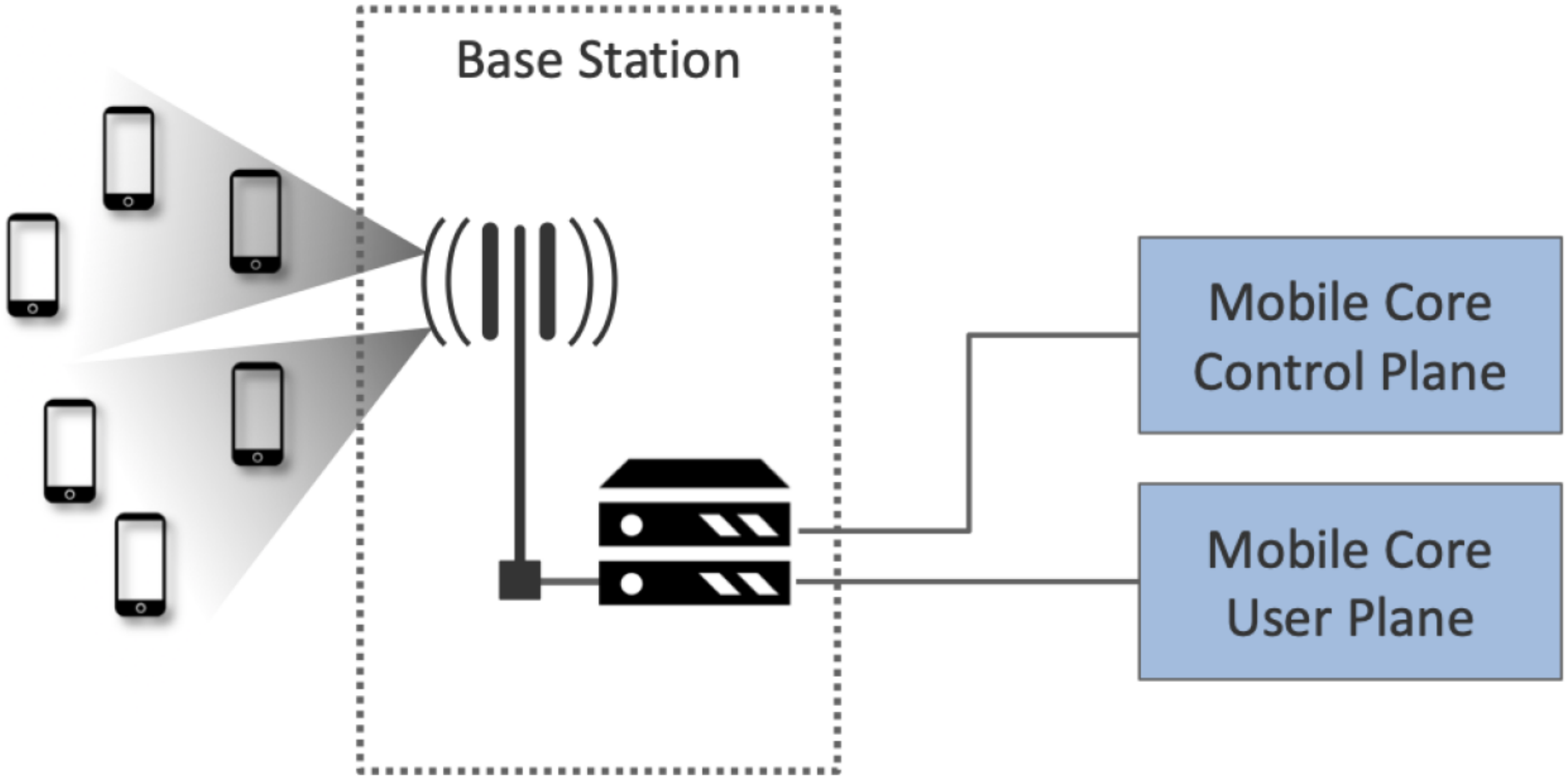
https://networking.umn.edu/research-projects/5g-measurements

5G Network



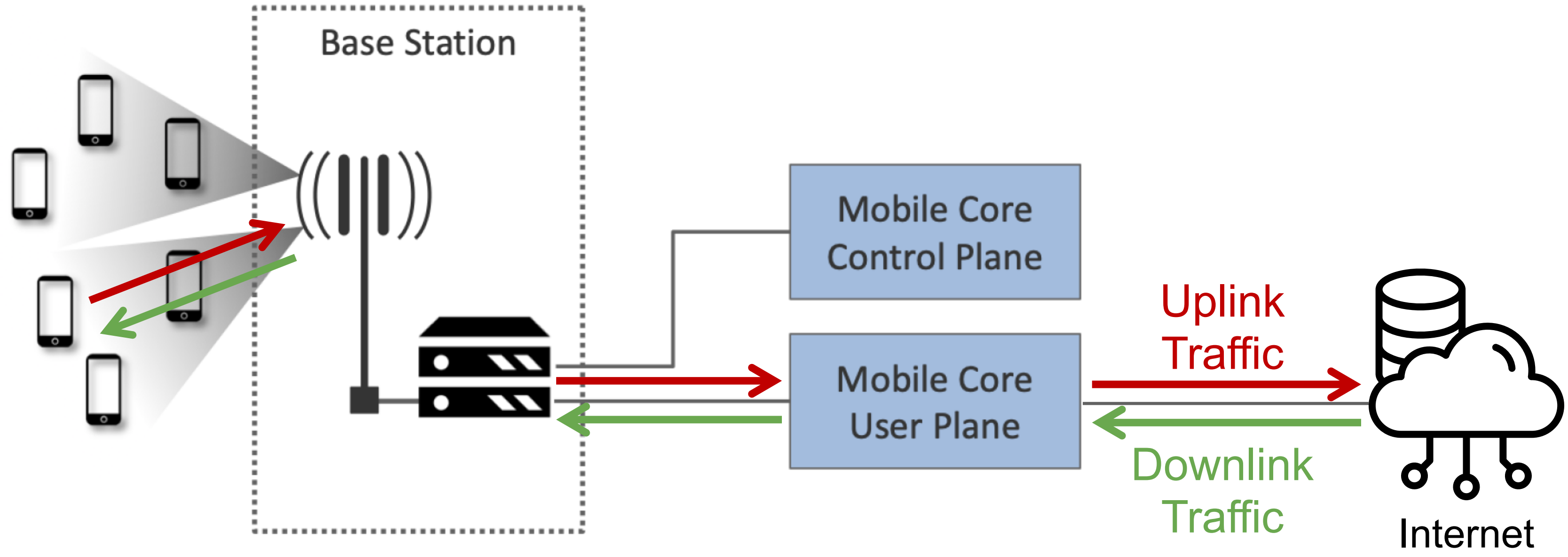
- The 5G network consists of two subsystems.
  - The Mobile Core and the Radio Access Network (RAN)
- The Mobile Core provides and ensures Internet connectivity.
- The RAN corresponds to a distributed set of base stations, named gNodeB (or gNB).

Mobile Core



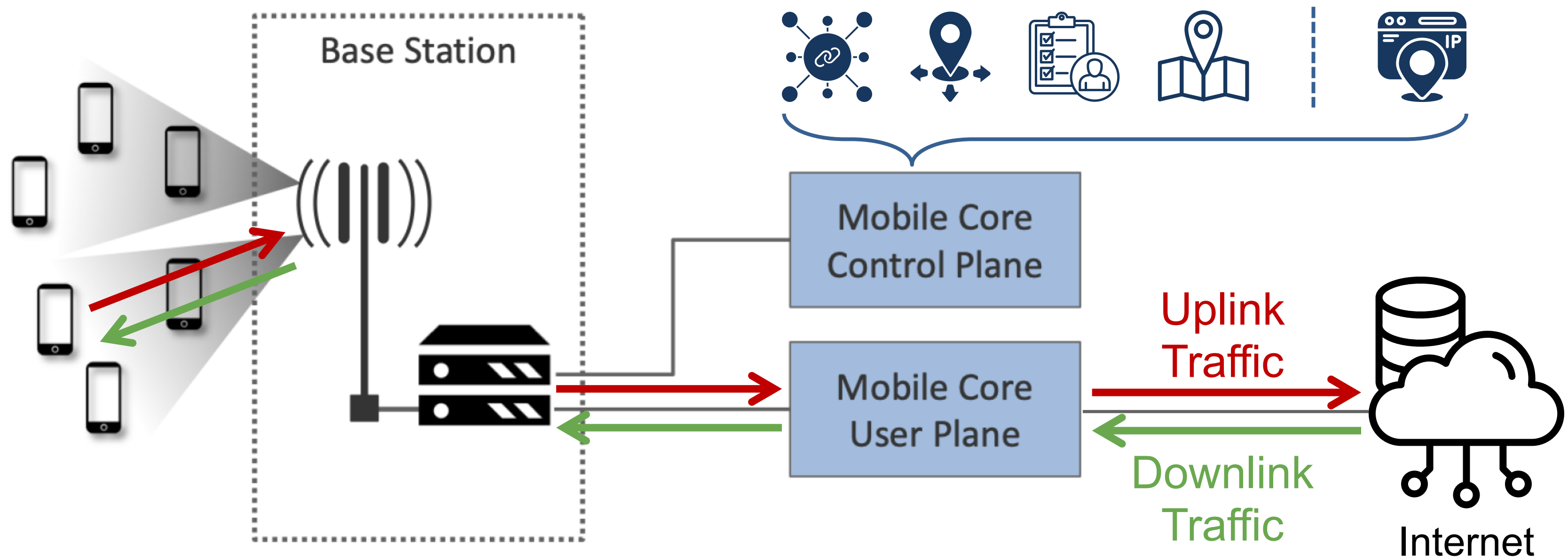
- The Mobile Core is divided into a Control Plane and a User Plane.
  - An architectural feature known as control and user plane separation

Mobile Core: User Plane



- The User Plane forwards traffic between the RAN and the Internet (i.e., IP packet forwarding)
  - It is also responsible for policy enforcement, lawful intercept, traffic usage measurement, and QoS policing

Mobile Core: Control Plane

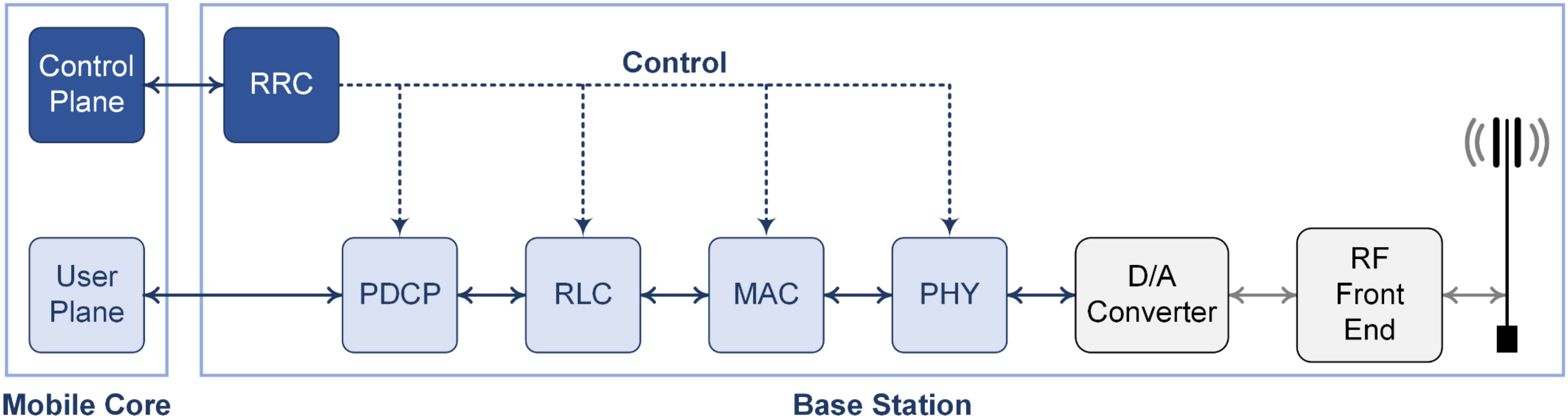


- The Control Plane contains the Access and Mobility Management Function (AMF) and the Session Management Function (SMF)
  - The AMF is responsible for connection and reachability management, mobility management, access authorization, and location services.
  - The SMF manages each UE session, such as IP address allocation.

Radio Access Network (RAN)

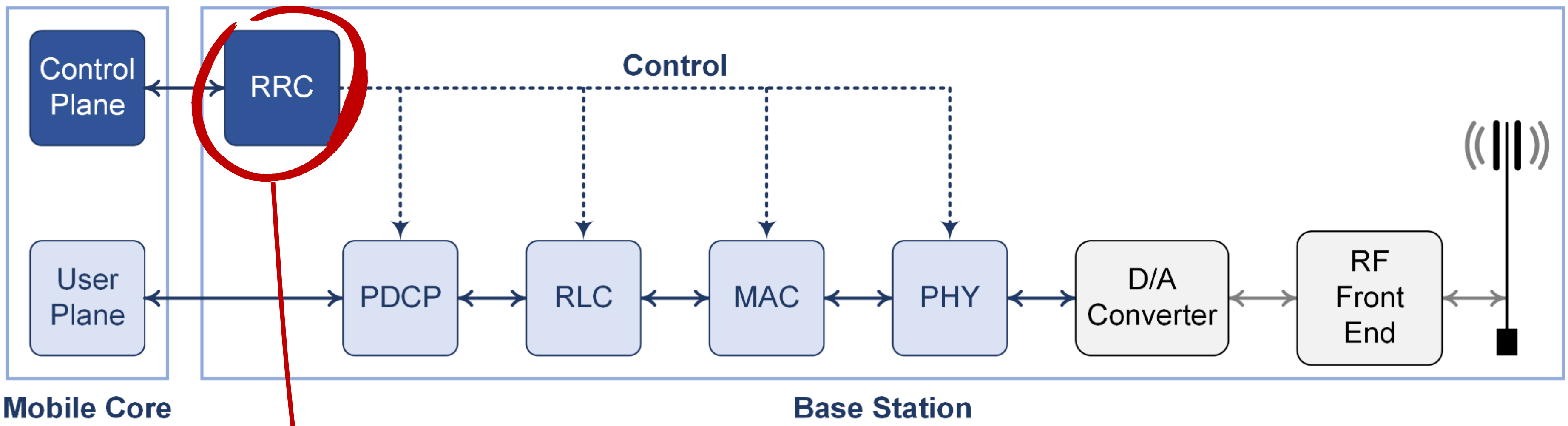
- The main function of the RAN is to transfer packets between the Mobile Core and a set of UEs.
  - Deeply involved in the management and scheduling of radio spectrum

RAN Processing Pipeline (Protocol Stack)



- The packet processing pipeline integrated in 5G base stations
  - Specified by the 3GPP standard
  - Including both user and control plane components
- It can also be viewed as the 5G protocol stack

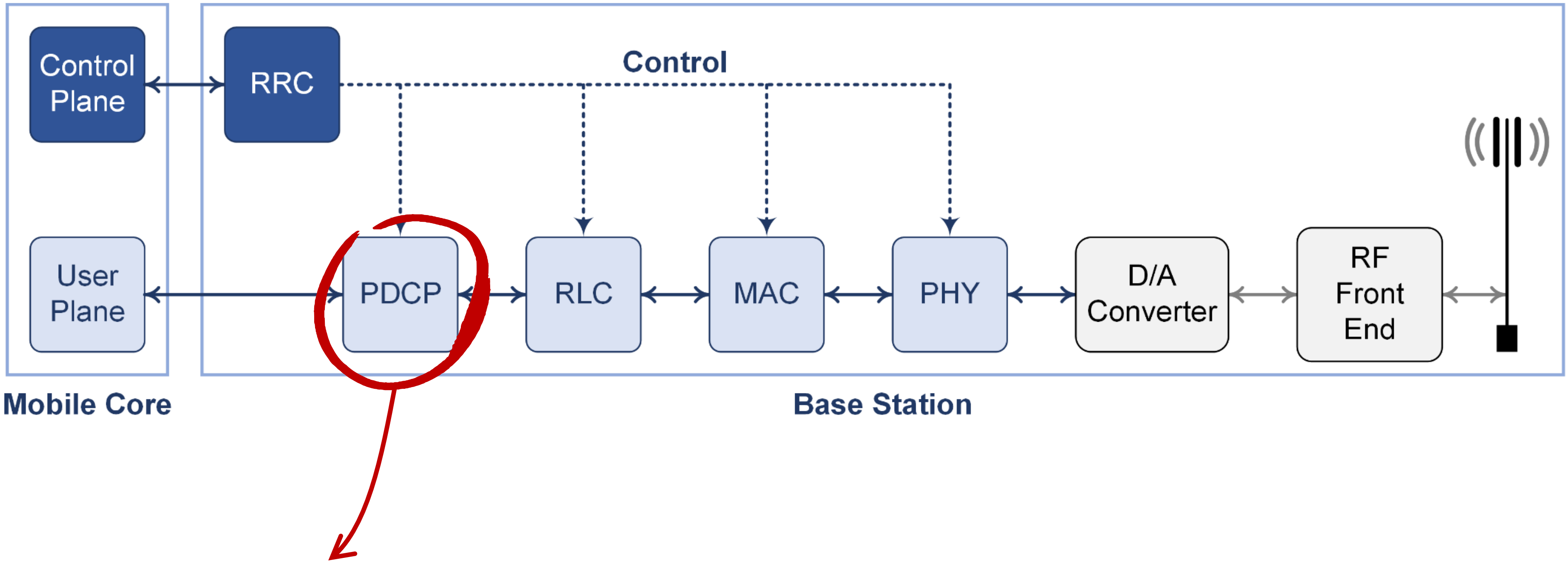
RAN Processing Pipeline: RRC



Radio Resource Control (RRC) layer

- This layer is responsible for the establishment, configuration, maintenance, and release of radio bearers (logical channels between the base station and the UE).

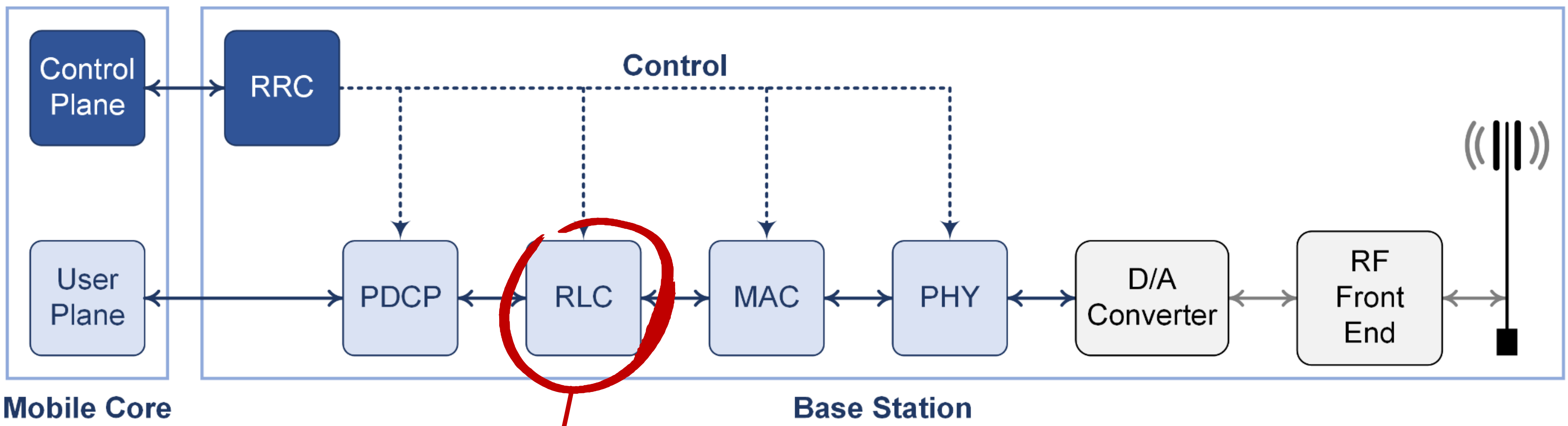
RAN Processing Pipeline: PDCP



Packet Data Convergence Protocol (PDCP) layer

- This layer handles tasks such as header compression and decompression, ciphering and deciphering, and integrity protection and verification.

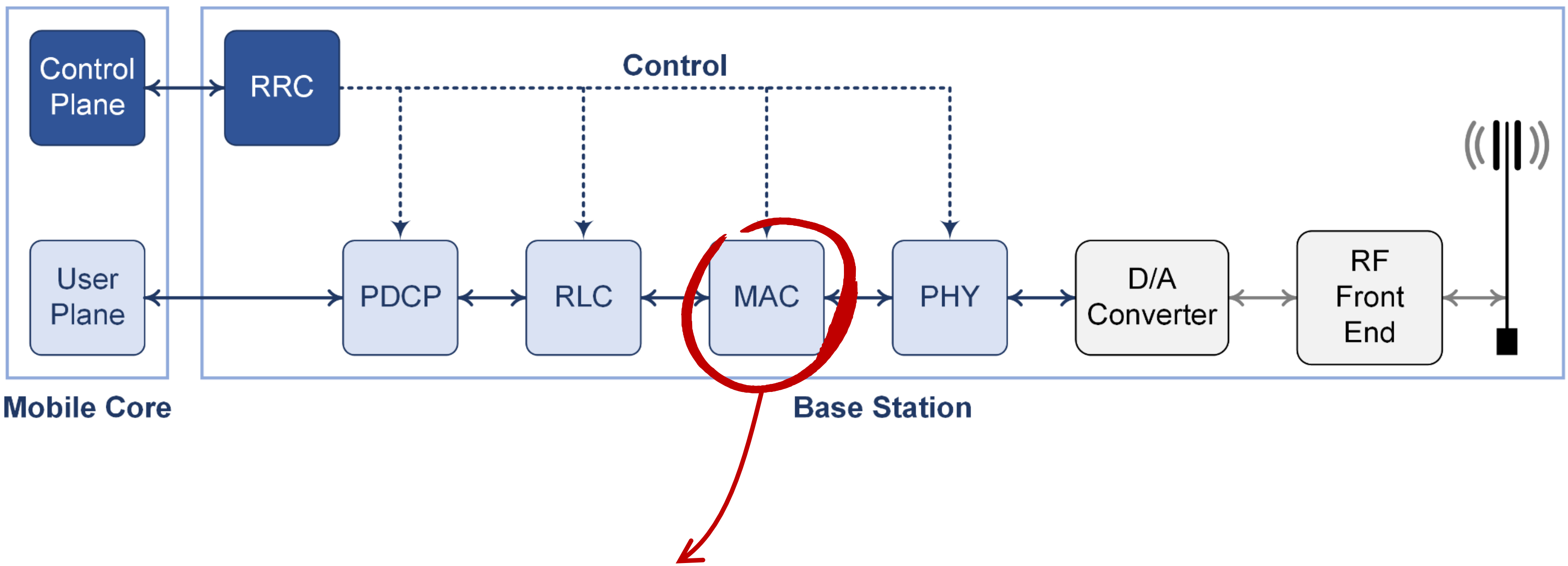
RAN Processing Pipeline: RLC



Radio Link Control (RLC) layer

- This layer is responsible for segmentation and reassembly, as well as reliably transmitting or receiving segments using error correction through automatic repeat request (ARQ).

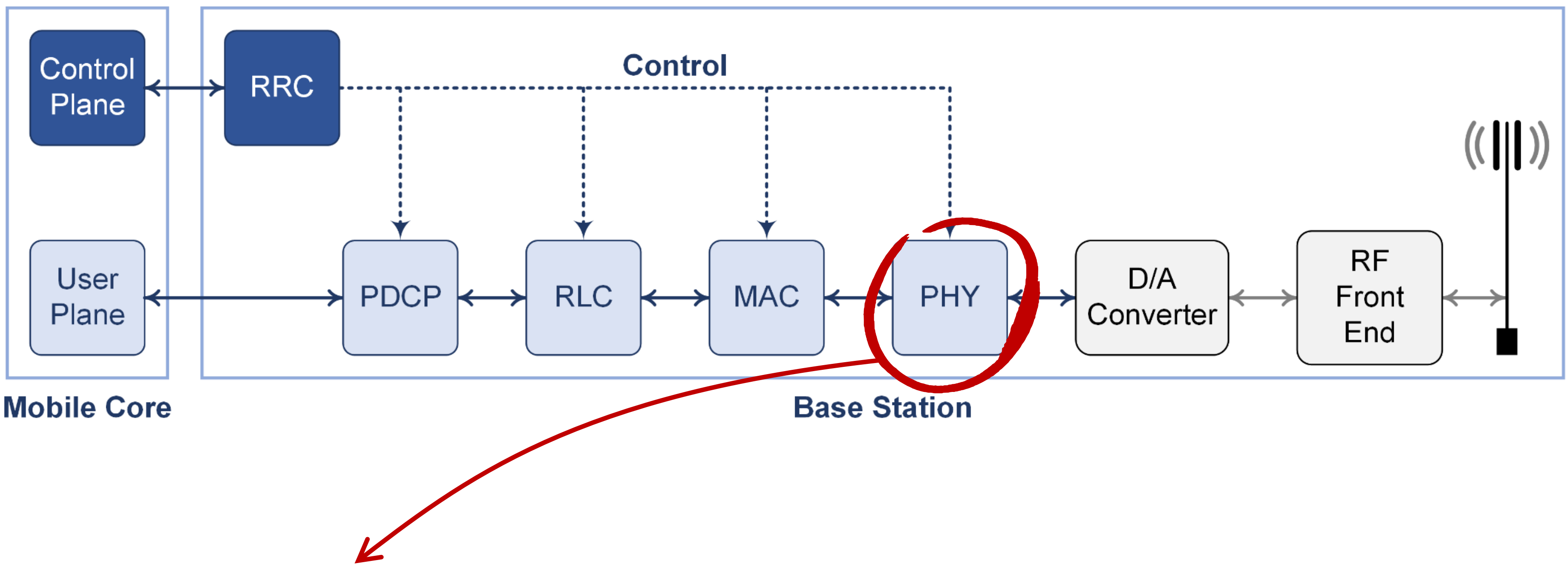
RAN Processing Pipeline: MAC



Media Access Control (MAC) layer

- This layer addresses all real-time scheduling regarding physical resource allocation.

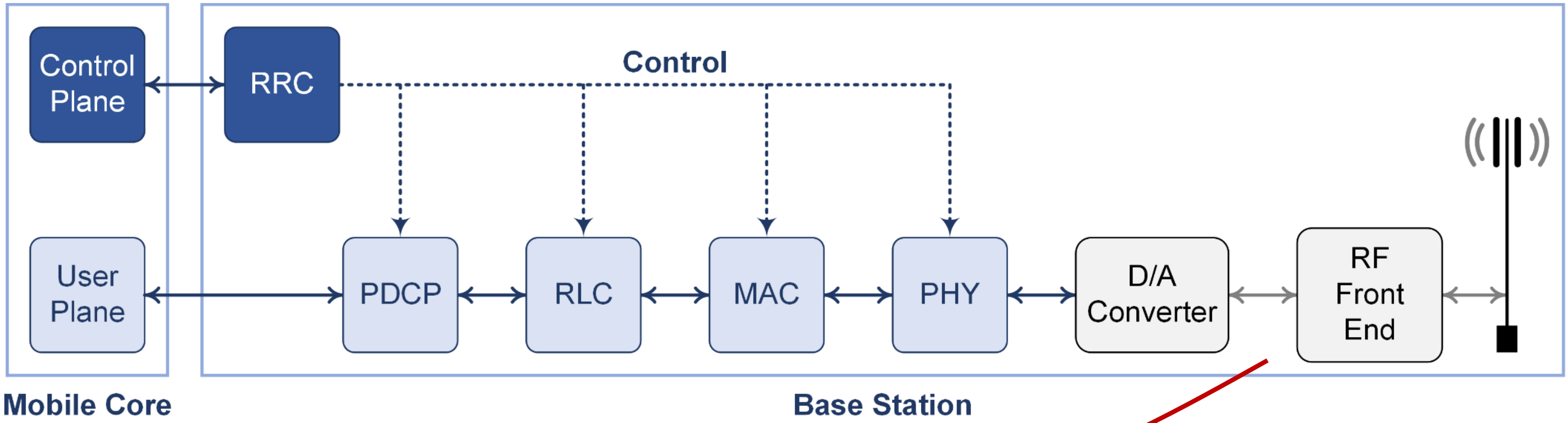
RAN Processing Pipeline: PHY



Physical (PHY) layer

- This layer, including the upper and lower PHY layers, manages (de)coding and (de)modulation.

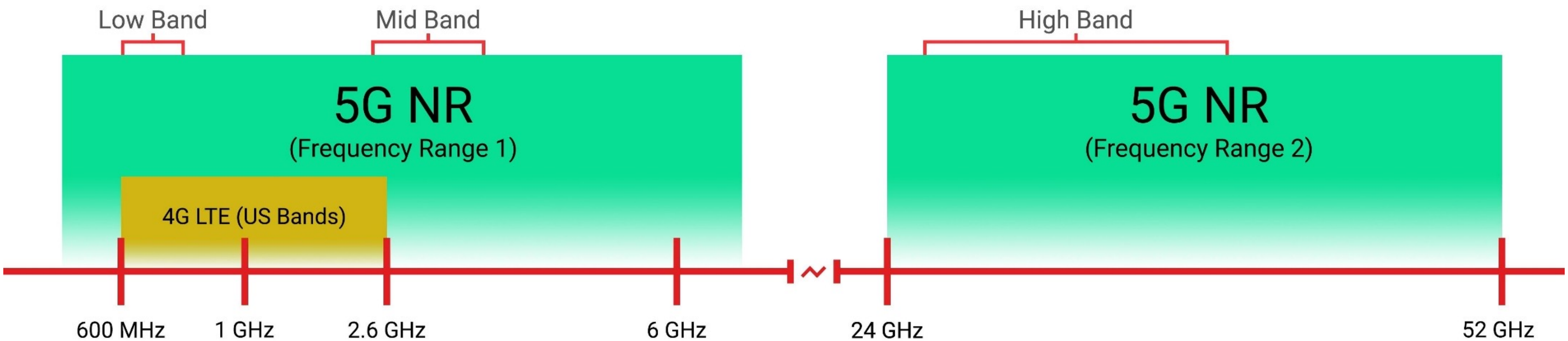
RAN Processing Pipeline: Radio Head



Radio head (RH)

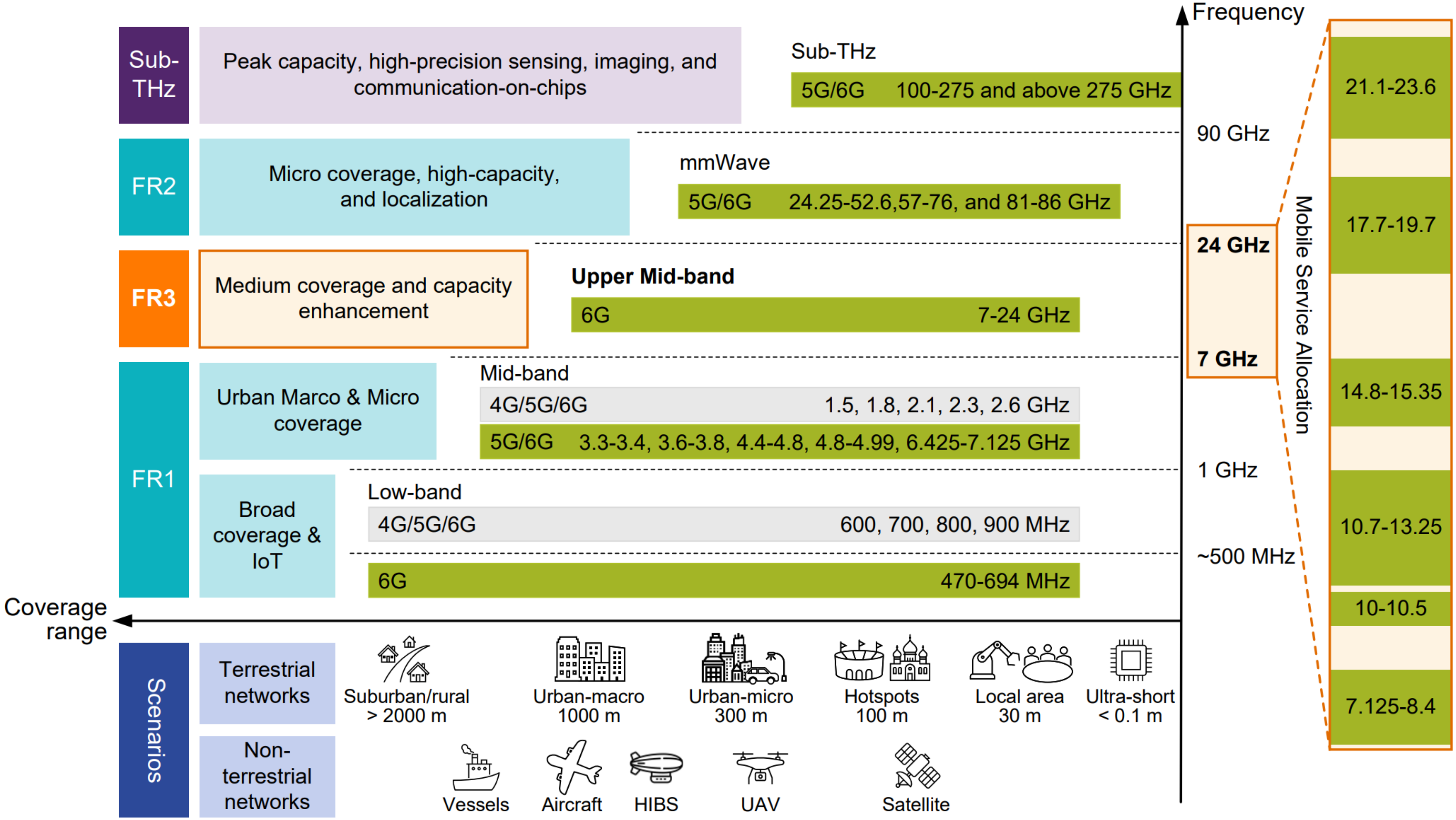
- The RH converts Radio Frequency (RF) signals into digital data and vice versa.

Frequency Bands



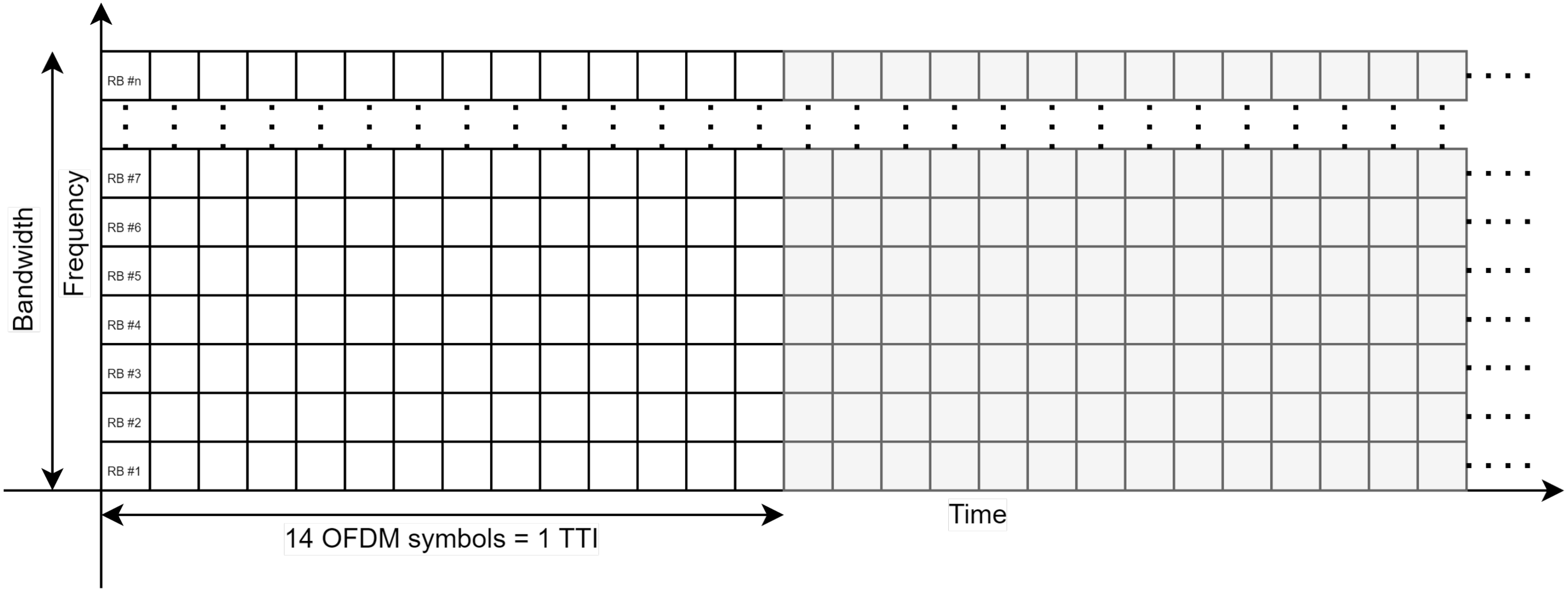
Credit: Dallas Thomas/Gadget Hacks

Frequency Bands



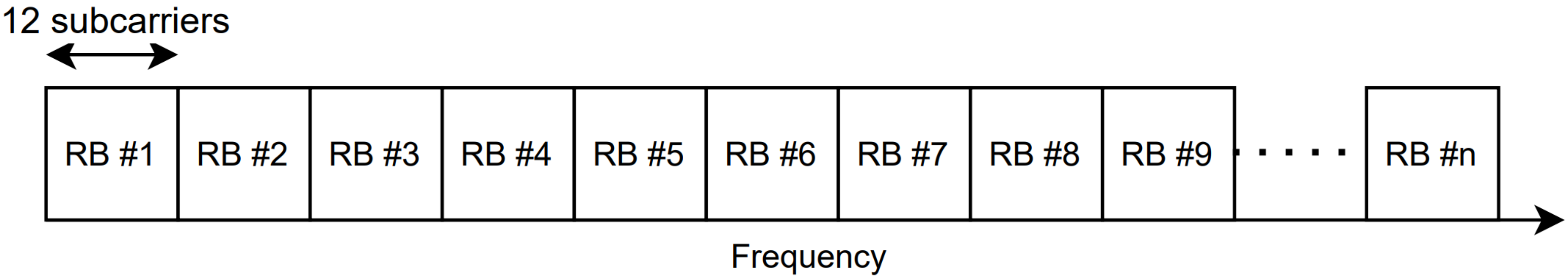
Credit: 6G Wireless Communications in 7-24 GHz Band: Opportunities, Techniques, and Challenges

Scheduling



- Centralized scheduling
  - The base station manages physical resource allocation to UEs
- OFDM modulation
  - 14 OFDM symbols = Time transmission interval (TTI) (or time slot)

Scheduling



Numerology (μ) table

μ	SCS [kHz]	T_{slot} [ms]	FR1	FR2
0	15	1	✓	×
1	30	0.5	✓	×
2	60	0.25	✓	✓
3	120	0.125	×	✓
4	240	0.0625	×	✓
5	480	0.03125	×	✓
6	960	0.015625	×	✓

- Subcarrier spacing
  - $\text{SCS} = 15\ \text{kHz} \cdot 2^{\mu}$
- Slot duration
  - $T_{slot} = 14 \cdot \left(\frac{1}{\text{SCS}} + \text{CP}\right)$

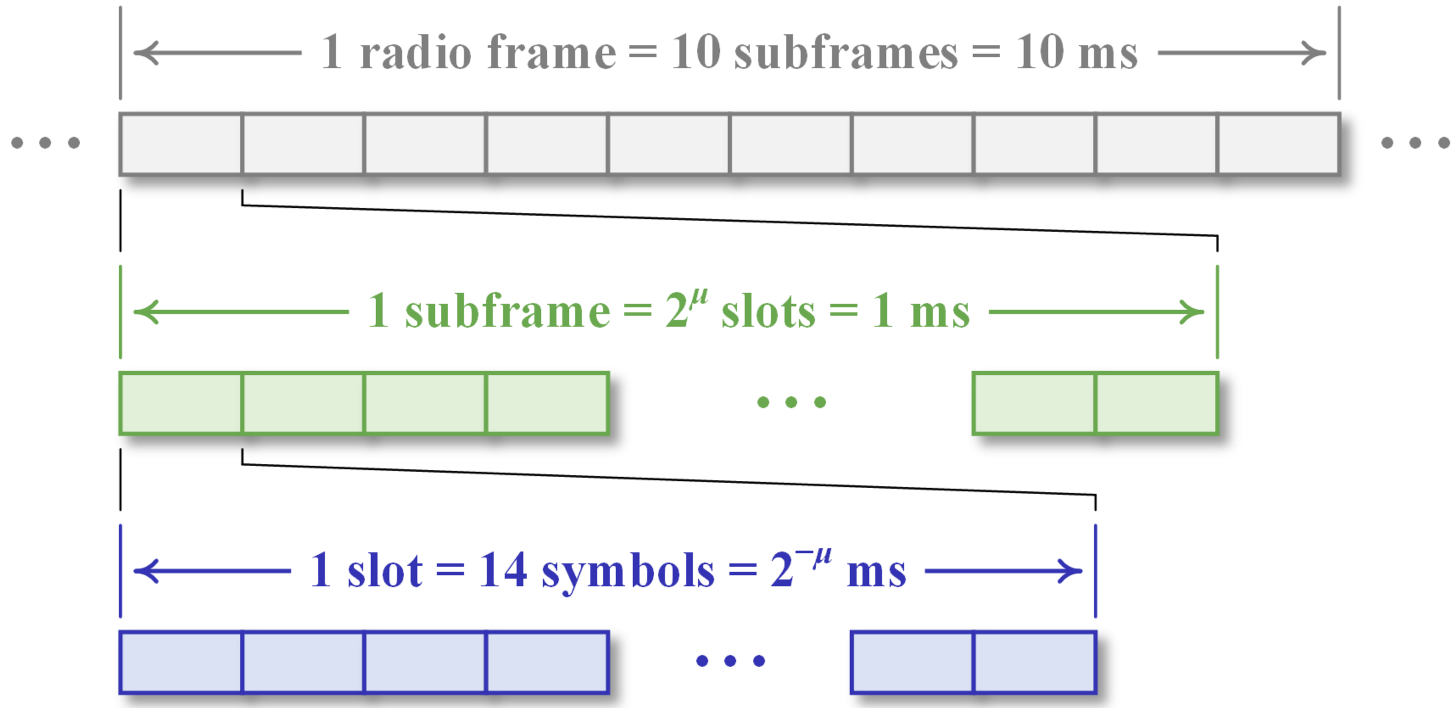
Scheduling

MCS Index I_{MCS}	Modulation Order Q_m	Target code Rate x [1024] R	Spectral efficiency
0	2	120	0.2344
1	2	193	0.377
2	2	308	0.6016
3	2	449	0.877
4	2	602	1.1758
5	4	378	1.4766
6	4	434	1.6953
7	4	490	1.9141
8	4	553	2.1602
9	4	616	2.4063
10	4	658	2.5703
11	6	466	2.7305
12	6	517	3.0293
13	6	567	3.3223

MCS Index I_{MCS}	Modulation Order Q_m	Target code Rate x [1024] R	Spectral efficiency
14	6	616	3.6094
15	6	666	3.9023
16	6	719	4.2129
17	6	772	4.5234
18	6	822	4.8164
19	6	873	5.1152
20	8	682.5	5.332
21	8	711	5.5547
22	8	754	5.8906
23	8	797	6.2266
24	8	841	6.5703
25	8	885	6.9141
26	8	916.5	7.1602
27	8	948	7.4063

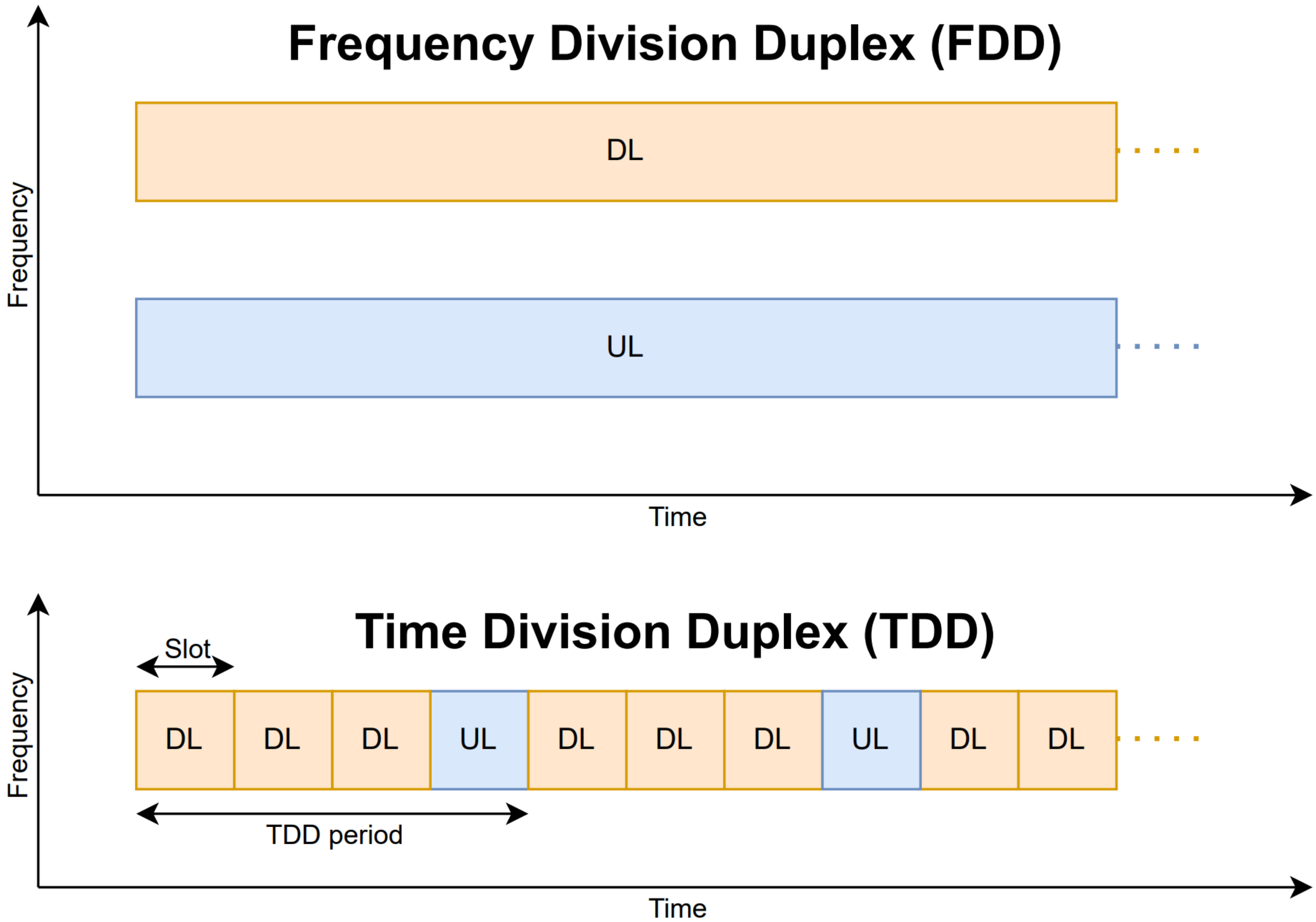
Modulation and Coding Scheme (MCS) Table 2

5G Frame Structure



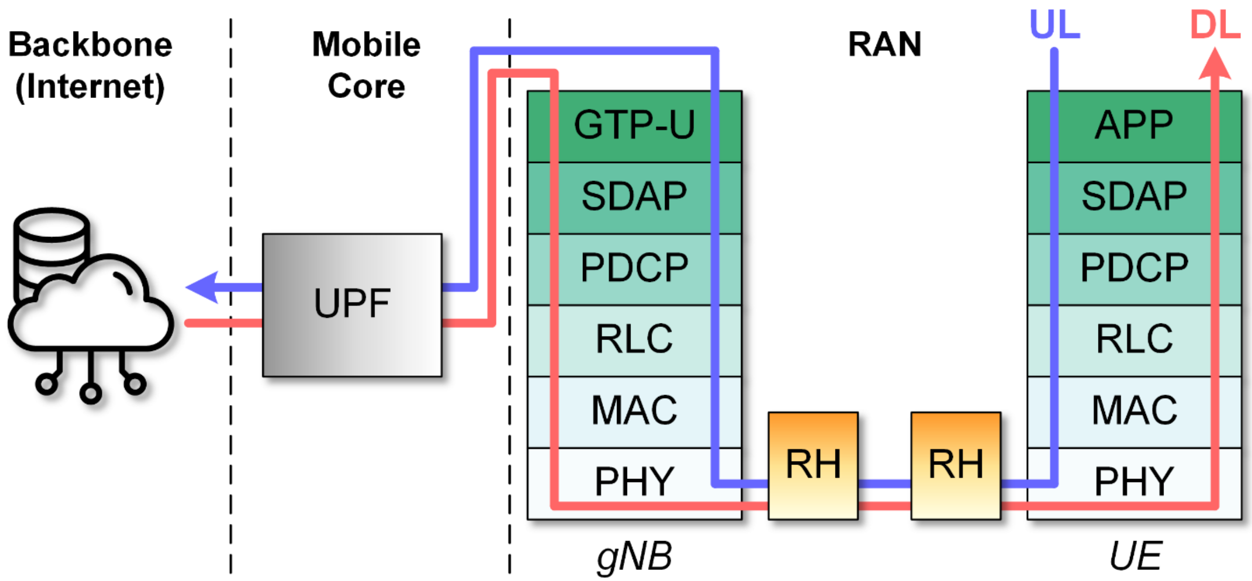
- 5G introduces a novel frame structure, which is designed to be more flexible than its predecessors.
- At the heart of this flexibility is the concept of numerology, labelled by μ.

Duplex Modes



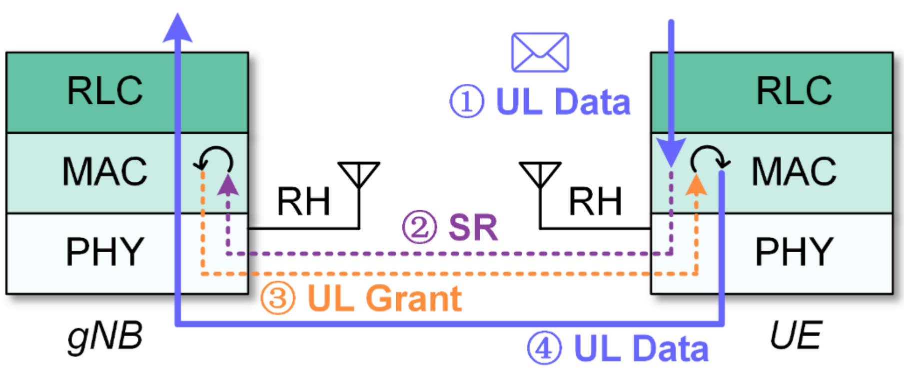
Downlink Scheduling & Uplink Scheduling

- Downlink scheduling
  - The gNB has full knowledge on its queue and buffer
  - The gNB needs Channel Quality Indicators (CQI) from UEs
- Uplink scheduling
  - The gNB has no knowledge on UEs' queues and buffers
  - The gNB knows the SNR of UEs



Grant-Based Access & Grant-Free Access

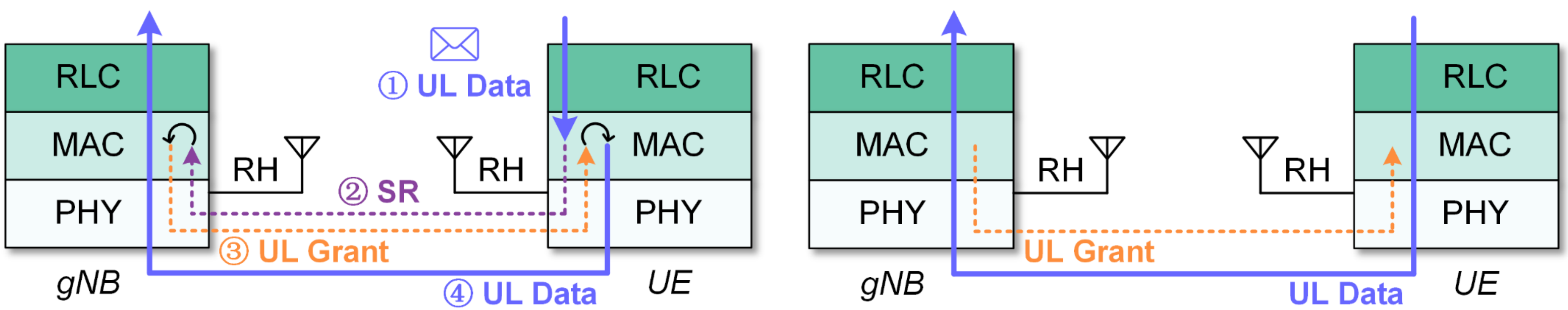
- Grant-based access
  - A UE first sends a scheduling request to the gNB
  - The gNB schedules and sends an uplink grant to the UE
  - The UE transmits uplink data to the gNB



Grant-based access

Grant-Based Access & Grant-Free Access

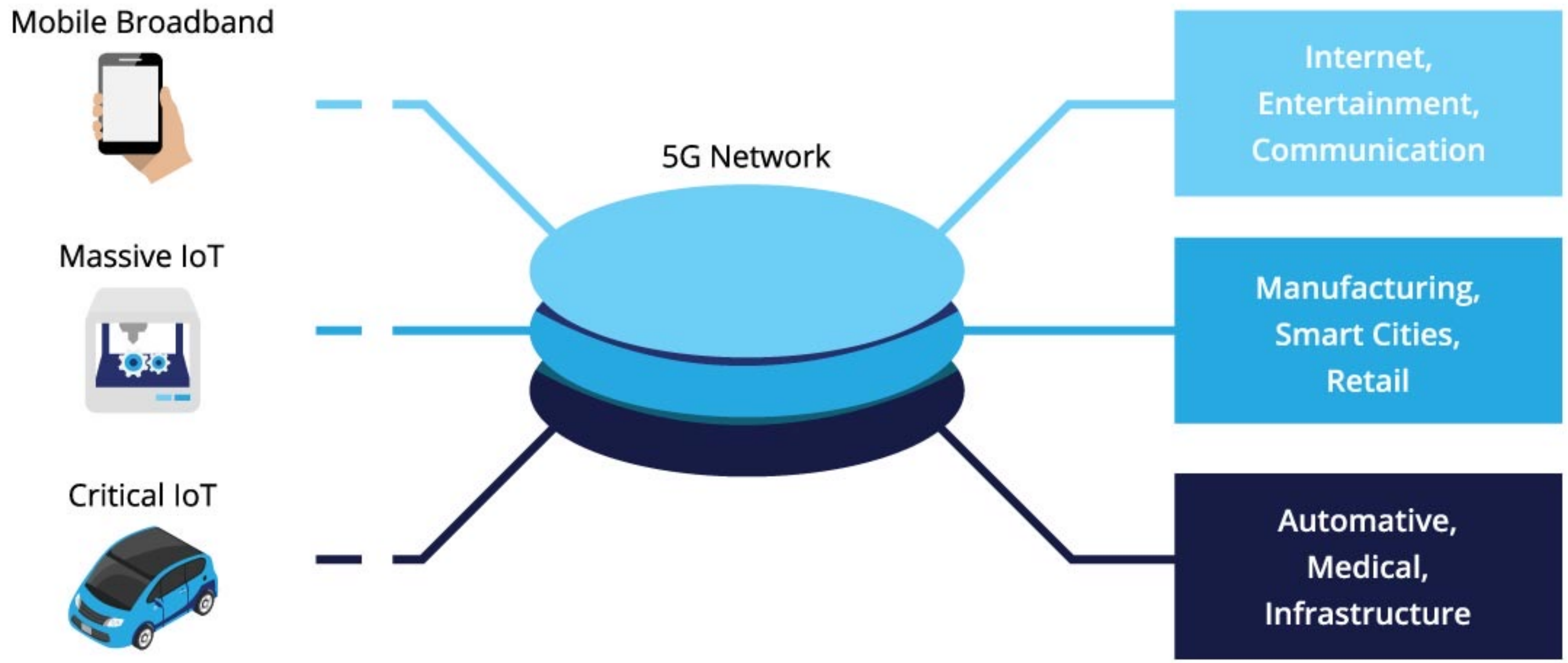
- Grant-based access
  - A UE first sends a scheduling request to the gNB
  - The gNB schedules and sends an uplink grant to the UE
  - The UE transmits uplink data to the gNB
- Grant-free access
  - The gNB always allocates a fixed number of resources to the UE
  - The UE can directly transmit uplink data to the gNB



Grant-based access

Grant-free access

5G Network Slicing



- With its high capacity and low latency, 5G paves the way for new business models across various vertical markets

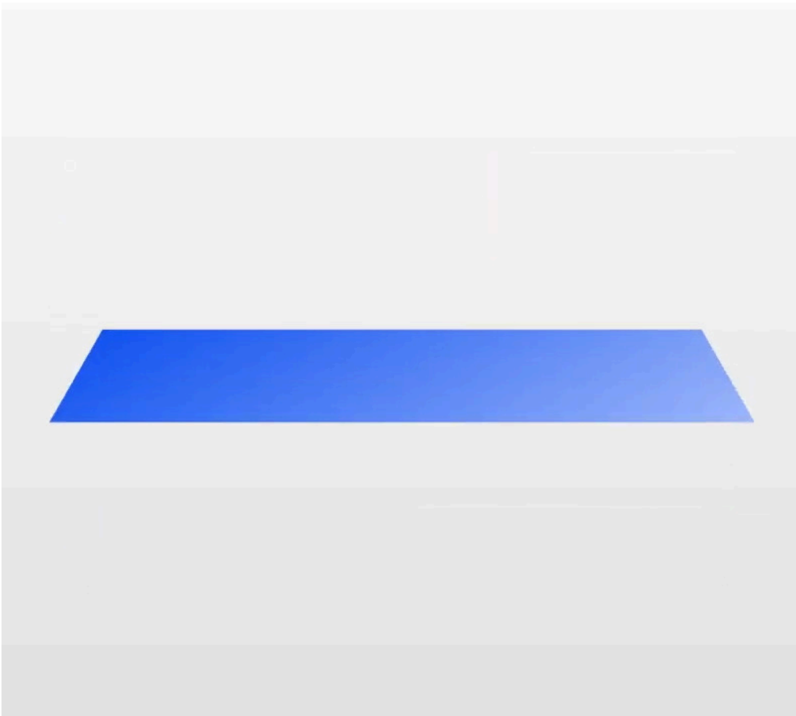
Credit: https://brunch.co.kr/@b047a588c11b462/90

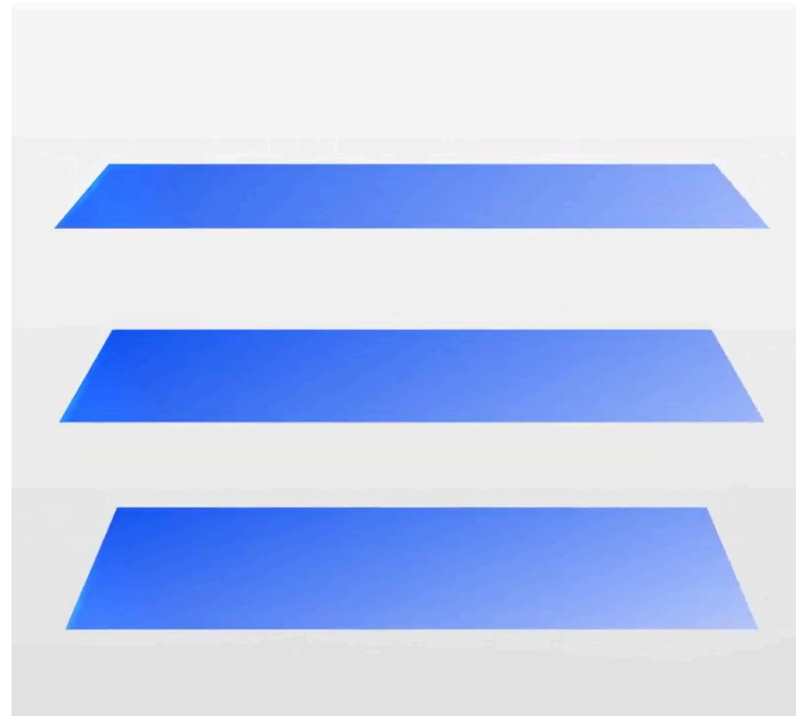
5G Network Slicing

Traffic Class	SST	Slice Type	Acronym
eMBB	1	eMBB	Enhanced Mobile Broadband
URLLC	2	URLLC	Ultra-Reliable Low-Latency Communication
mMTC	3	mIoT	Massive Internet of Things
	4	V2X	Vehicle-to-Everything
	5	HMTC	High-Performance Machine-Type Communication

- With its high capacity and low latency, 5G paves the way for new business models across various vertical markets
- A 5G network is usually shared among many users and may not always be able to guarantee different requirements

5G Network Slicing





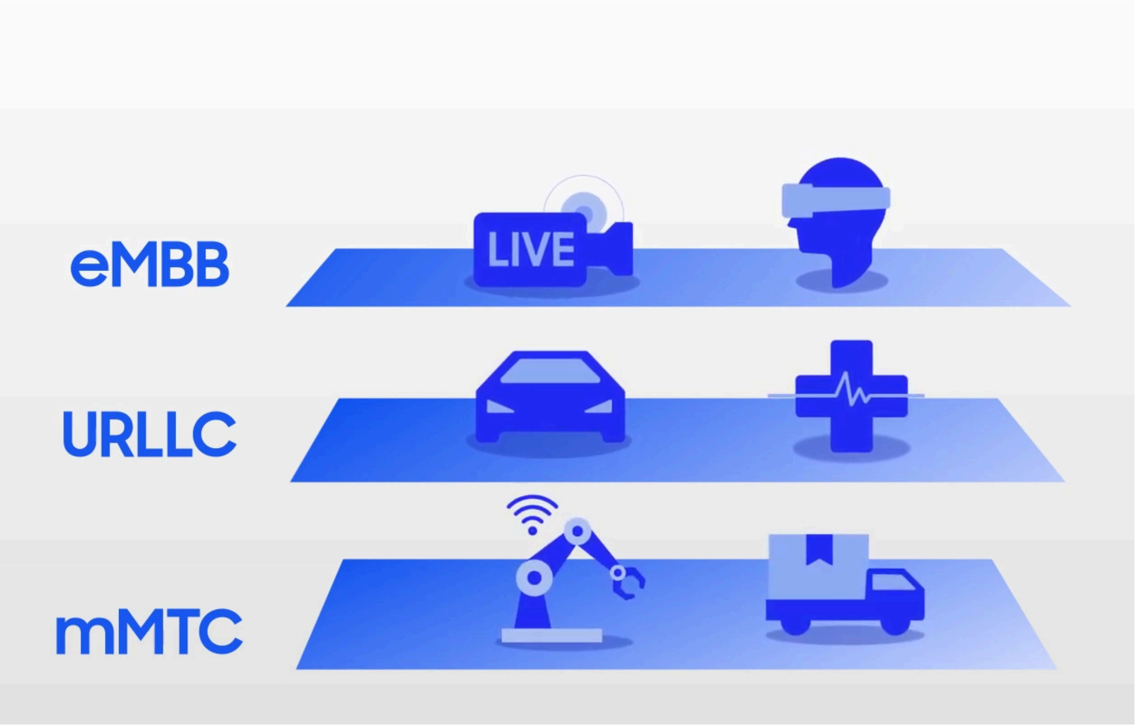
- 5G network slicing is a technique that divides a single physical network into several virtualized slices

Credit: What is network slicing? | https://www.youtube.com/watch?v=kqpo9LCspiI

5G Network Slicing

- 5G network slicing is a technique that divides a single physical network into several virtualized slices
- Each slice can be designed to guarantee diverse service level agreements (SLA) as for throughput, latency, and reliability

5G Network Slicing



- Network slices can be specialized to meet eMBB, URLLC, and mMTC and dedicated for specific services.
  - eMBB: Live broadcasting, VR/AR
  - URLLC: Automotive, health & wellness
  - mMTC: Utilities & logistics

Traditional RAN vs Open RAN

- Traditional RANs focused on providing end-to-end service from a geographical perspective to millions of customers.
  - These networks follow the 3GPP standard.

Credit: 5G Challenge - Traditional RAN vs. O-RAN | https://www.youtube.com/watch?v=RtYwkDYSBFU

Traditional RAN vs Open RAN

- Each operator tends to buy equipment for large markets from a single vendor (e.g., Ericsson and Nokia).
  - It is unlikely to be interoperable with other vendors’ equipment.

Credit: 5G Challenge - Traditional RAN vs. O-RAN | https://www.youtube.com/watch?v=RtYwkDYSBFU

Traditional RAN vs Open RAN

- This end-to-end focus and single vendor solution raised significant barriers to new entrants.
  - Traditional RAN typically relied on specialized hardware.

Credit: 5G Challenge - Traditional RAN vs. O-RAN | https://www.youtube.com/watch?v=RtYwkDYSBFU

Traditional RAN vs **Open RAN**

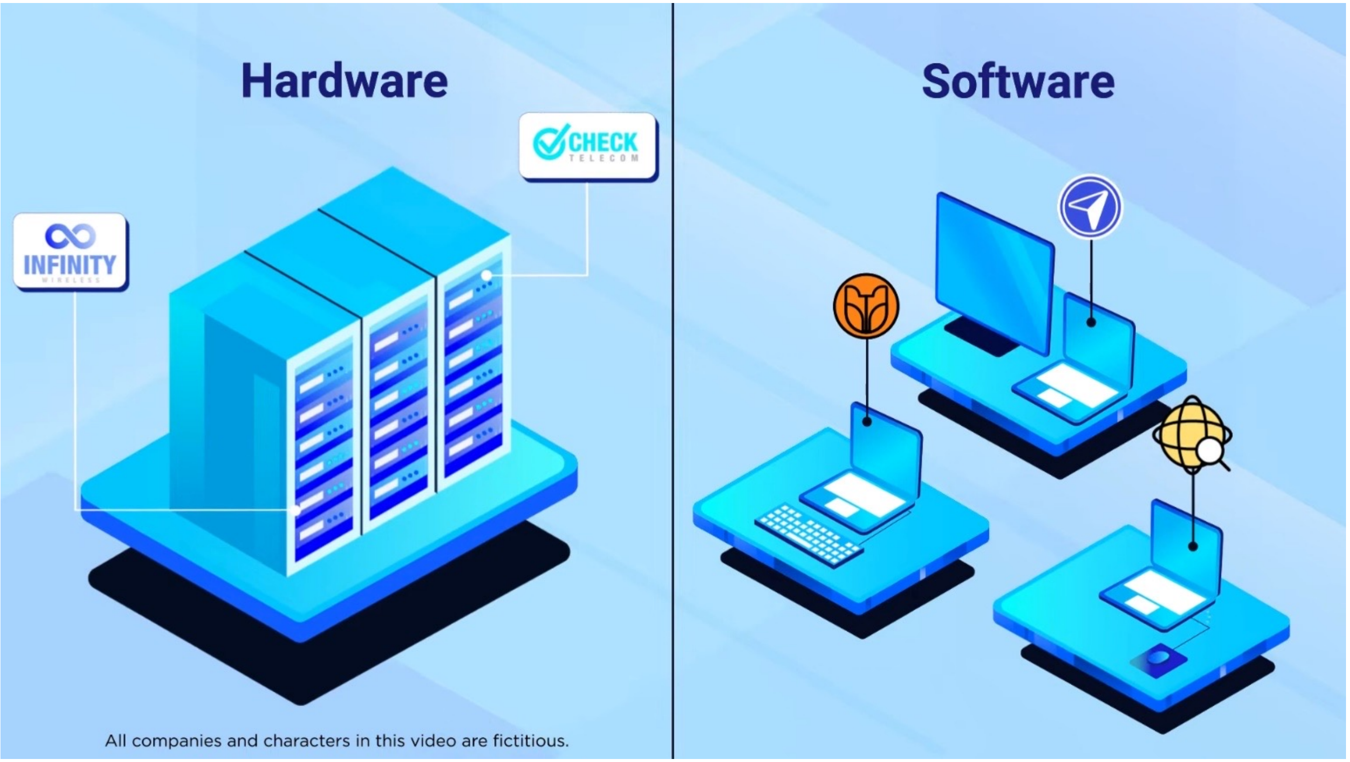
- Open RAN (O-RAN) represents an ongoing shift from closed, proprietary solutions towards open, modular, interoperable, multi-vendor solutions.

Credit: 5G Challenge - Traditional RAN vs. O-RAN | https://www.youtube.com/watch?v=RtYwkDYSBFU

Traditional RAN vs **Open RAN**

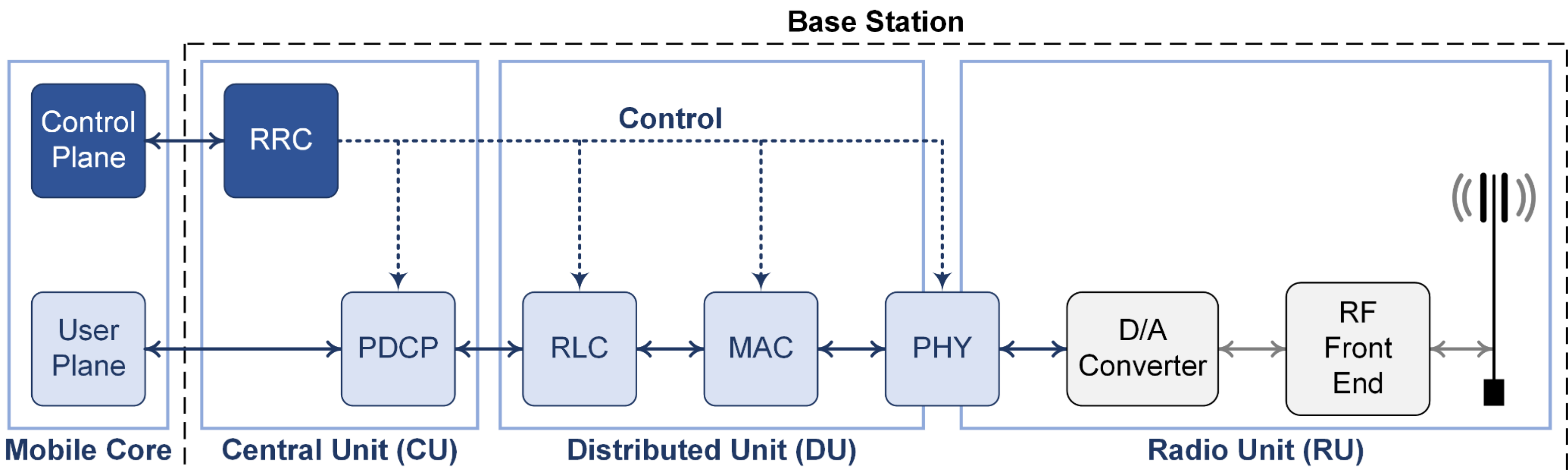
- O-RAN seeks to separate the hardware and software within the RAN segment of the network and to create open interfaces between these segments.

Traditional RAN vs **Open RAN**



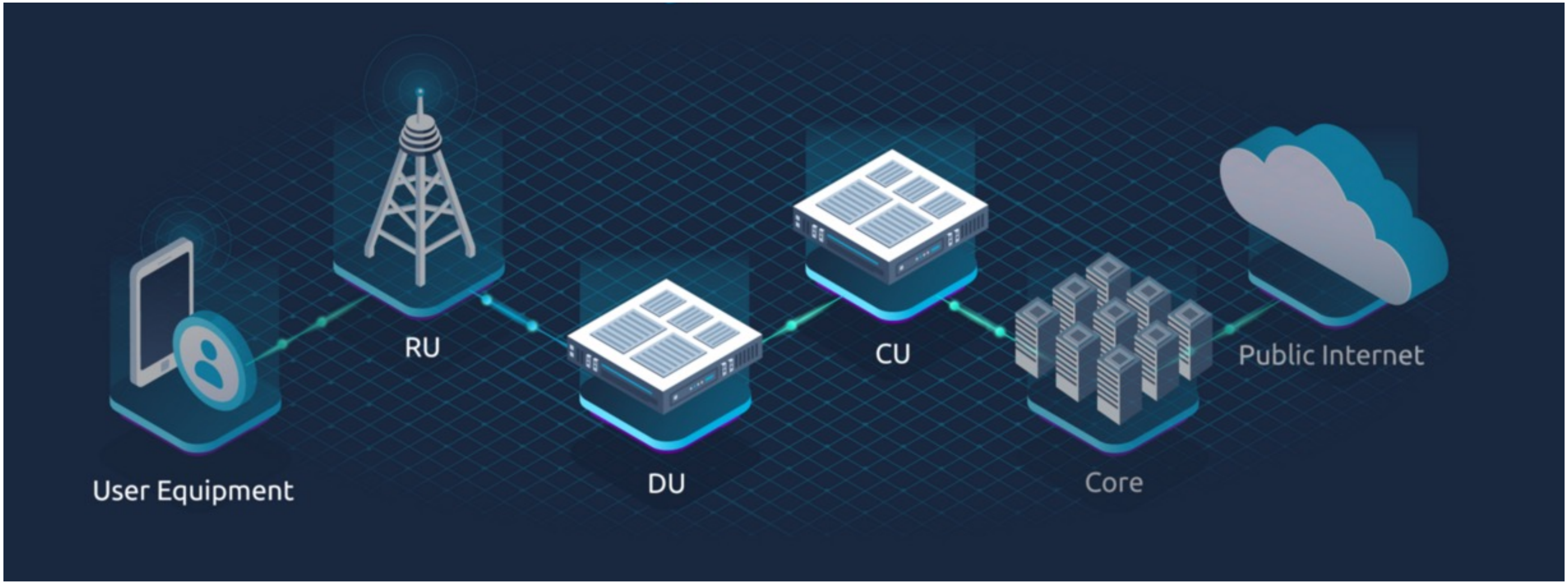
- Allow more competition in building the hardware and software
- Allow multiple vendor components to interoperate
  - Like how keyboards, monitors, and mice can connect to any computer

O-RAN Alliance



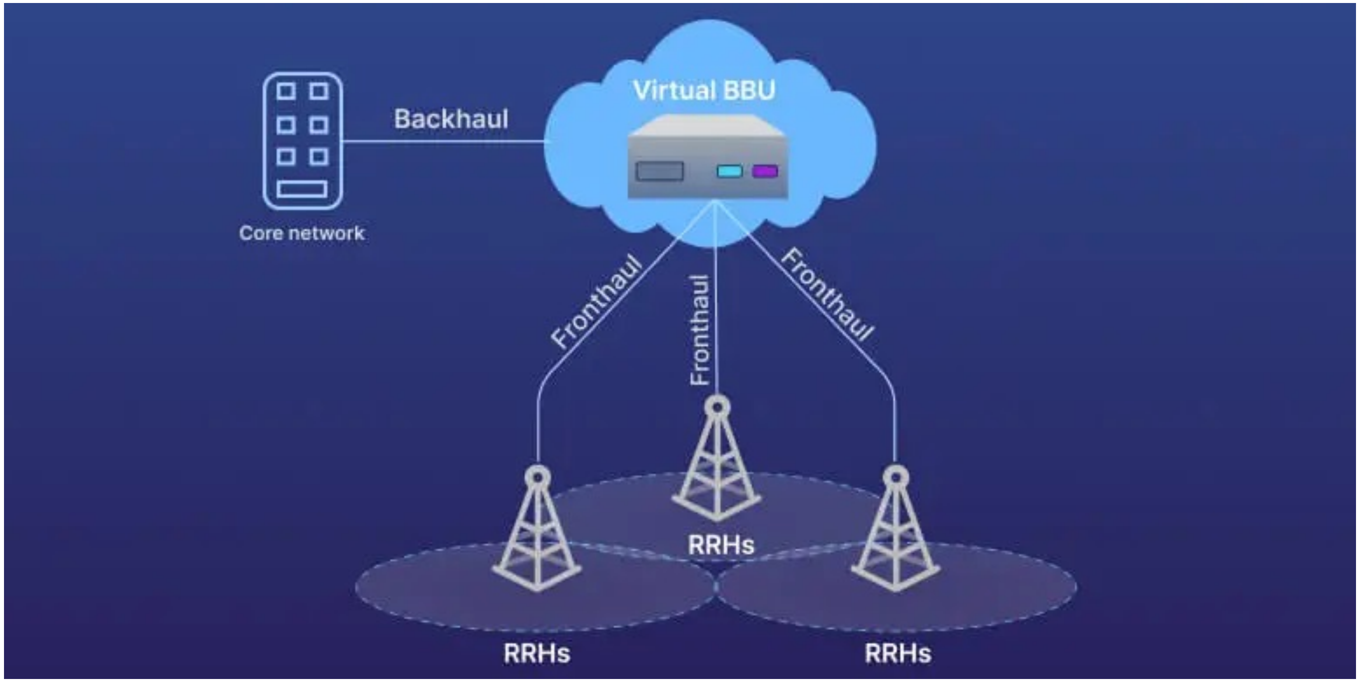
- The O-RAN Alliance defines the specifications for Open RAN.
- It disaggregates the RAN's functionalities into central units (CUs), distributed units (DUs), and radio units (RUs), many of which can be virtualized or containerized.

O-RAN Splitting



- The RAN's functionalities is split across centralized and distributed locations.
  - The CU can be located near the Mobile Core.
  - The DU is physically located at or near the RU.

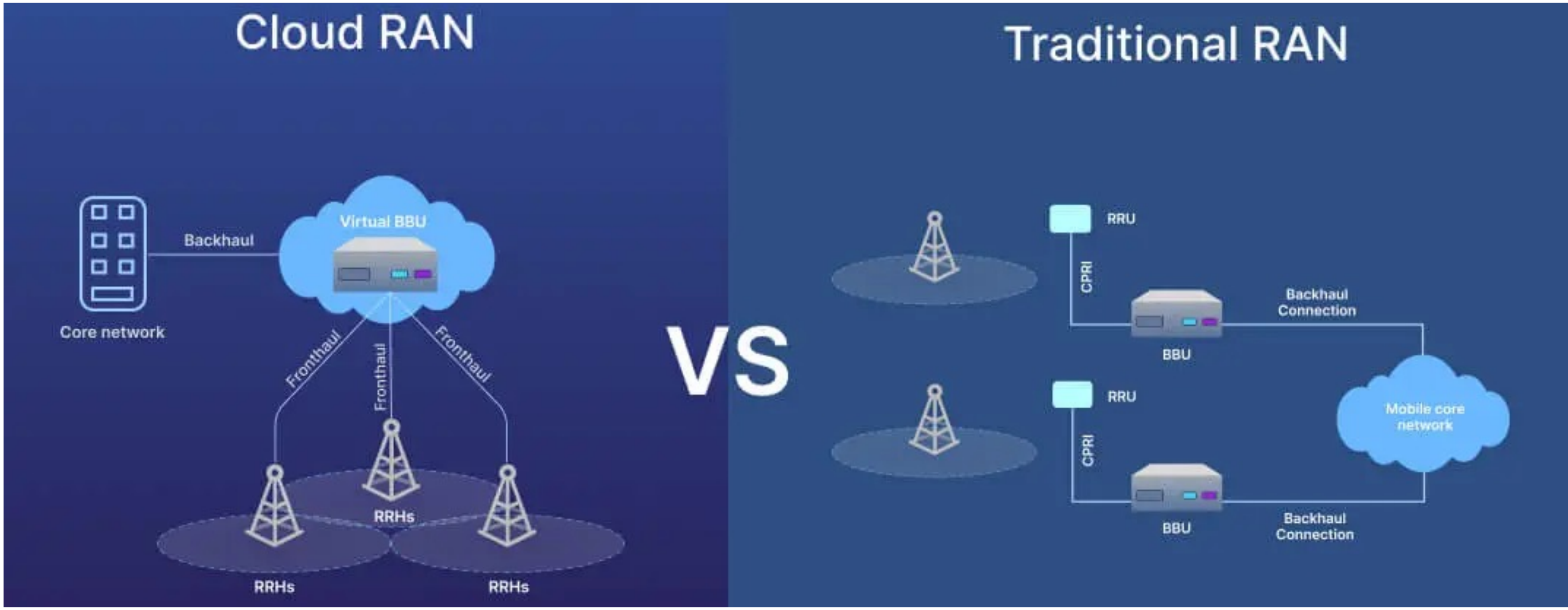
Cloud RAN (C-RAN)



- Cloud RAN operates by centralizing the baseband processing functions of mobile networks into cloud-based environments
  - Baseband processing functions, such as (de)coding and (de)modulation of radio signals, are centralized in a data center.
  - The remote radio heads are distributed across various cell sites.

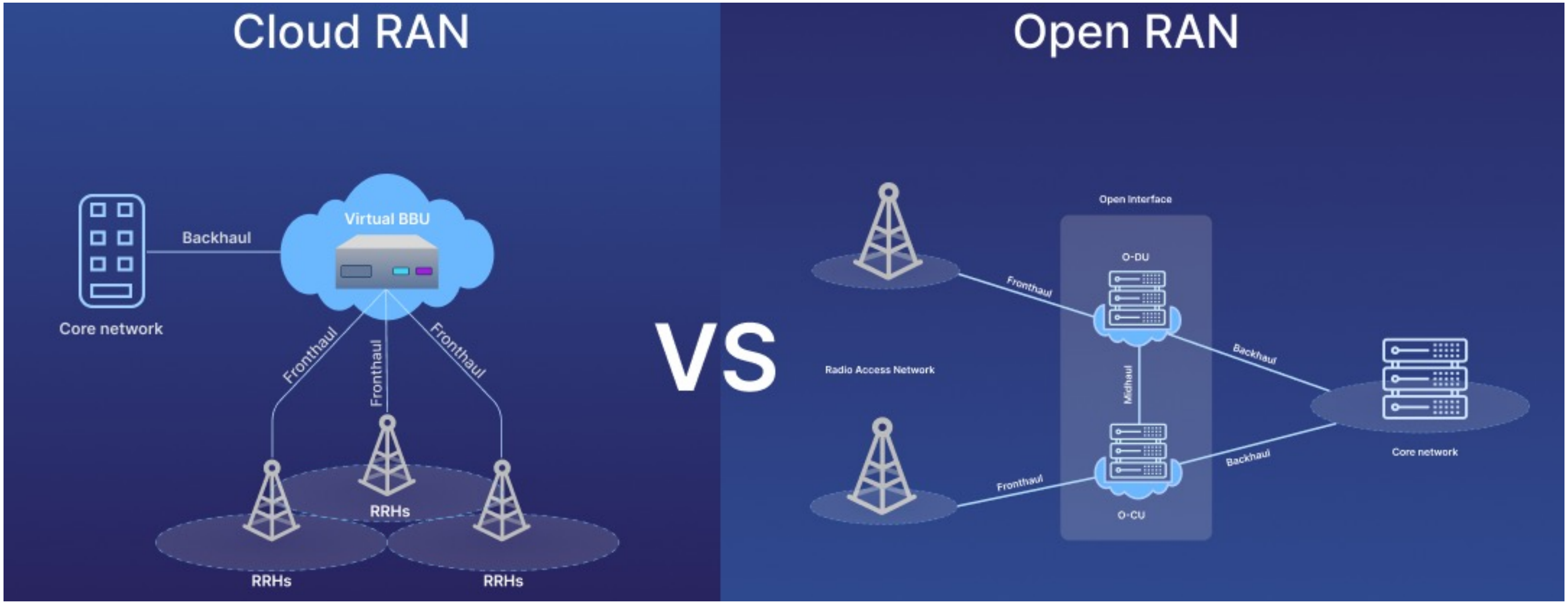
Credit: What Is Cloud RAN & How Does It Work? | https://nybsys.com/what-is-cloud-ran/

C-RAN vs Traditional RAN



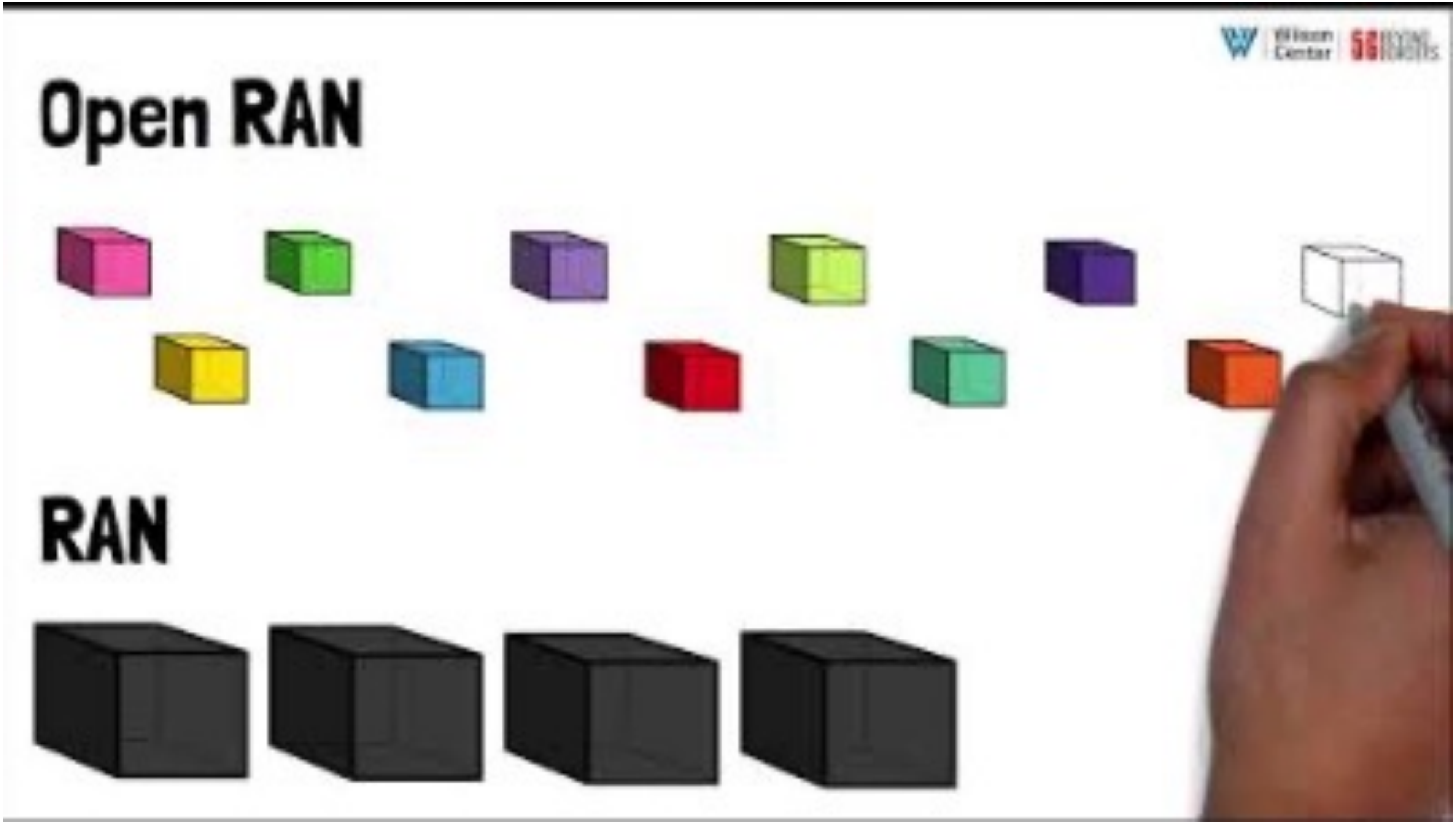
- C-RAN centralizes baseband processing in a data center.
  - Enable efficient resource utilization and easier management
- Traditional RAN keeps baseband processing distributed across individual cell sites.

C-RAN vs O-RAN

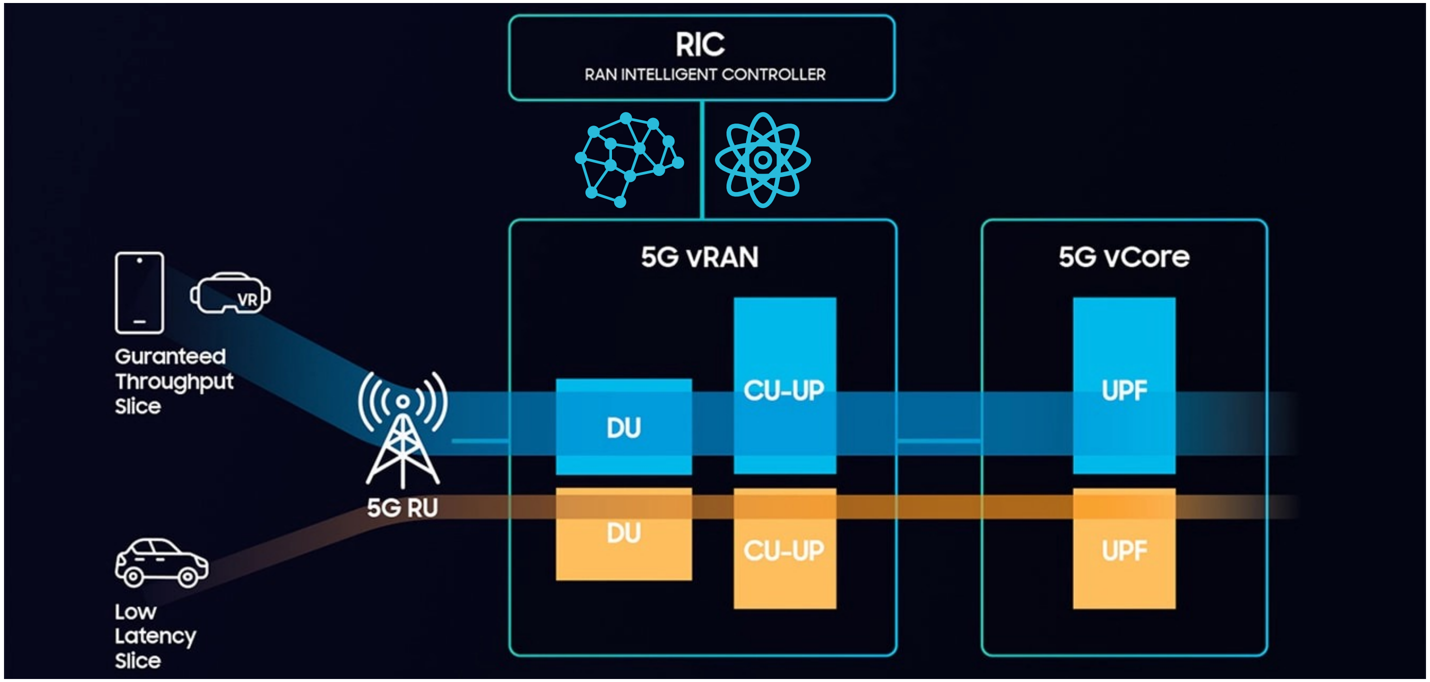


- C-RAN centralizes baseband processing in a data center.
  - Enable efficient resource utilization and easier management
- O-RAN disaggregates the RAN components.
  - Allow standardized, open interfaces between various network functions

O-RAN & V-RAN & C-RAN

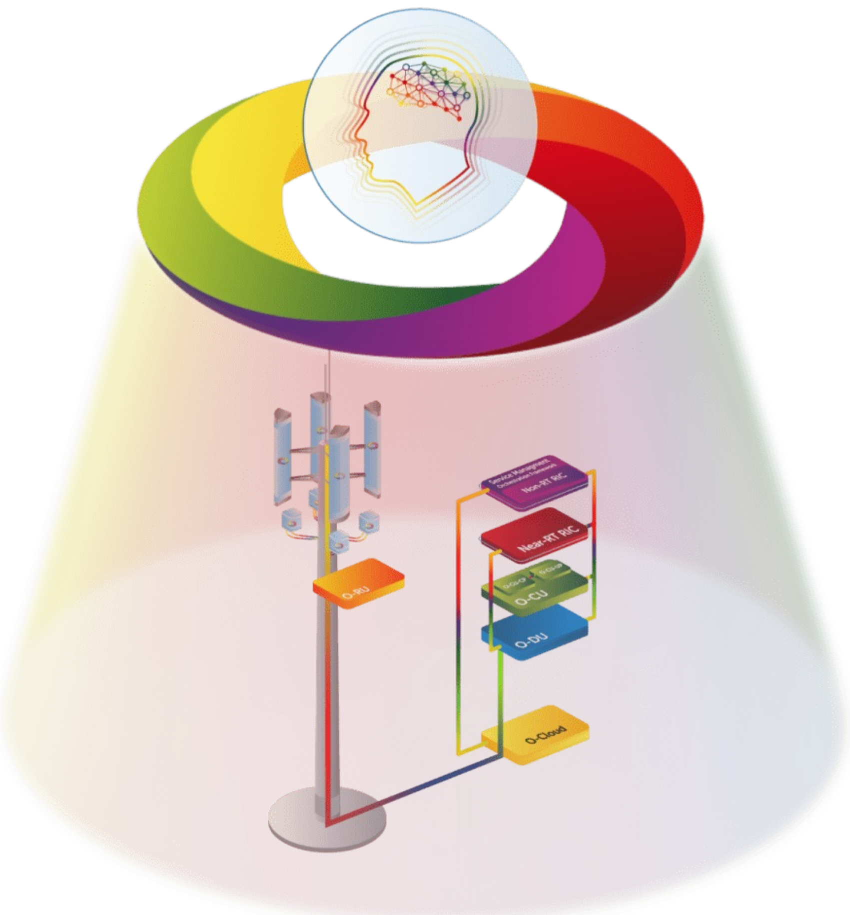


RAN Intelligent Controller (RIC)



- The RIC is a key component in the O-RAN framework
  - It enables intelligent and dynamic control of RAN resources
- Near-real-time (near-RT) RIC and non-real-time (non-RT) RIC
  - The near-RT RIC manages RAN functions within milliseconds
  - The non-RT RIC handles them with a longer time horizon

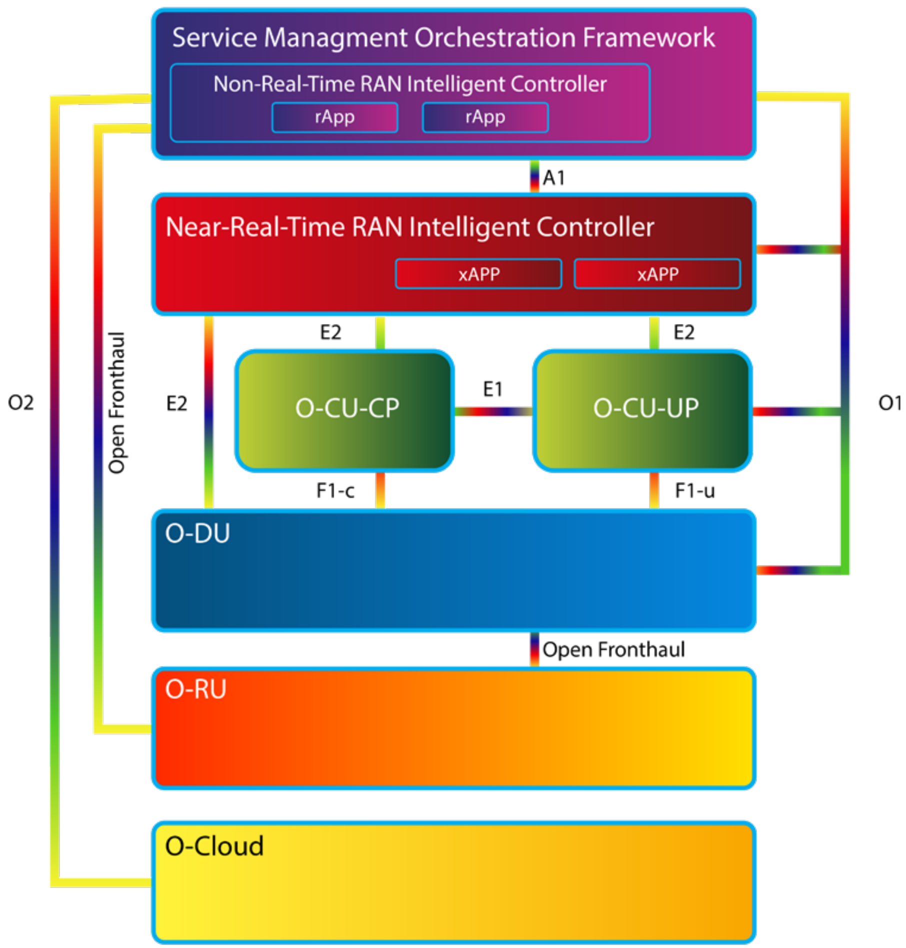
RAN Intelligent Controller (RIC)



- Intelligent Control
  - Artificial intelligence
  - Machine learning
  - Optimize network performance

Credit: O-RAN ALLIANCE e.V | https://www.o-ran.org/

RAN Intelligent Controller (RIC)



- **Intelligent Control**
  - Artificial intelligence
  - Machine learning
  - Optimize network performance
- **Open Interfaces (e.g., E2, A1)**
  - Open, standardized interfaces
  - Interoperability between vendors
  - Seamless integration

RAN Intelligent Controller (RIC)

- **Intelligent Control**
  - Artificial intelligence
  - Machine learning
  - Optimize network performance
- **Open Interfaces (e.g., E2, A1)**
  - Open, standardized interfaces
  - Interoperability between vendors
  - Seamless integration
- **Dynamic Orchestration**
  - Adaptive resource allocation
  - Adaptive Load balancing
  - Automated configuration adjustments

Open-Source 5G RAN Software

srsRAN: https://www.srslte.com/

- Written in C and C++
- GNU Affero General Public License v3.0
- 3GPP Release 17

Open Air Interface: https://openairinterface.org/

- Written in C
- OAI Public License V1.1
- 3GPP Release 17

Both offers software-based implementation of 5G RANs

Open-Source 5G Mobile Core Software

Open5GS: https://open5gs.org/

- Written in C
- GNU Affero General Public License v3.0
- 3GPP Release 17

free5GC: https://free5gc.org/

- Written in Golang
- Apache License 2.0
- 3GPP Release 15

Both offers software-based implementation of 5G Mobile Cores

A Real-World 5G System

Open Projects

- **Build Real-World 5G Testbed**
  - Simplify complex 5G deployment tasks through an intuitive framework with minimal overhead, making it easier to scale, monitor, and troubleshoot
- **Comprehensive API for Private 5G Network Control**
  - Develop comprehensive API for private 5G networks to provide seamless control over user management, network slicing, and infrastructure optimization.
- **Offloading 5G Lower PHY Processing onto Digital Signal Processors (DSPs)**
  - Offload lower PHY processing onto dedicated DSPs to maximize efficiency and reduce latency
- **Customized RF Amplifier Circuit with Digital Predistortion**
  - Create a high-power amplifier with digital predistortion to boost software-defined radio integrated circuits for reliable 5G communication
- **Developing Interference-Resilient RAN for Robust 5G Connectivity**
  - Build a RAN that resists both self and external interference by exploring adaptive interference mitigation techniques for enhanced network stability