Innovation and Prototyping in O-RAN using Open-Source Testbeds

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Institute for the Wireless Internet of Things at Northeastern

EURECOM Sophia Antipolis

5G OPERA

Indian Institute of Science
भारतीय विज्ञान संस्थान

IOS MCN

Institute for the Wireless Internet of Things (WIoT)

1. **Research:** Be a leading institution for research and development in smart and connected systems
2. **Education:** Train the next generation of researchers and professionals in interdisciplinary and hands-on skills
3. **Think Tank:** Shape and influence the global conversation on the future of connectivity
4. **Technology Incubator:** Generate IP, software, commercialize through spinoffs and industry

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WIoT

National Science Foundation

Air Force Research Laboratory

Office of Naval Research

Department of Transportation

NASA

OUSD (R&E)

13

Sponsoring Agencies

MassTech Collaborative

NTIA

+

Industry Consortium

DARPA

Department of Homeland Security

Army Research Office

IARPA

AFOSR

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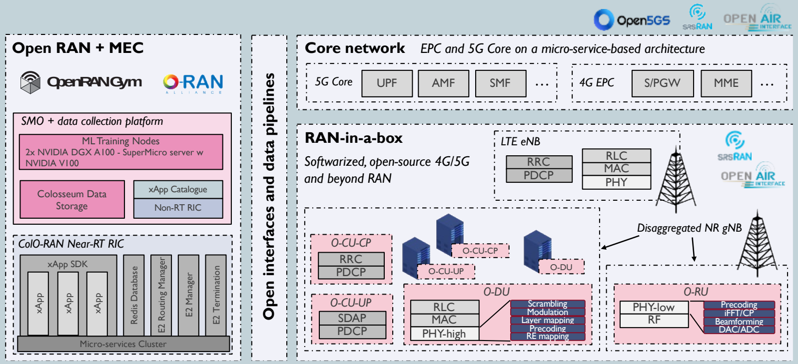
bionet
Qylur
EpiSci

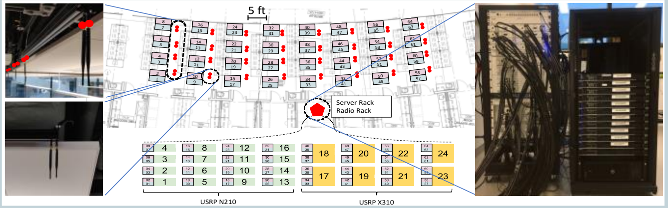
Testbeds and Platforms

Colosseum

End-to-end programmable cellular

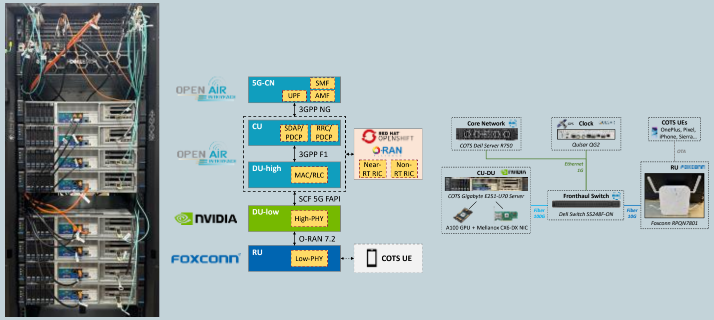


Arena + PAWR

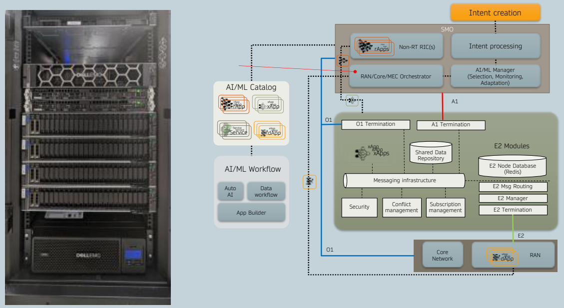


FCC Innovation Zones

X5G



Production 5G+AI automation



Institute for the Wireless Internet of Things
at Northeastern

EURECOM

- A Leading Teaching and Research Institution
- Fields of Research
  - Communication Systems
  - Data Science
  - Digital Security
- Courses are thought in English!

Home of OpenAirInterface!

KEY FIGURES 2023

- 330 Master students
- 100 PhD students
- 1 engineer degree
- 5 study tracks
- 4 Master's Degrees
- 2 Post Master's Degrees
- 3000+ Alumni graduates

Budget :

2023 : 16,5 M€
Contract turnover in 2022 : 8,7 M€

- European contracts : 3,1 M€
- National contracts : 1,5 M€
- Industrial contracts : 4M€

106 persons in research and teaching

- **26** faculty
- **50** research staff
- **30** administrative and support staff
- **28** nationalities

380 scientific international publications in 2022, of which:

- **147** cosigned with foreign institutions
- **21** theses defended

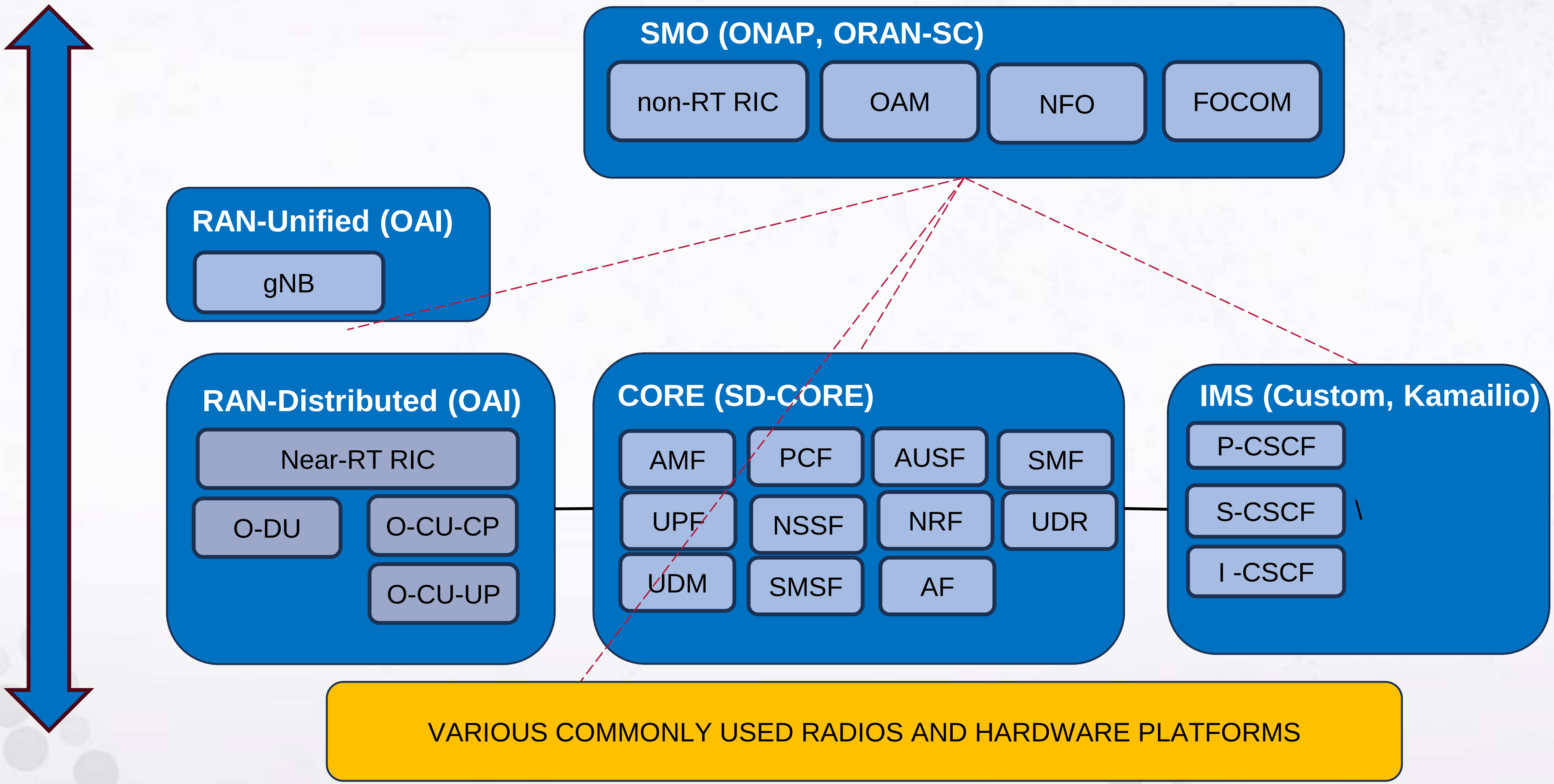
India’s Open-Source Mobile Communications Network (IOS-MCN)

What are we building?

FULLY INTEGRATED AND TESTED

OPEN SOURCE

TIED TO UPSTREAM PROJECTS

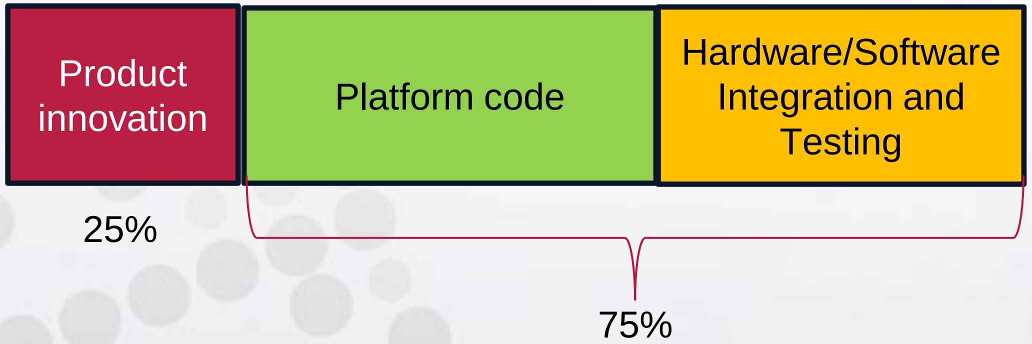


Why are we doing this?

TODAY in 5G:

- **Available Open-Source code is buggy. Components often from different sources and do not work together.**
- **Companies spend excessive effort on undifferentiated development to reach parity**
- **Smaller product companies are locked out even if they have innovative ideas**

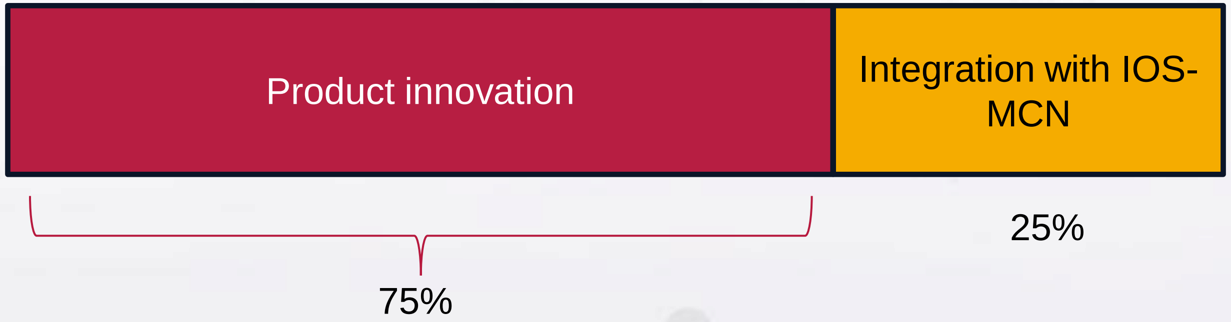
EFFORT SPENT IN TYPICAL PRODUCT DEVELOPMENT



WITH IOS-MCN:

- **A reliable, end-end integrated and tested Open Source stack that works "out-of-the-box"**
- **Smaller companies can build on IOS-MCN and focus on differentiated value**
- **Researchers have an open platform for innovation**

EFFORT SPENT IN TYPICAL PRODUCT DEVELOPMENT



When can you expect it?

Agartala Release will go public!

Q4 2024

- 5G SA TDD
- O-RAN Compliant Solution – RAN, CORE, SMO
- VVDN, Lekha Indoor RU Integration
- Handover

Q1 2025

- VoNR
- Paging
- RIC
- Unified SMO
- Outdoor deployment

Q2 2025

- Capacity enhancements
- URLLC
- Private 5G apps – Manufacturing, Mining
- RIC apps

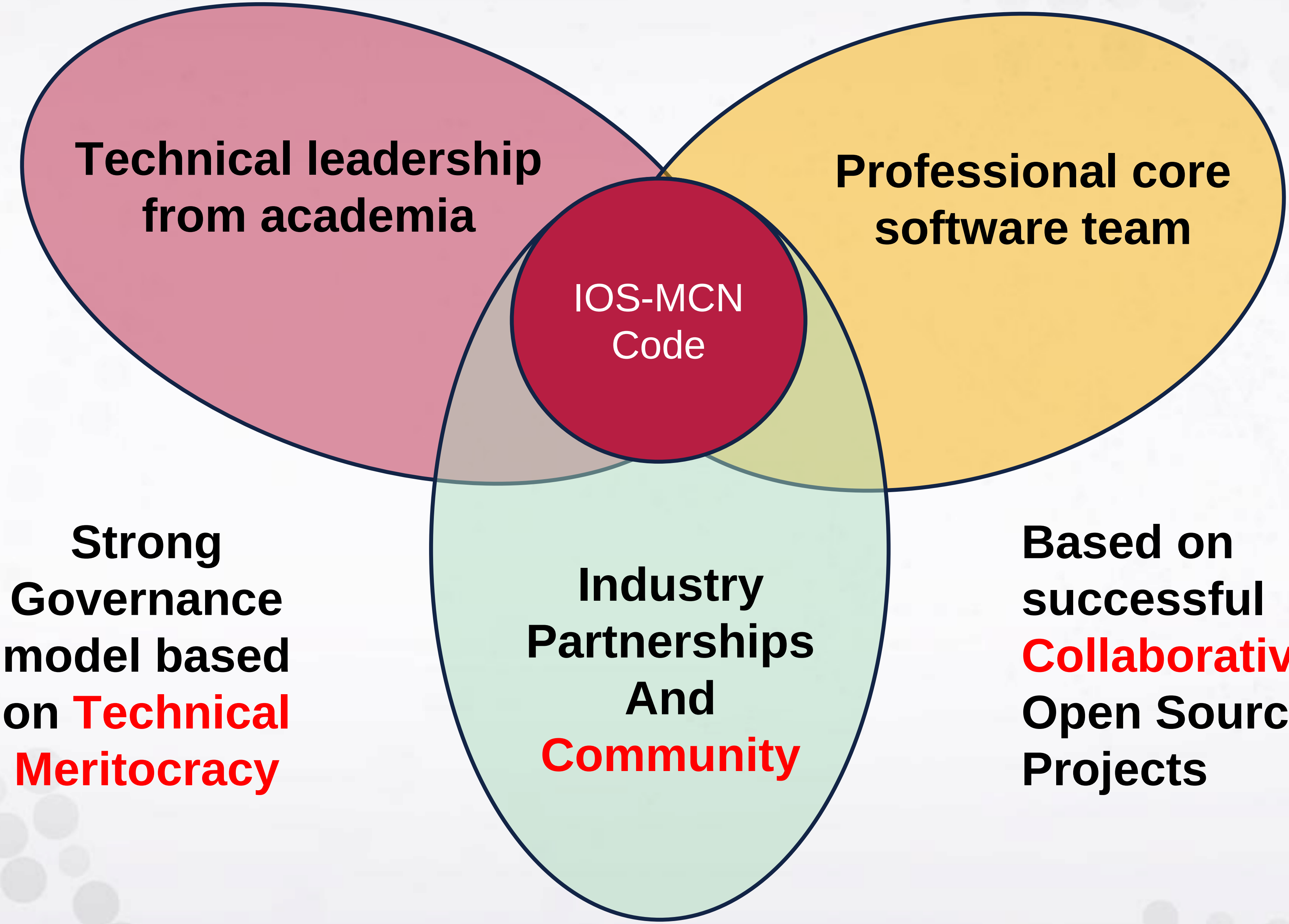
Q3 2025

Small Indoor Factory/Manufacturing Unit

Indoor & Outdoor Larger Campus

Multi-Site Indoor/Outdoor Private 5G

How are we doing it?

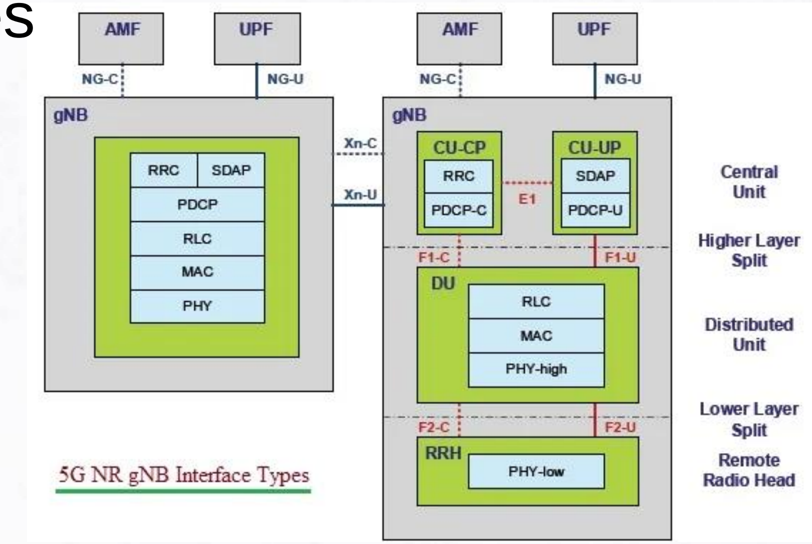


Strong Governance model based on Technical Meritocracy

Based on successful Collaborative Open Source Projects

Accomplishments so far

- Simplified compilation and deployment of RAN distribution
- Support 7.2 split architecture, with F1 and E1 interfaces
- Support for Radio units from multiple vendors
  - E.g. VVDN, Lekha Wireless
- Maximum throughput achieved so far:
  - 350Mbps in 1x1 SISO
  - 600Mbps in 2x2 MIMO
- F1 and Xn handovers
- Integration of research algorithms
- Integration with non-realtime RAN intelligent controller
- Acknowledgements:



www.rfwireless-world.com

Outline

Part I

- Open Radio Access Networks (O-RAN)
- OpenAirInterface (OAI)
- Open-source for Innovation, Prototyping and Standardization

Part II

- 5G System Architecture
- OAI Network Components and Modes
- OAI gNB Software Architecture

Part III

- Hands-on Session
- Live Demonstrations

Logistics

- Morning session mostly presentation based.
- Recommended to have a laptop with access to OAI repository

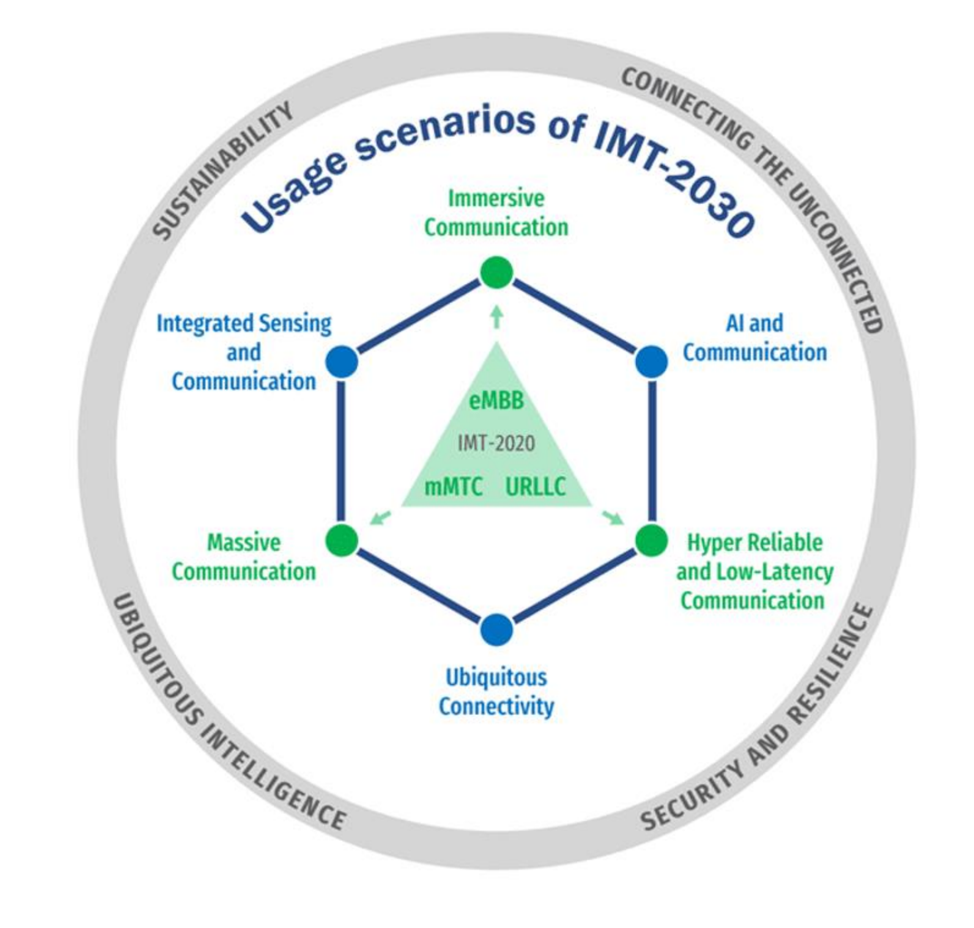
- Hands-on session in the afternoon (Exciting!)
- Mandatory to have a laptop with access to Google Cloud Platform
- Recommended to follow instruction on the tutorial GitHub page before attending

- How many have followed the instructions in the ReadMe?
- How many have access to GCP?
- How many have created a VM on GCP?
- How many have already installed OAI on it?

Part I : 5G Networks Overview

5G Technology

- **I**nternational **M**obile **T**elecommunications
  - International Telecommunications Union (ITU) produces network requirements and the framework for standards every ~10 years
  - IMT 2020 (5G), IMT 2030 (6G)
- Third Generation Partnership Project (3GPP)
  - Standardization body for cellular communications
- Some 5G features
  - Higher bandwidth (100 MHz in <=6GHz, 400 MHz in >6 GHz)
  - Bandwidth parts, Network Slicing
  - Different service categories
    - Enhanced mobile broadband (eMBB)
    - Ultra reliable low latency communication (URLLC)
    - Massive machine type communication (mMTC)



IMT 2020 (5G) and IMT 2030 (6G)

https://www.etsi.org/technologies/5G

https://techblog.comsoc.org/2024/07/06/itu-r-imt-2030-6g-backgrounder-and-envisioned-capabilities/

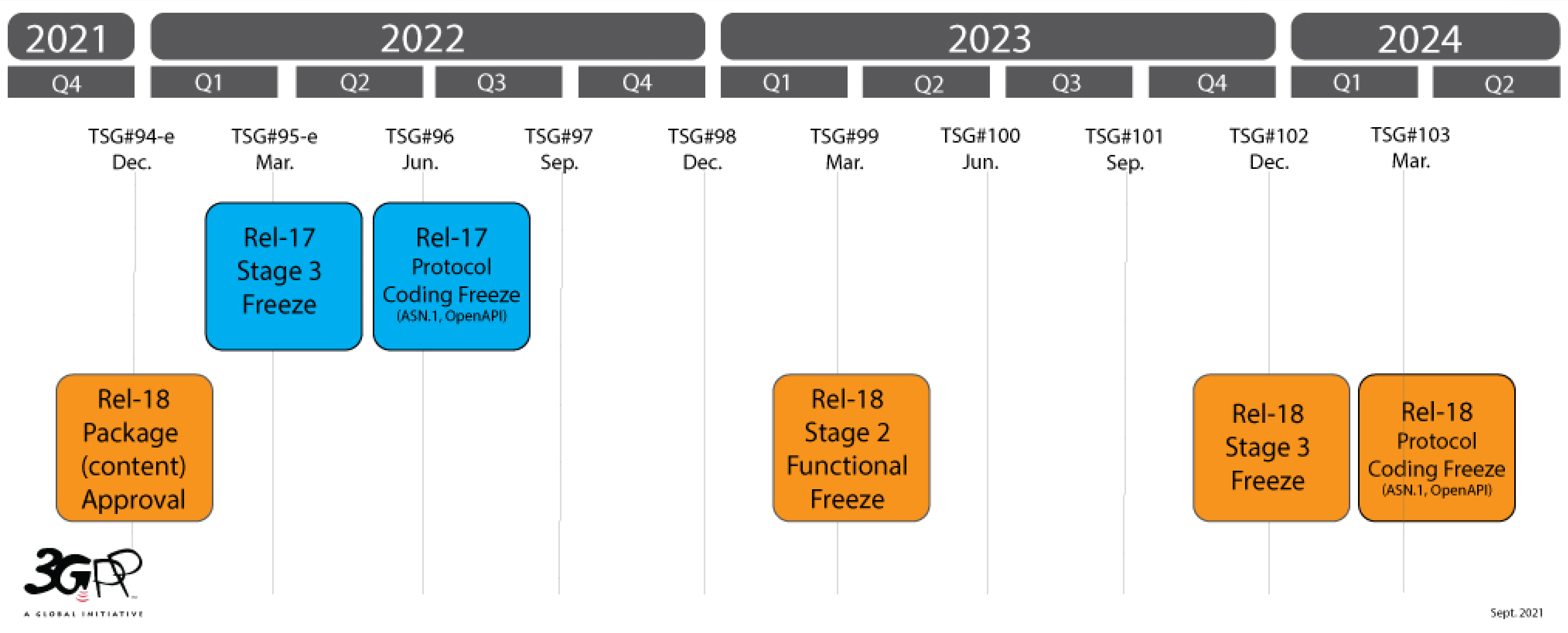
3GPP Specifications

- 3GPP is an international collaboration between seven telecommunications standards organizations
- 3GPP Organizes its work into three streams, or Technical Specifications Groups (TSGs)
    - Radio Access Networks (RAN)
    - Services and Systems Aspects (SA)
    - Core Network and Terminals (CT)
- Standards are structured as specifications and releases
- Each release represent an evolving set of functionalities

- Way to read a 3GPP document
    - 5G; NR; Multiplexing and channel coding (3GPP TS 38.212 version 16.2.0 Release 16)
    - LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Multiplexing and channel coding (3GPP TS 36.212 version 16.2.0 Release 16)
    - 5G; System architecture for the 5G System (5GS) (3GPP TS 23.501 version 17.5.0 Release 17)

https://www.3gpp.org/specifications-technologies/specifications-by-series

Standards Timeline

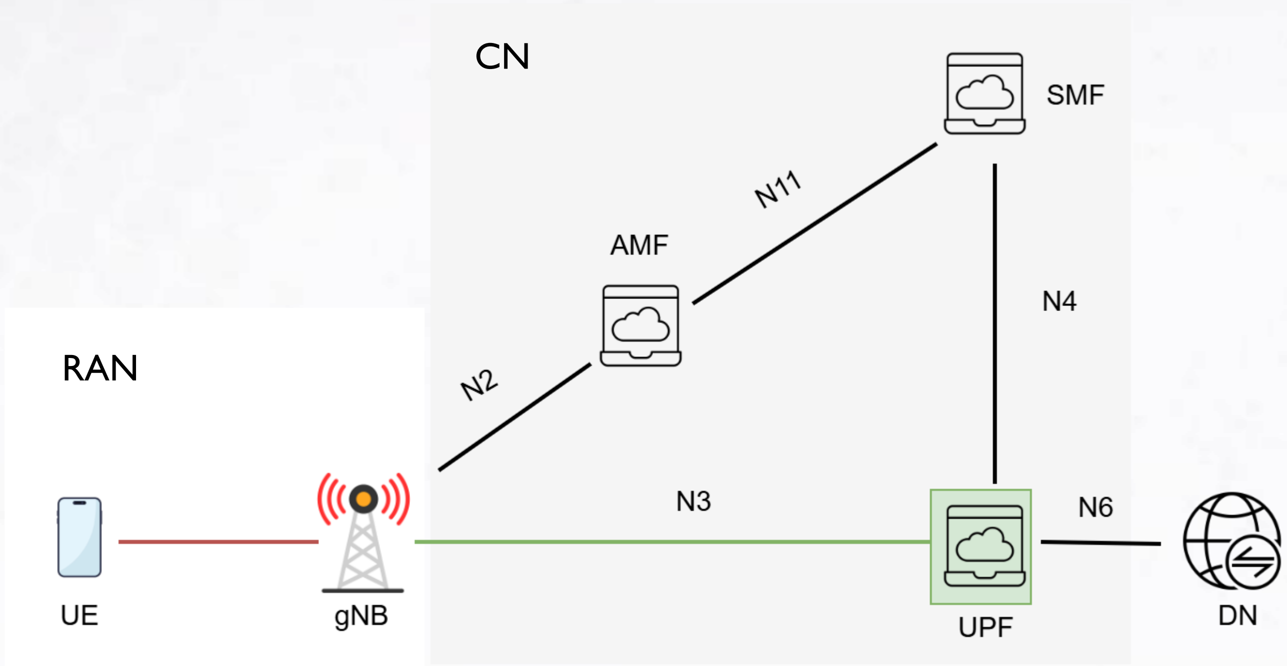


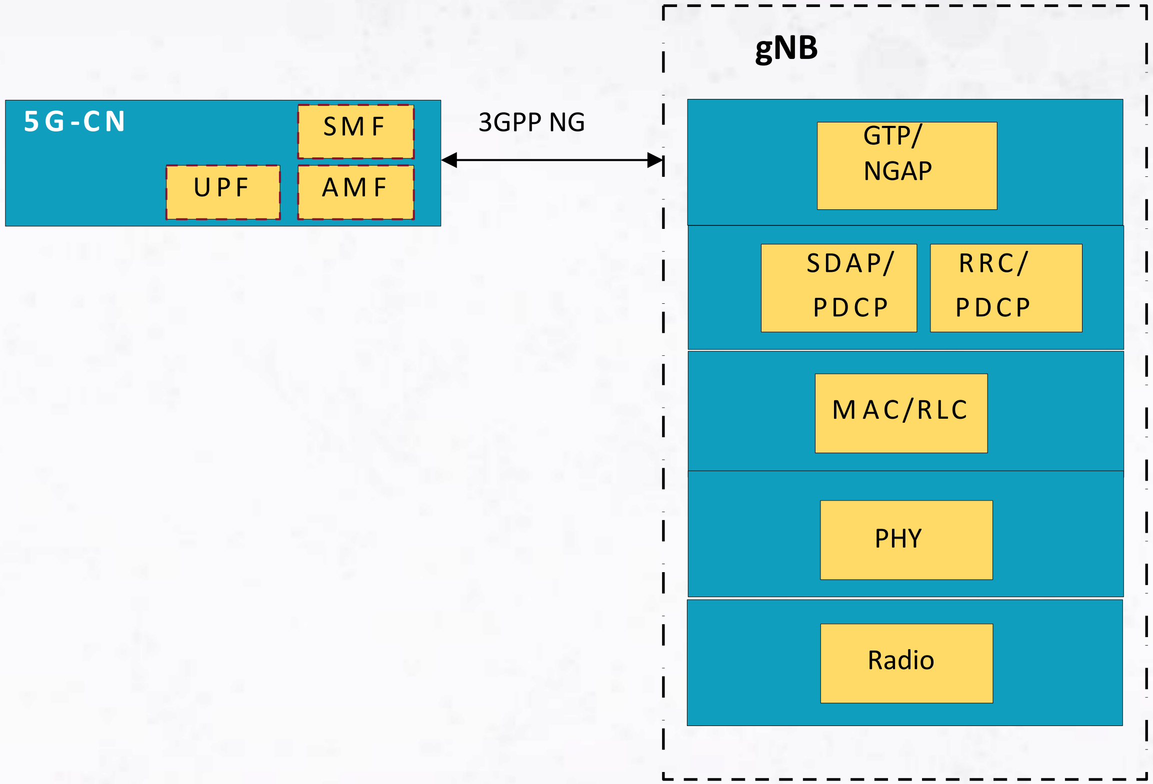
https://www.3gpp.org/news-events/3gpp-news/rel-17-f2f

Summary

- Cellular technology evolution
- Who defines it?
- Who sets the standards?
- How to read and interpret the standards?

5G Architecture





UE: User Equipment
gNB: gNodeB/Base Station
RAN: Radio Access Network
CN: Core Network

AMF: Access Management Function
SMF: Session Management Function
UPF: User Plane Function
DN: Data Network

GTP: GPRS Tunneling Protocol
NGAP: Next Generation Application Protocol
SDAP : Service Data Application Protocol
PDCP: Packet Data Convergence Protocol

RRC: Radio Resource Control
RLC: Radio Link Control
MAC : Medium Access Control
PHY : Physical Layer

A Roadmap Toward 6G

1. Conquering the Spectrum
2. Open, Programmable, Virtualized
3. AI-Native Processing and Control
4. Sensing and Positioning
5. Connecting the Metaverse

Part I : Open Radio Access Networks

O-RAN

"O-RAN ALLIANCE is a world-wide community of mobile operators, vendors, and research & academic institutions with the mission to re-shape Radio Access Networks to be more **intelligent**, **open**, **virtualized** and **fully interoperable**"

https://www.o-ran.org/who-we-are

Small Digression …Virtualization




Network Function Virtualization

Network Function (NF)

- A functional building block within a network infrastructure with
  - Well-defined external interfaces
  - Well-defined functional behavior
- Can be physical or virtual

Network Function Virtualization (NFV)

- Software implementation of NFs on COTS hardware ⟹ Virtual NFs (VNF)
- VNFs can run on Virtual Machines (VMs) or Containers (ex: LXC, Docker)
- VNFs can be hosted on cloud

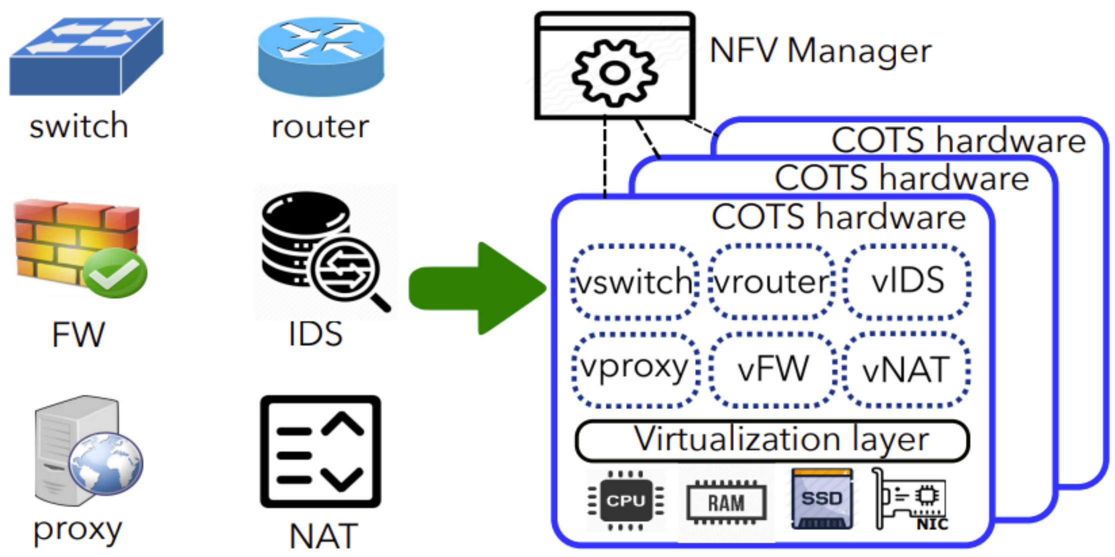


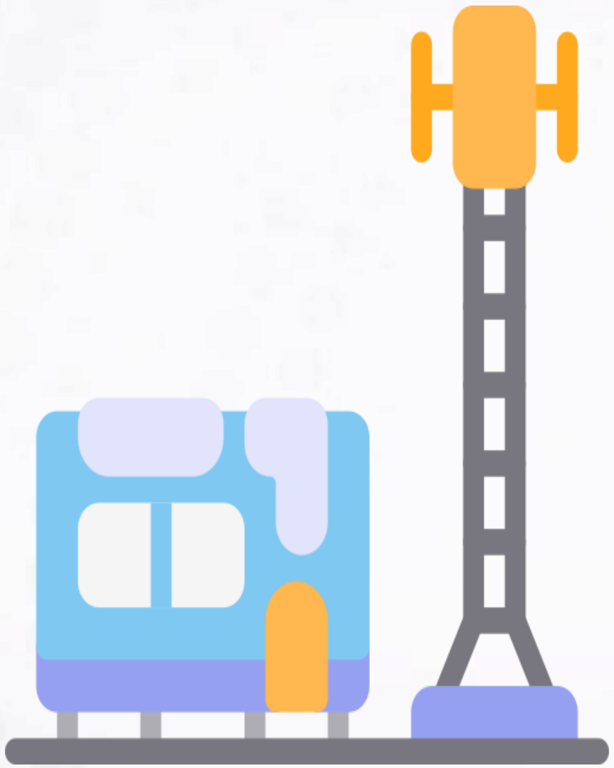
Fig. 1: Traditional vs. NFV paradigm

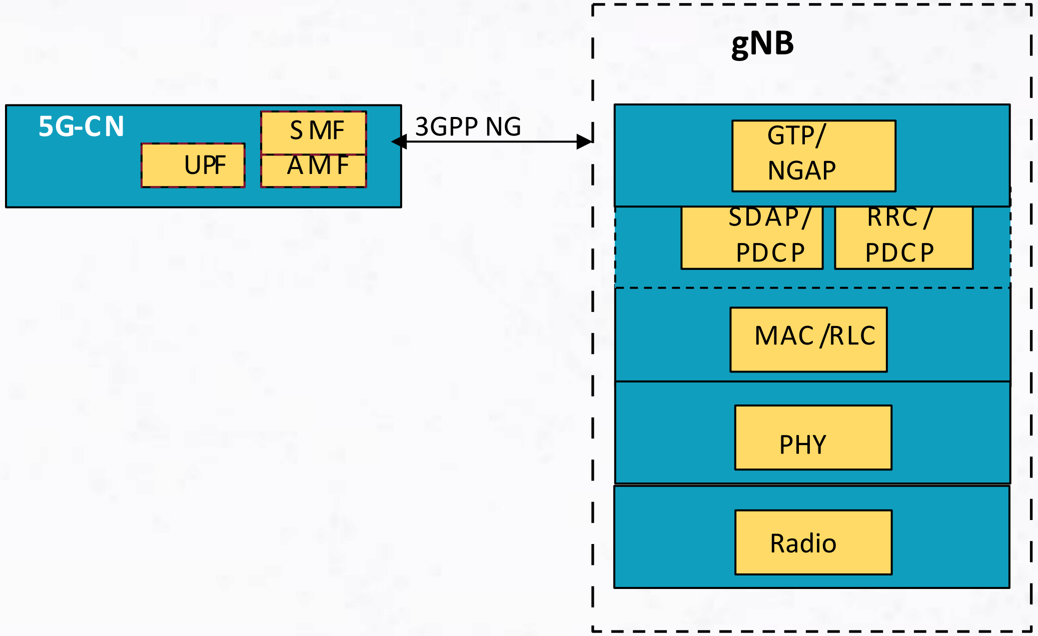
Source: T. Zhang, et al , "NFV Platforms: Taxonomy, Design Choices and Future Challenges," in *IEEE Transactions on Network and Service Management*, vol. 18, no. 1, pp. 30-48, March 2021,

Advantages

- Programmability, Automation and Orchestration
- Reduced dependence on custom hardware => avoiding vendor lock-in

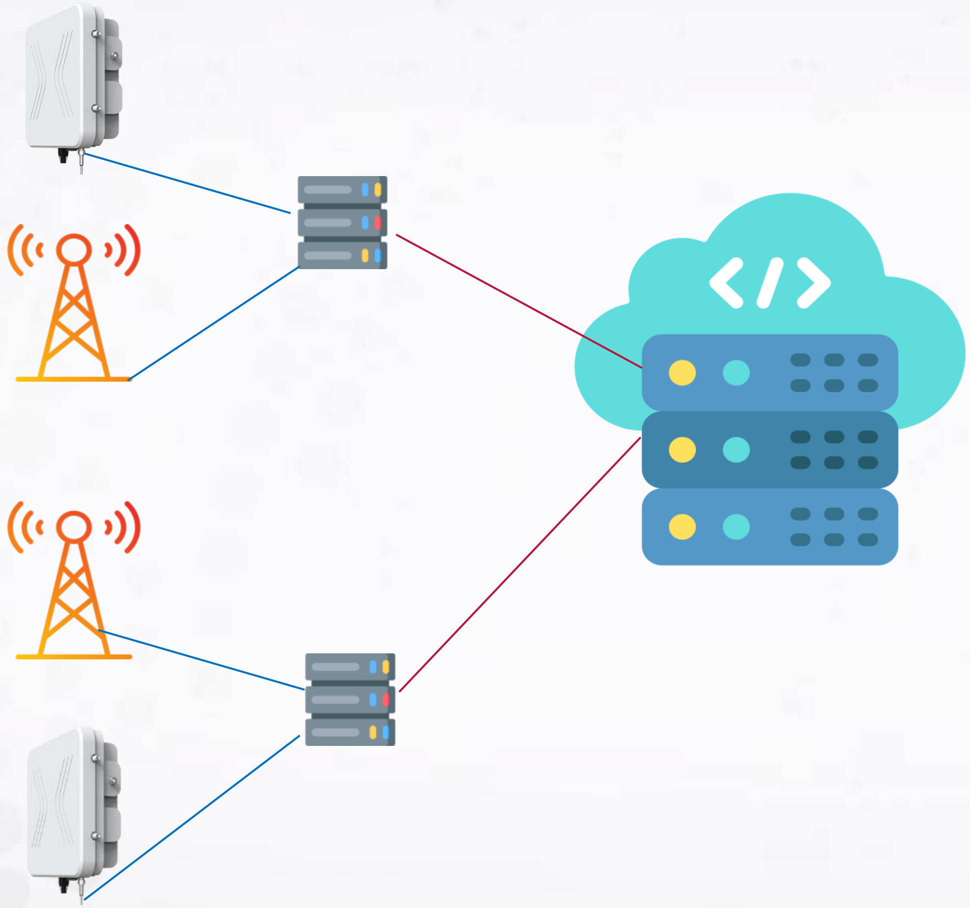
Traditional RAN

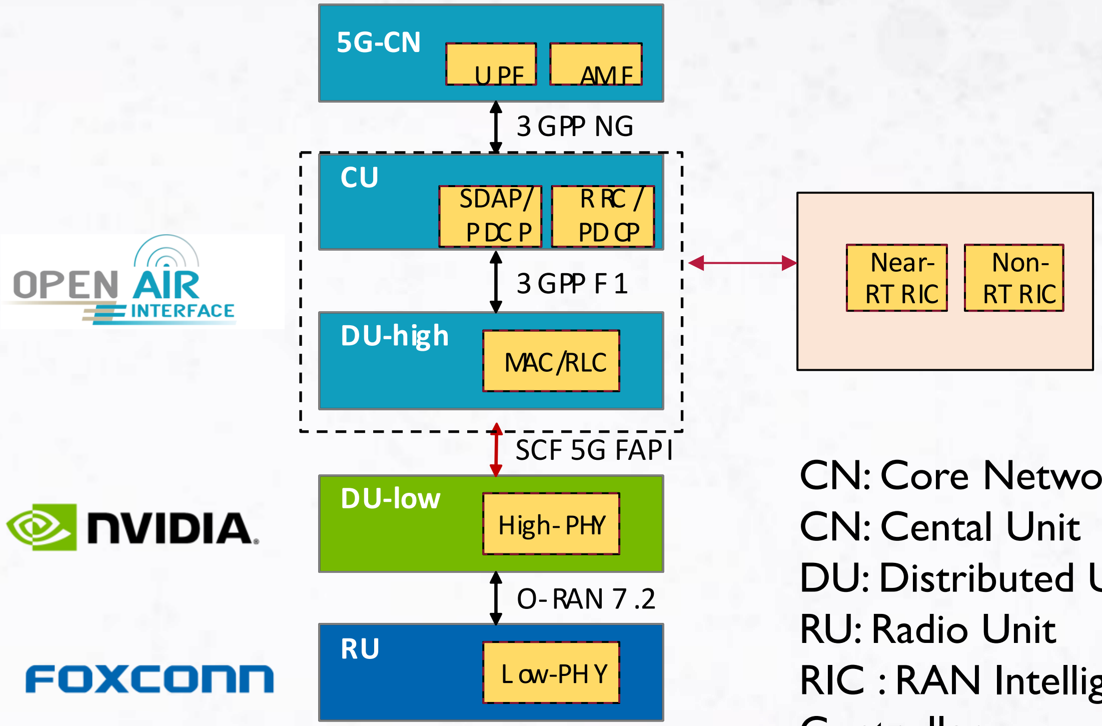




Monolithic Architecture

O-RAN



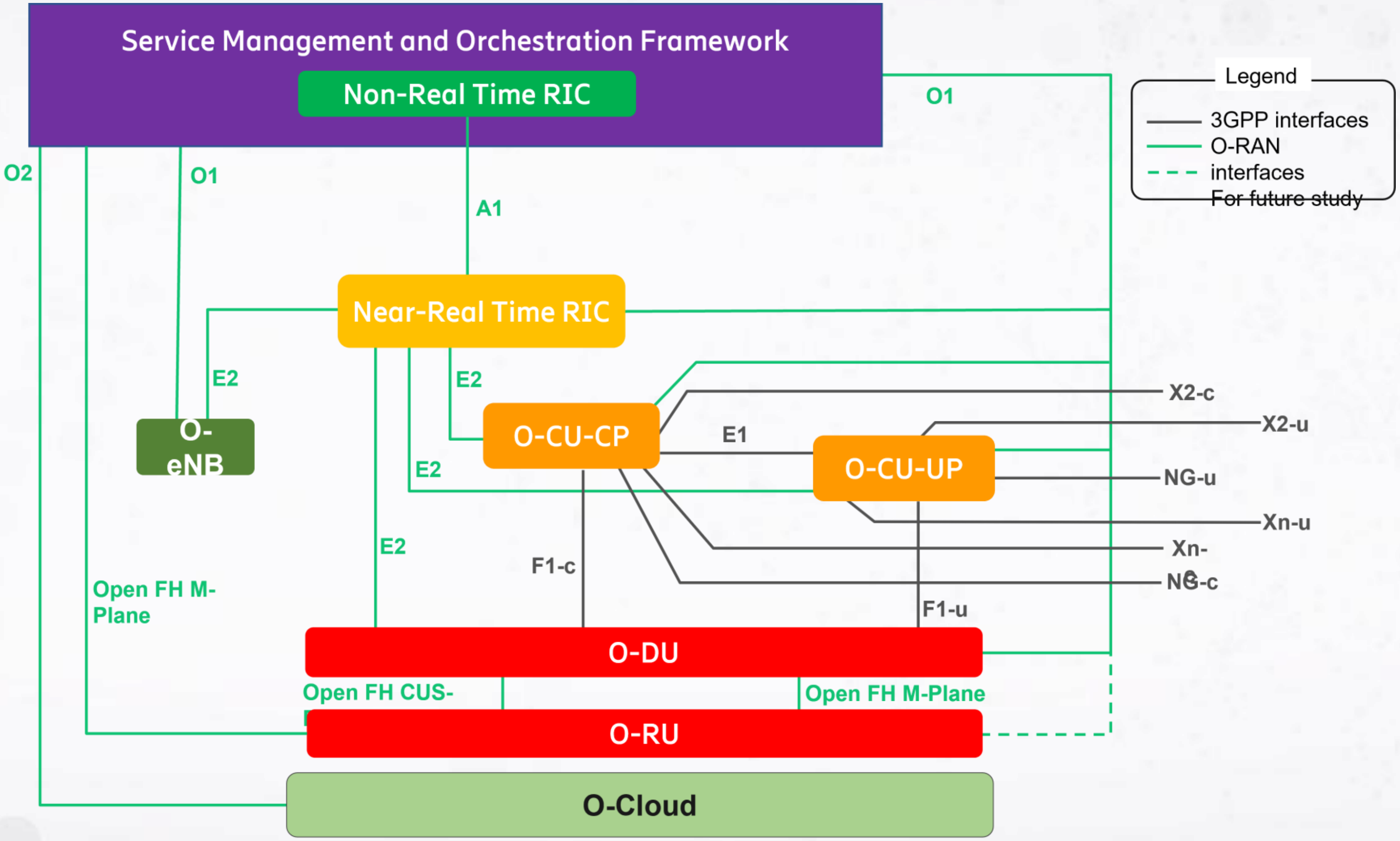


CN: Core Network
CN: Cental Unit
DU: Distributed Unit
RU: Radio Unit
RIC : RAN Intelligent Controller

x5G O-RAN Testbed

D. Villa, I. Khan, F. Kaltenberger, N. Hedberg, R. Soares da Silva, S. Maxenti, L. Bonati, A. Kelkar, C. Dick, E. Baena, J. M. Jornet, T. Melodia, M. Polese, and D. Koutsonikolas, "***X5G: An Open, Programmable, Multi-vendor, End-to-end, Private 5G O-RAN Testbed with NVIDIA ARC and OpenAirInterface***," arXiv:2406.15935

O-RAN Architecture

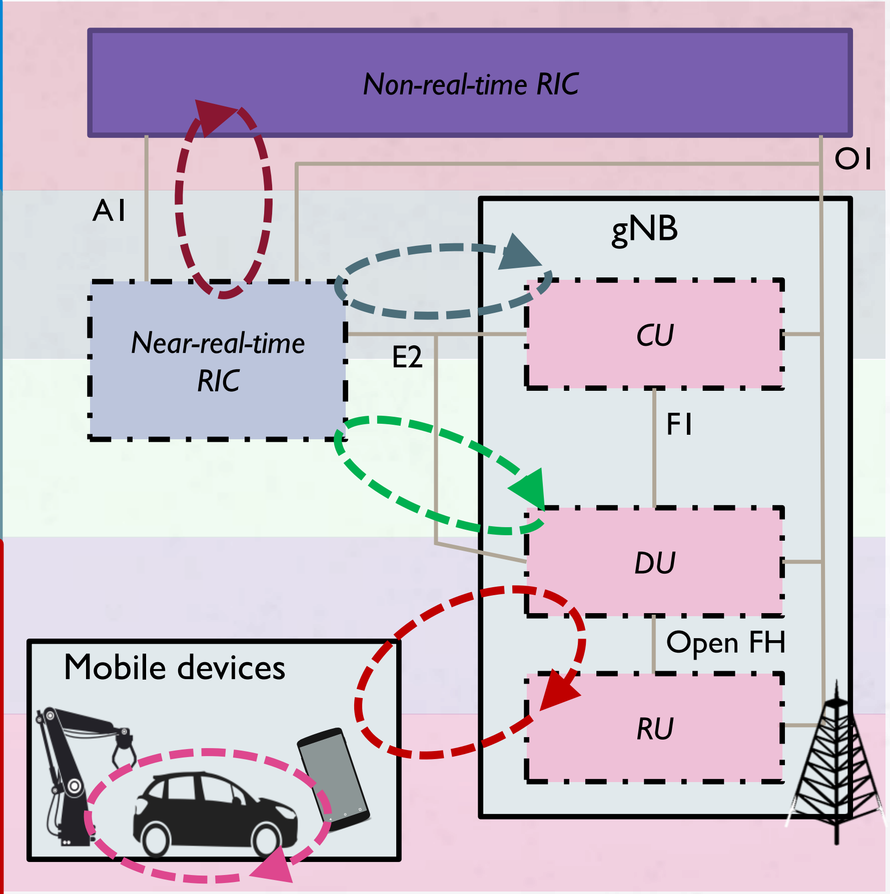


https://docs.o-ran-sc.org/en/i-release/architecture/architecture.html

Intelligent Control Loops in O-RAN

	Objective	Scale	Input data	Timescale
rApps	Policies, models, slicing	> 1000 devices	Infrastructure-level KPIs	> 1 s Non real-time
xApps	User Session Management e.g., load balancing, handover	> 100 devices	CU-level KPIs e.g., number of sessions, PDCP traffic	10-1000 ms
xApps	Medium Access Management e.g., scheduling policy, RAN slicing	> 100 devices	MAC-level KPIs e.g., PRB utilization, buffering	10-1000 ms Near real-time
dApps	Radio Management e.g., resource scheduling, beamforming	~10 devices	MAC/PHY-level KPIs e.g., PRB utilization, channel estimation	< 10 ms
dApps	Device DL/UL Management e.g., modulation, interference, blockage detection	1 device	I/Q samples	< 1 ms Real-time

Architecture



Not yet standardized by O-RAN (discussion ongoing in O-RAN nGRG) *

* D'Oro, S., Polese, M., Bonati, L., Cheng, H., & Melodia, T. (2022). dApps: Distributed Applications for Real-time Inference and Control in O-RAN. IEEE Communications Magazine, 2022.

O-RAN

Advantages

Avoid Vendor Lock-in

Lifting the Entry Barrier

Virtualization
&
Softwarization

Accelerate Innovation

Rapid Prototyping
&
Quick Time to Market

Challenges

X-haul Infrastructure

Security
&
Data Exposure

Interoperability

Reliability

Testing & Integration

Opportunities

Lifting Entry Barrier for New Players

Data Center Approach

Private 5G Networks

Open Test and Integration Centre

Summary

- Concept of Virtualization and its application to networks
- The motivation and key design considerations behind O-RAN?
- O-RAN architcture
- Flexible and adaptable cellular network design with r/x/dApps through RIC

Part I: OSA and OAI

OpenAirInterface Software Alliance (OSA)

HOME ABOUT US OAI PROJECTS NEWS & EVENTS COMMUNITY LEGAL BECOME A MEMBER

About the OpenAirInterface Software Alliance

Established in 2014, the OSA is a French non-profit organization ("Fonds De Dotation"), funded by corporate sponsors.

Our board comprises the representatives from Strategic Members of the Alliance.

The OSA is the home of OpenAirInterface, an open software that gathers a community of developers from around the world, who work together to build wireless cellular Radio Access Network (RAN) and Core Network (CN) technologies.

The Alliance is responsible for :

– the development roadmap,
– the quality control,
– the promotion of the OAI software packages, deployed by our academic and industrial community for varied use-cases.

The Alliance's mission is to facilitate OpenAirInterface adoption.

https://openairinterface.org/about-us/

OSA

Founding Member

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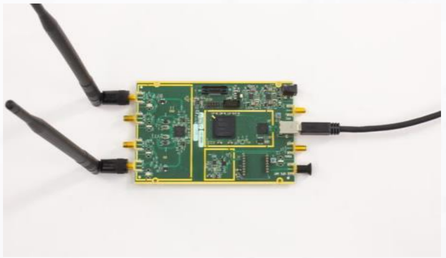
Role of OAI in O-RAN

- OpenAirInterface (OAI) is an open-source project
- Reference implementation 3GPP technology (LTE, 5G NR)
- Royalty-free licensing for study, research and testing
- General purpose computing hardware (x86/ARM)

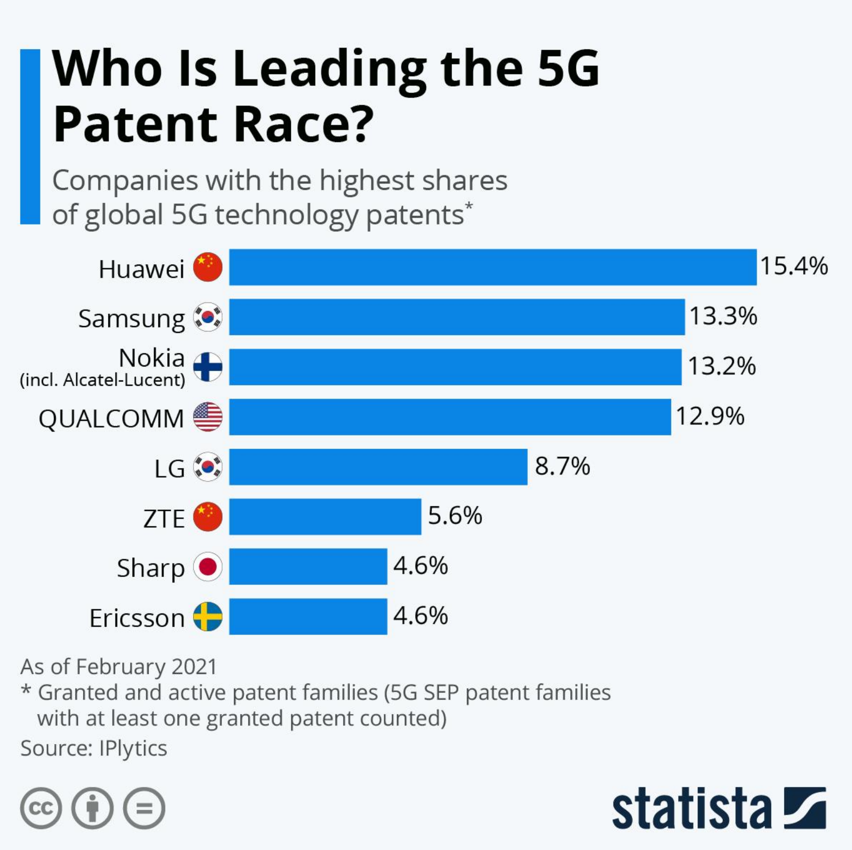
  +

  Software Defined Radio (SDR) cards, Radio Units (RUs)
- Easy to deploy a fully functional end-to-end 5G network
- Supports some O-RAN and FAPI splits and interfaces



Role of OAI in Innovation

- Rapid prototyping in cellular technologies at fingertips
- IP creation and Standard driven research
- Skillset development in experimental research and platform development
- What's in it for a
  - Researcher
  - Faculty setting up a lab
  - Policy makers and standardization bodies

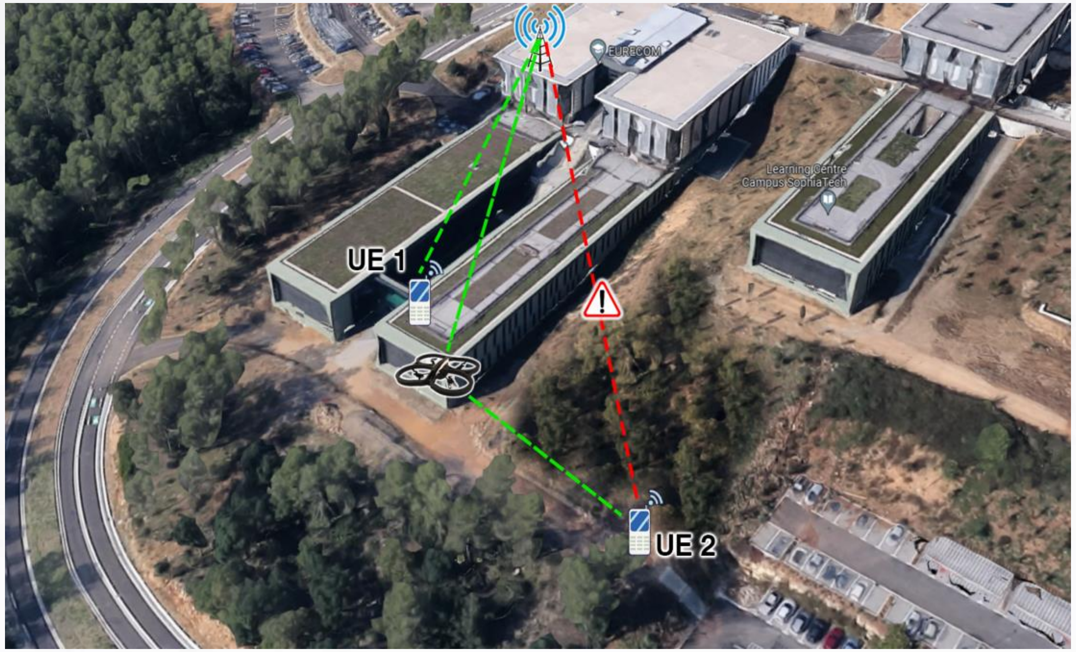


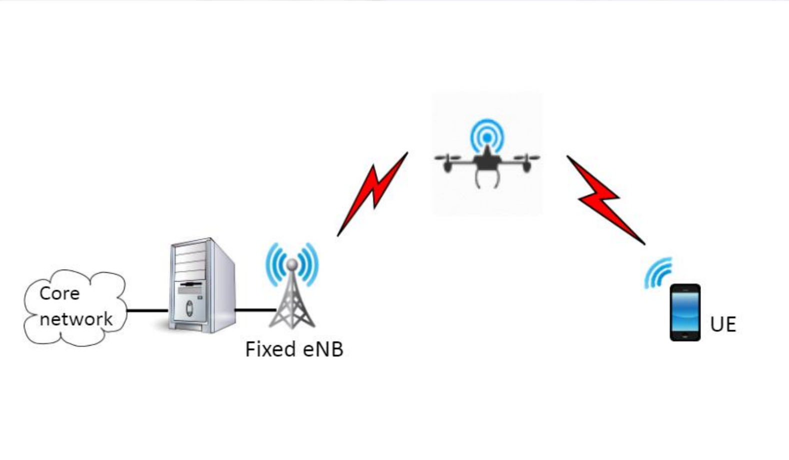
SEP : Standard Essential Patents

https://techblog.comsoc.org/category/5g-patents/

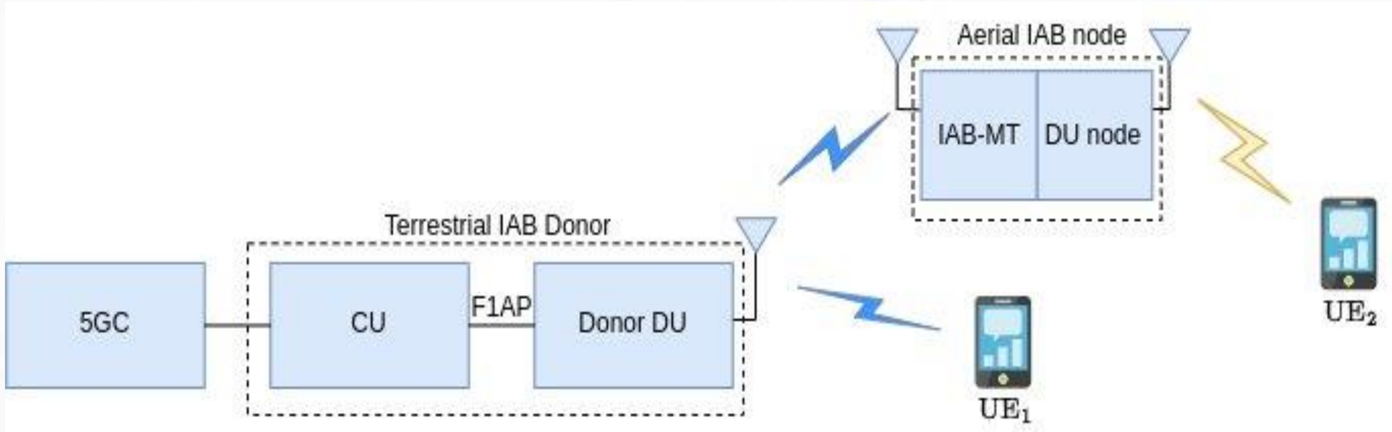
Part I : Innovation and Prototyping with OAI

Aerial Radio Access Networks





Aerial LTE Relaying, NOV 2017



Aerial IAB, May 2023

R. Gangula, O. Esrafilian, D. Gesbert, C. Roux, F. Kaltenberger and R. Knopp, "Flying Rebots: First Results on an Autonomous UAV-Based LTE Relay Using OpenAirinterface,“ *IEEE SPAWC 2019.*

R. Mundlamuri, O. Esrafilian, R. Gangula, R. Kharade, C. Roux, F. Kaltenberger, R. Knopp, and D. Gesbert. "Integrated Access and Backhaul in 5G with Aerial Distributed Unit using OpenAirInterface.", demo, In ACM WINTECH, 2023.

IAB Demo

https://youtu.be/GI_lOsg_qmQ?feature=shared

Flying Rebots: First Results on an Autonomous UAV-Based LTE Relay Using Open Airinterface

Publisher: IEEE Cite This PDF

Rajeev Gangula ; Omid Esrafilian ; David Gesbert ; Cedric Roux ; Florian Kaltenberger ; Raymond Knopp

All Authors

https://youtu.be/FlA2UADS6Sg?feature=shared

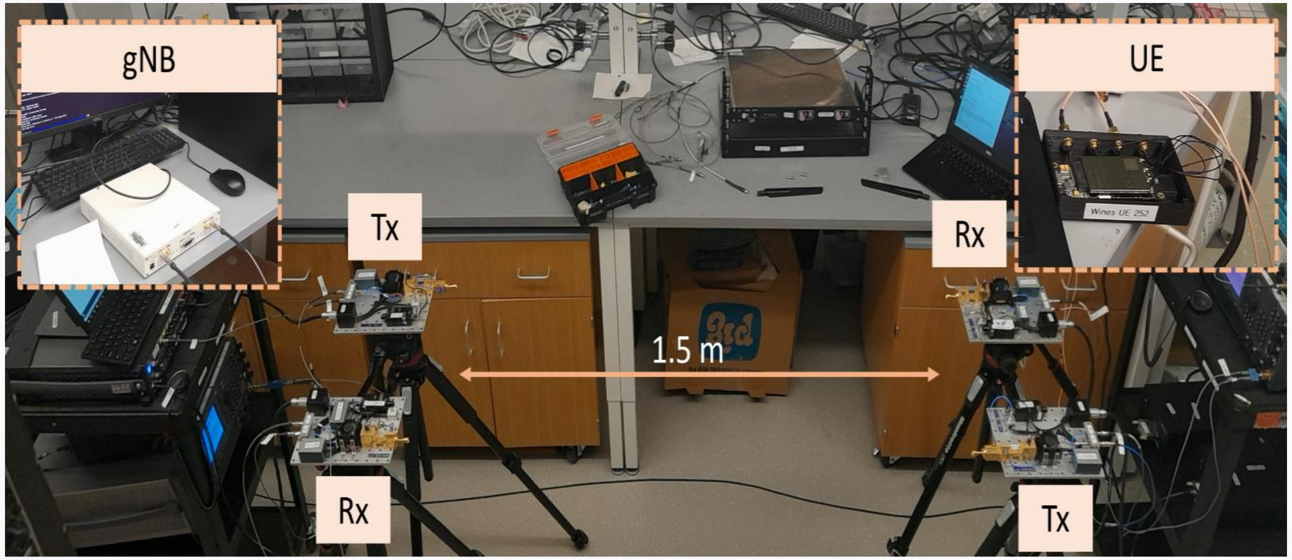
Integrated Access and Backhaul in 5G with Aerial Distributed Unit using OpenAirInterface

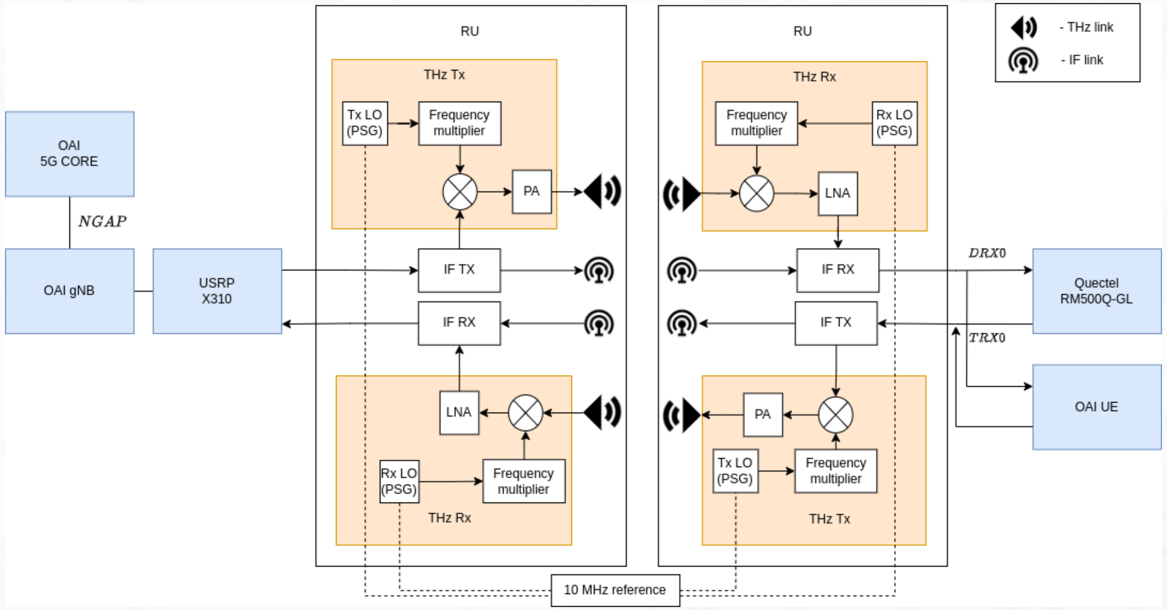
Rakesh Mundlamuri, Omid Esrafilian, Rajeev Gangula, Rohan Kharade, Cedric Roux, Florian Kaltenberger, Raymond Knopp, David Gesbert

https://www.drone4wireless.com/home

5G Over Terahertz Using OAI

- THz communication applications : Fixed backhaul, Inter-satellite communication, Sensing
- TerraNova Testbed@ NEU RF front-ends with a frequency range support 0.095–1.05 THz



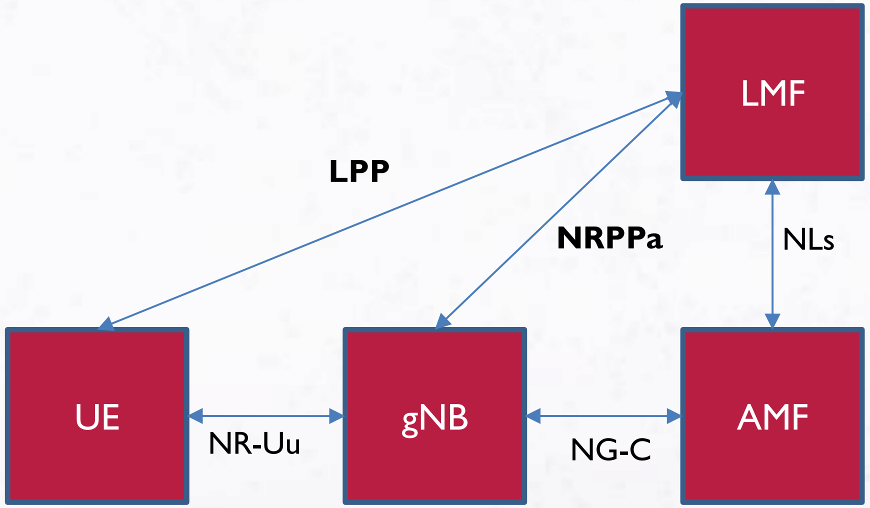


Rakesh Mundlamuri, Sherif Badran, Rajeev Gangula, Florian Kaltenberger, Josep M. Jornet, and Tommaso Melodia. "5G over Terahertz Using OpenAirInterface." *In IEEE WONS, 2024.*

Positioning with OAI

- Timing based positioning methods in 5G
  - Downlink time difference of arrival (DL-TDoA)
  - Uplink time difference of arrival (UL-TDoA)
  - Multi-cell round trip time (multi-RTT)
- OAI supports both DL and UL TDoA using sounding reference signals (SRS) and positioning reference signals (PRS)
- NRPPA protocol and localization management function in development
- This work: Two novel RTT methods!

LMF : Localization management function
AMF : Access Mobility Function
gNB : next gen node B
UE : User Equipment
LPP: LTE Positioning Protocol (Rel 16)
NRPPa: NR Positioning Protocol A (Rel 15)



Multi-RTT

- 2D position estimation using trilateration
- RTT schemes in 3GPP standards
  - RACH and Timing Advance : Enhanced Cell ID (ECID) type II
  - Rx-Tx time difference : ECID type I, Multi-RTT
- Drawbacks:
  - Low accuracy (ECID type II)
  - Overhead and Latency (ECID type I, Multi-RTT)

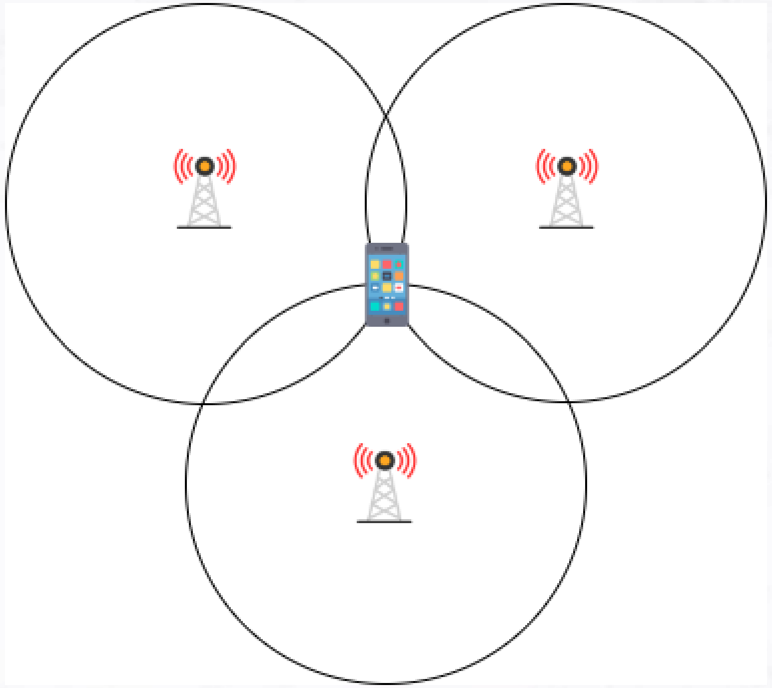
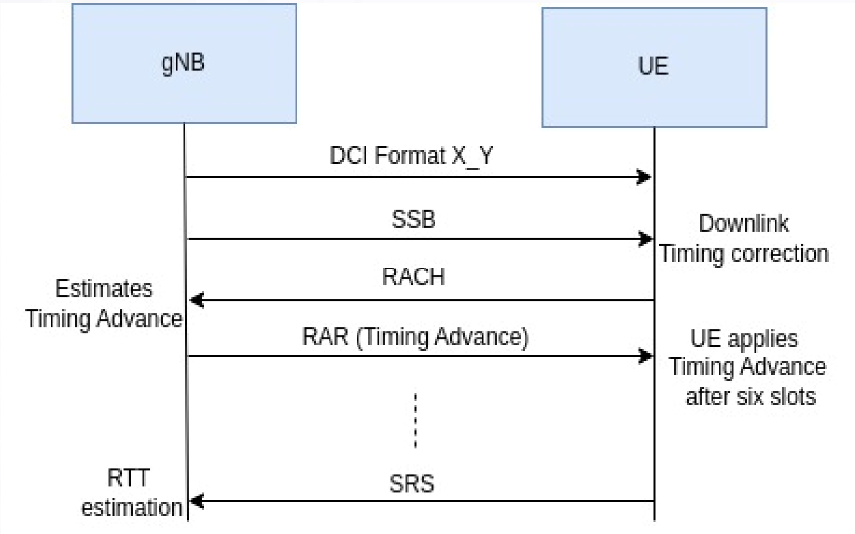


Figure: Multi-RTT positioning

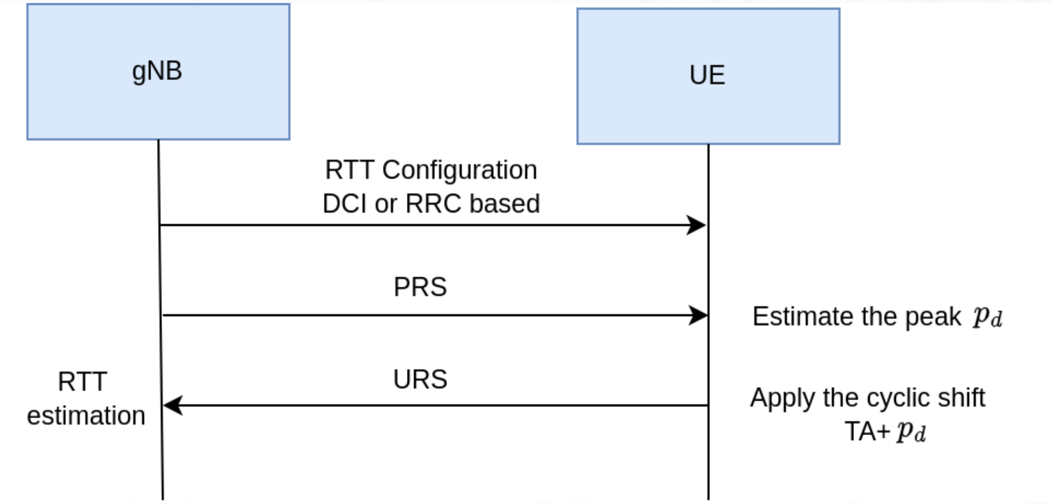
Novel RTT Methods

- Send SRS immediately after PRACH
- New signaling scheme



Method I

- Cyclic-shift method
- New signaling scheme and new Uplink Reference Signal (URS)



Method II

R. Mundlamuri, R. Gangula, O. Esrafilian, F. Kaltenberger, R. Knopp, D. Gesbert, S. Wagner, and K. L. Trung, "System and a method for improved round trip time estimation," in final stage of grant EUROPEAN PATENT23306847.7, October 2023.

R. Mundlamuri, R. Gangula, F. Kaltenberger and R. Knopp "Novel Round Trip Time Estimation in 5G NR", *Accepted in IEEE GLOBECOM 2024*.

R. Gangula, T. Melodia, R. Mundlamuri and F. Kaltenberger, "Round Trip Time Estimation Utilizing Cyclic Shift of Uplink Reference Signal", Submitted to *IEEE ICC 2025*.

Real-world Experiments

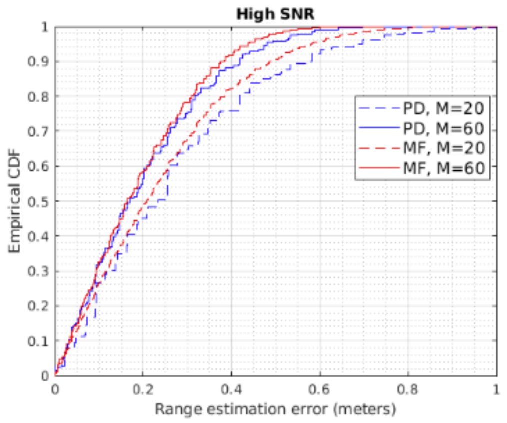


Figure 10. CDF of the range estimation error.

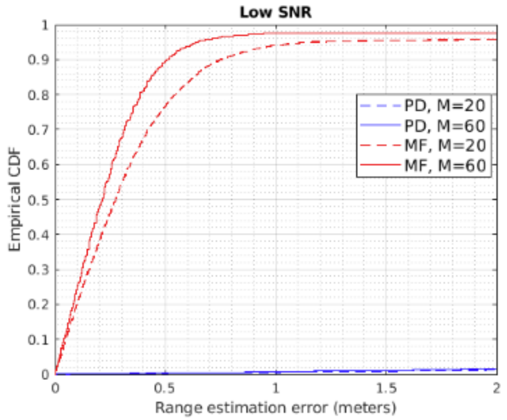
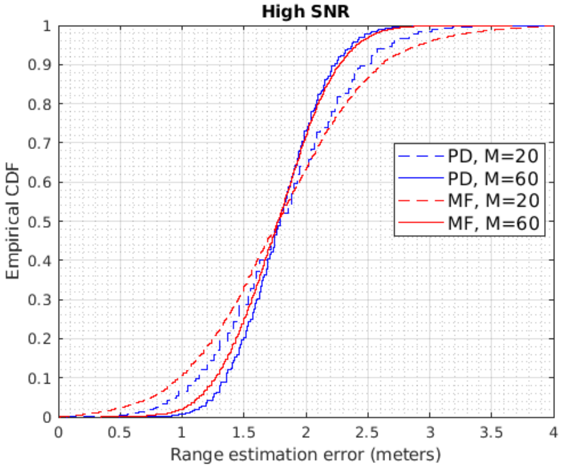
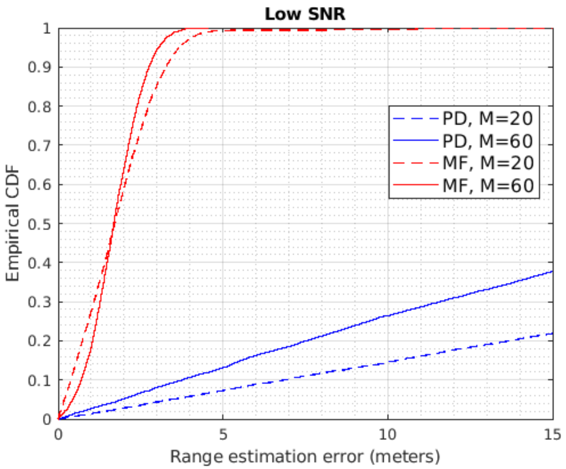


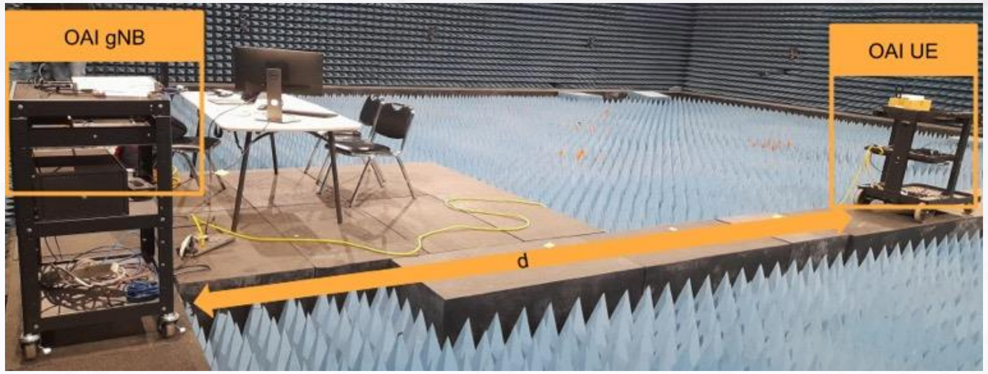
Figure 11. CDF of the range estimation error.

Method II





Method I



Parameters	Values
TDD slot configuration	DL DL DL DL DL DL DL Mixed UL UL
System bandwidth	38.16 MHz
Subcarrier Spacing (Δf)	30 KHz
Centre frequency (f_c)	3.69 GHz
Sampling rate (f_s)	46.08 MHz
FFT size (K)	1536
URS bandwidth	37.77 MHz
URS length (N_{ZC})	1259
PRS bandwidth	37.44 MHz
PRS symbols	12
PRS Comb	2

Method II

Parameters	Values
System bandwidth	38.16 MHz
Subcarrier Spacing (Δf)	30 KHz
Centre frequency (f_c)	3.69 GHz
Sampling rate (f_s)	46.08 MHz
FFT size (K)	1536
Cyclic prefix (N_{cp})	132
SSB bandwidth	7.2 MHz
SRS bandwidth	37.44 MHz
SRS comb size (K_c)	2

Method I

Loss Adaptive Fair Scheduling in 5G with Minimum Rate Guarantees

Dept. of Electrical Communication Engineering
Indian Institute of Science, Bangalore

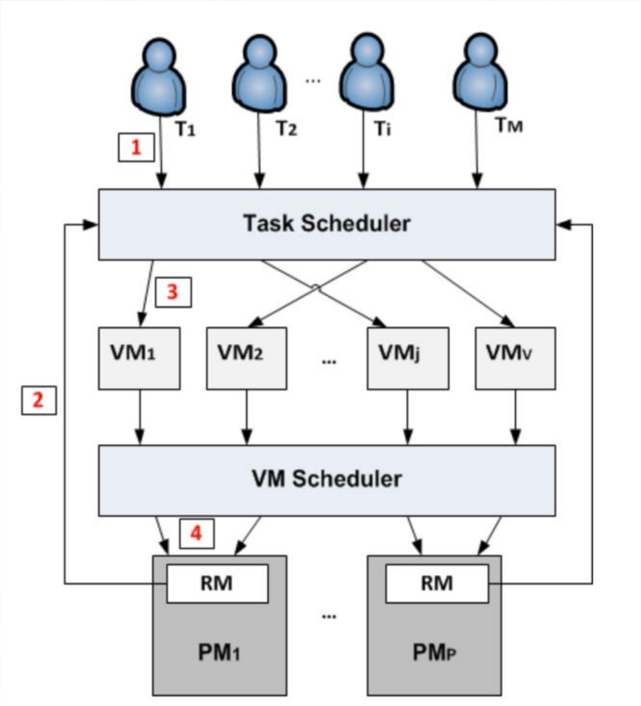
Joint work with Venkatareddy Akumalla, S. V. R. Anand
Anurag Kumar, Chandra R. Murthy, and Rajesh Sundaresan

The scheduler

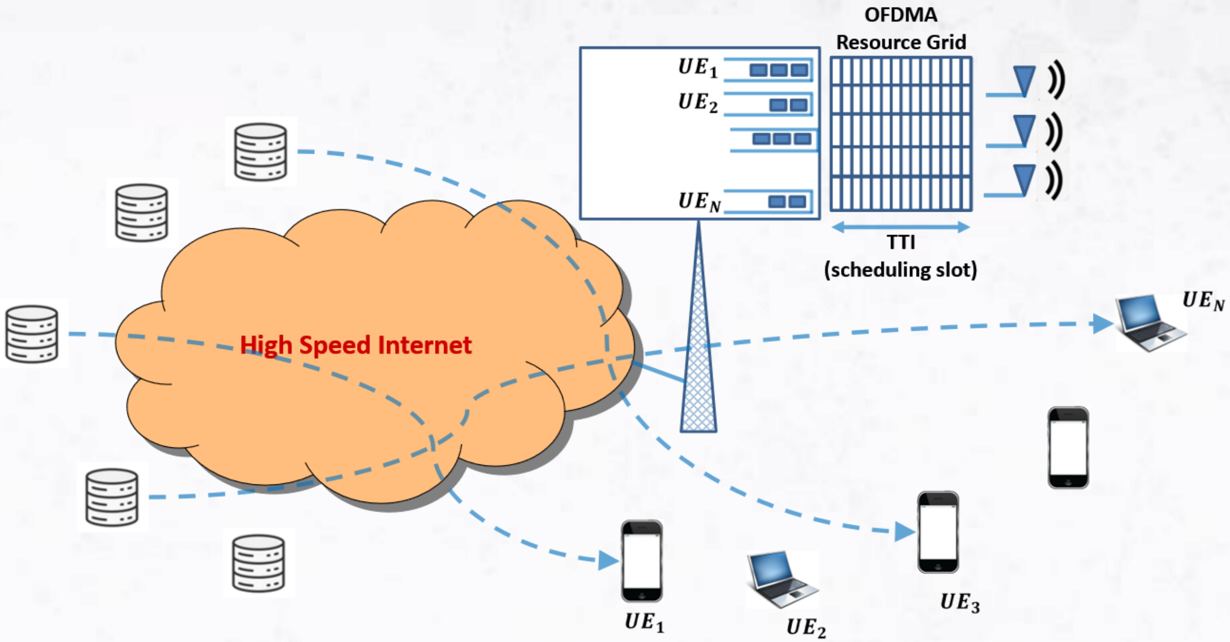
- The QoS profile at core network translates to DRB at RAN
- The bottleneck comes at the OFDMA resource grid
- The scheduler that manages the resource allocation to meet different requirements is the key
- Round Robin (RR) scheduler
  - Fair towards all the users in terms of the resources but suboptimal utility
- Max Rate scheduler
  - Favoring the UE which is in better channel condition (optimal utility but not fair)
- Proportional Fair (PF) scheduler
  - Fair in terms of the channel quality (directly proportional) and the throughput (indirectly proportional) - (r/theta)
  - Better utility than RR but suboptimal to max rate (there is fairness)

Scheduling is the Crucial Mechanism in Virtualisation

From: Alboaneen et al., 2017, Glowworm Swarm Optimization…



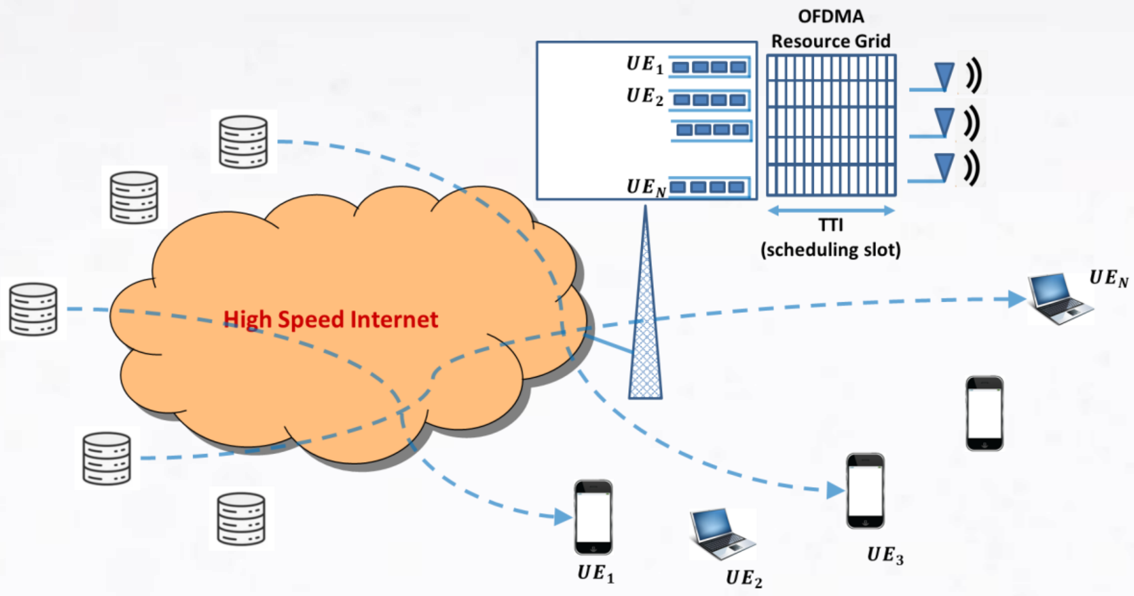
Cloud Computing: Scheduling tasks on Virtual Machines (VMs), which are then scheduled on Physical Machines (PMs)



Scheduling various Internet services on an OFDMA cellular system

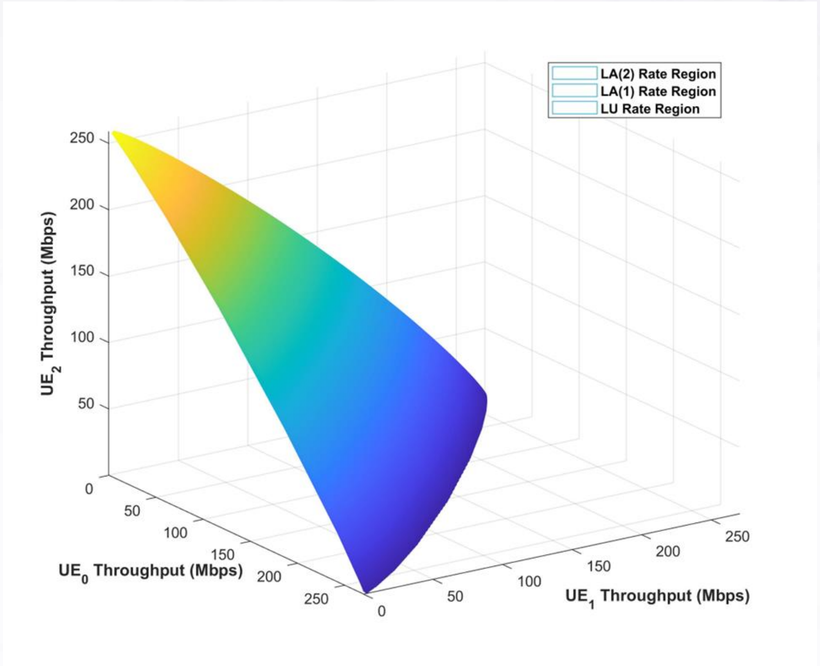
- Each task on the VM system, or service in the cellular system has QoS requirements
- A good scheduler needs to satisfy the QoS for each task/service
    - **While ensuring efficient utilization of the physical resources**

A Scheduling Problem



Backlogged downlink queues

Problem: In each slot, pack downlink data from one UE into the OFDMA grid

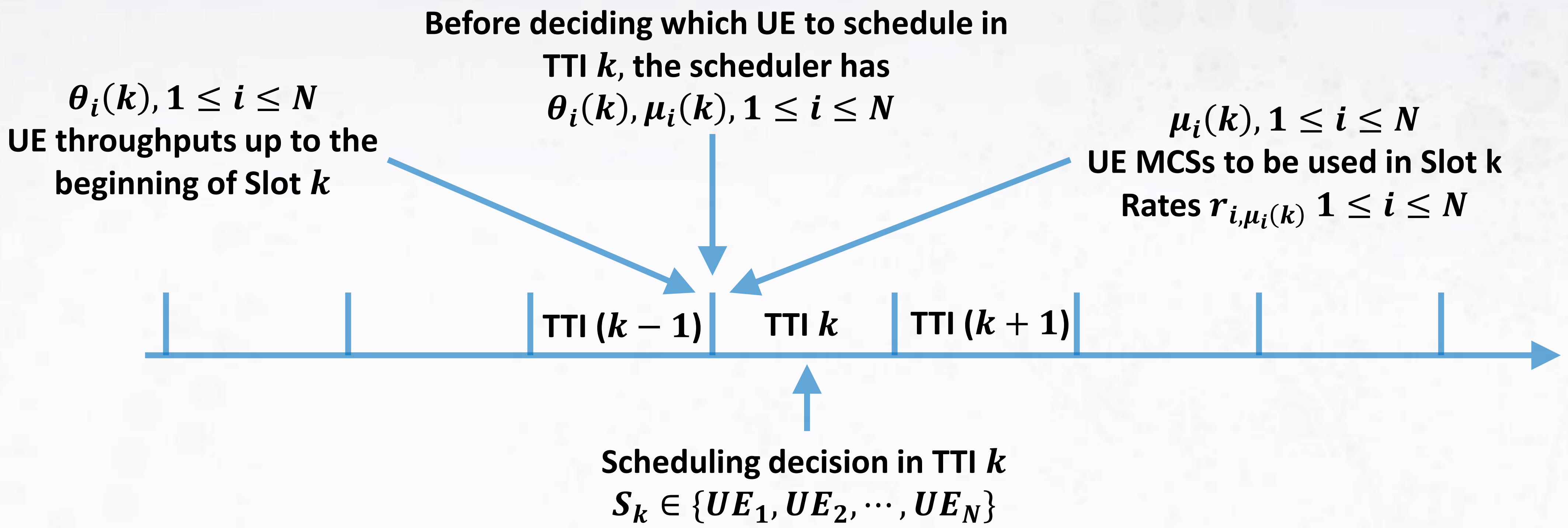


Stationary channel states and rates in slots

Rate Region $\mathcal{R}$

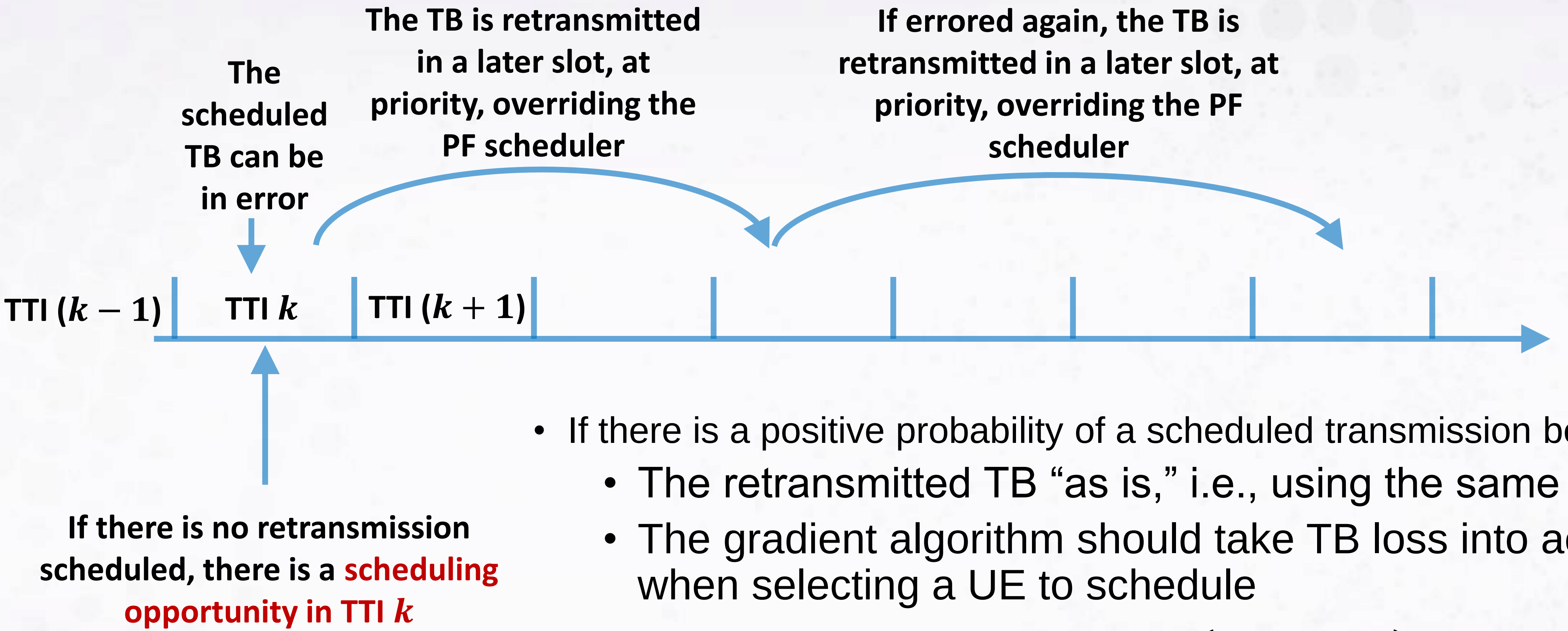
- Utility optimization formulation
  - $\sup_{\boldsymbol{r}\in\mathcal{R}} \sum_{1\le i\le N} U(r_i)$
  - $U(\cdot)$: strictly concave and increasing
- Scheduling algorithm
  - Schedule a UE in each slot to achieve utility optimal average UE rates

Classical Gradient Scheduling



- Gradient algorithm:
  - $\arg\max_{1 \le i \le N} \frac{r_{i,\mu_i(k)}}{\theta_i(k)}$
- If UE_i is scheduled, update the throughputs as follows
  - $\theta_i(k) = \theta_i(k-1) + \mathrm{a}\,(\mathrm{r}_{\mathrm{i},\mu_i(k)} - \theta_i(k-1))$
  - $\theta_j(k) = \theta_j(k-1) + \mathrm{a}\,(0 - \theta_j(k-1))$
  - a (e.g., 0.0005) determines the Averaging Window

Data Loss, Retransmission, Scheduling Opportunities

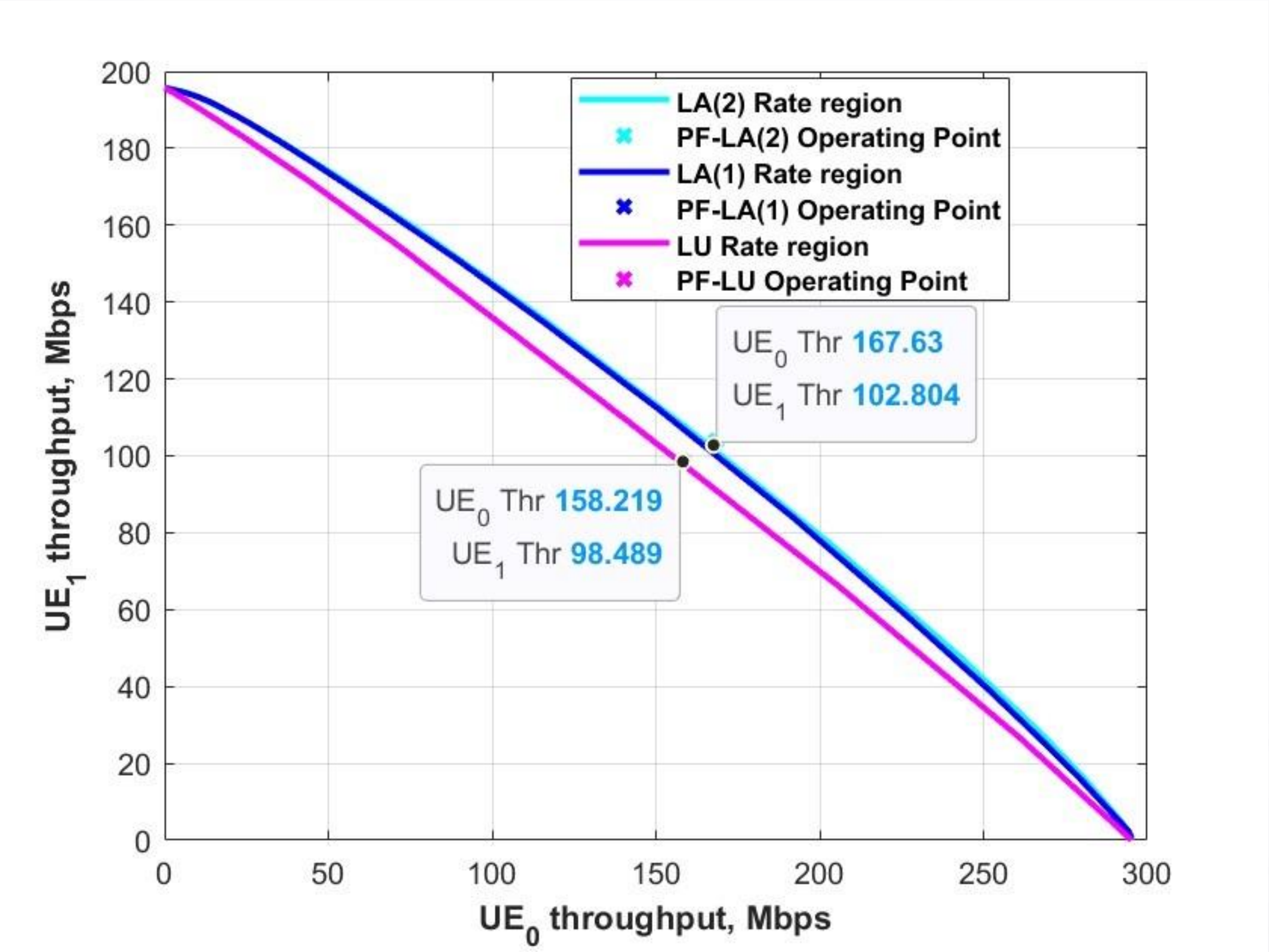


- If there is a positive probability of a scheduled transmission being lost
  - The retransmitted TB "as is," i.e., using the same MCS
  - The gradient algorithm should take TB loss into account when selecting a UE to schedule
- We consider the joint process $\boldsymbol{S}(k) = \big(\big(c_i(k), \mu_i(k)\big), 1 \le i \le N\big)$
  - $c_i(k)$: is the channel state that governs the probability of loss if there is a transmission for UEi
    - Not observed by the scheduler
  - $\gamma_{c,i,\mu}$: probability of transmission loss if channel state is c, and a transmission for UEi is made with MCS μ

Loss-Adaptive (LA) Schedulers

- For each $UE_i, 1 \leq i \leq N,$ and each MCS, $\mu, 1 \leq \mu \leq M$
  - We maintain estimates of
    - $\bar{g}_{i,\mu}$: the average number of reattempts to send a TB for UE_i when the MCS is μ
- At a scheduling opportunity we transmit a TB for the UE with index
  - Notation:
    - $\theta_i(k)$: is the throughput of UE_i up to the scheduling opportunity k
    - $r_{i,\mu_i(k)}$: is the TB size for UE_i for MCS $\mu_i(k)$
  - $\boldsymbol{arg\,max \left(\frac{1}{\theta_i(k)}\right)\left(r_{i,\mu_i(k)} - \theta_i(k)\,\bar{g}_{i,\mu_i(k)}\right)}$: algorithm obtained from theory
    - Interpretation of $\frac{r_{i,\mu_i(k)}}{\theta_i(k)} - \bar{g}_{i,\mu_i(k)}$: reduce the no. of slots of throughput we can get by scheduling UE_i with MCS $\mu_i(k)$, by the average number of retransmissions of a TB
  - $\boldsymbol{arg\,max \left(\frac{1}{\theta_i(k)}\right)\left(\frac{r_{i,\mu_i(k)}}{1+\bar{g}_{i,\mu_i(k)}}\right)}$: a heuristic
- The classical gradient scheduler is called Loss Unadaptive (LU)
- We have found that both these LA schedulers give almost the same rate regions

System Throughput Increases with LA: Equivalent SNR Increase?

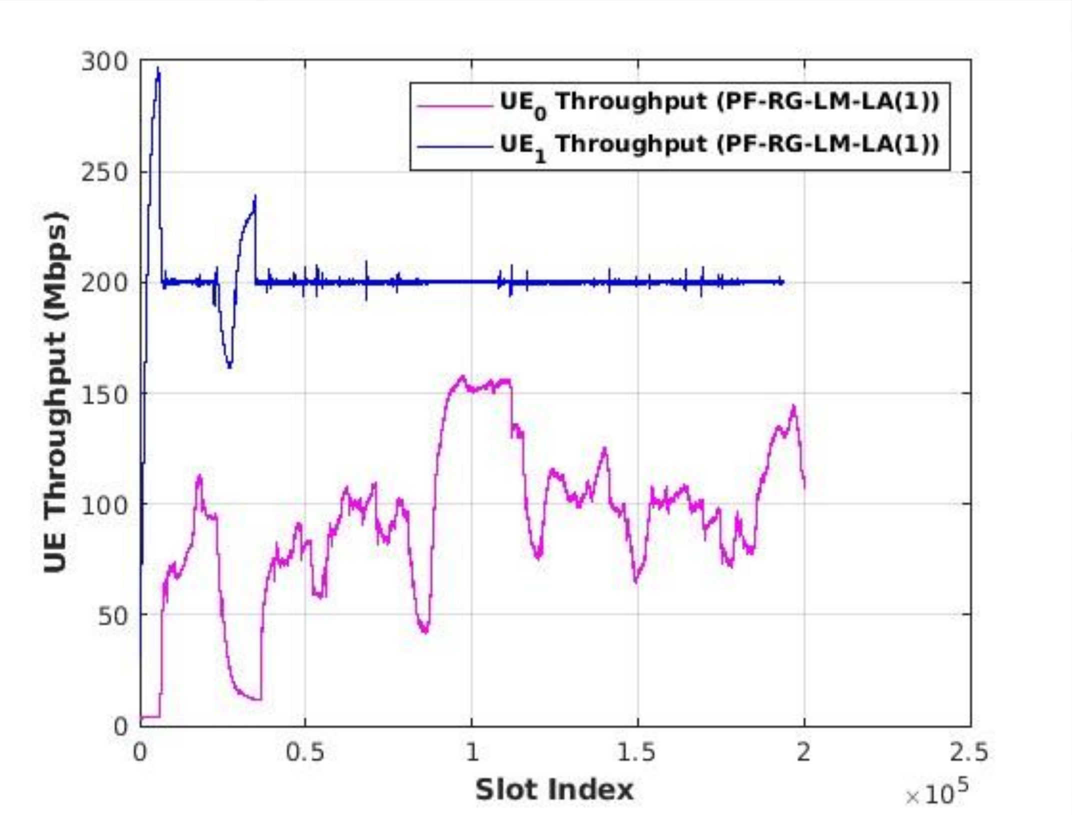


- Example measurements on the OAI-based test-bed
- PF(LA) provides 5% increase in system throughput
  - Compared to PF scheduling
- For a 30 dB operating SNR
  - 5% increase in throughput…
  - …is equivalent to a 1.5 dB increase in SNR
- Effort required for LA
  - A new measurement: $\bar{g}_{i,\mu_i(k)}$
  - Minor changes in the scheduler code

The PF Scheduler with Rate Guarantee (PF(LA)-RG-LM)

- For each $UE_i, 1 \le i \le N,$ and each MCS, $\mu, 1 \le \mu \le M$
- We maintain estimates of
  - $\bar{g}_{i,\mu}$: the average number of reattempts to send a TB for UE_i when the MCS is μ
- At a scheduling opportunity we transmit a TB for the UE with index
  - $\arg\max \left(\frac{1}{\theta_i(k)} + \nu_i(k)\right)\left(\frac{r_{i,\mu_i(k)}}{1+\bar{g}_{i,\mu_i(k)}}\right)$
  - where
    - $\theta_i(k)$: is the EWMA throughput of UE_i up to the scheduling opportunity k
    - $r_{i,\mu_i(k)}$: is the TB size for UE_i for MCS $\mu_i(k)$
  - and
    - $\nu_i(k)$: is the index-bias, updated as
      - $\nu_i(k+1) = \nu_i(k) + b\,(\theta_{i,\min} - \theta_i(k))$
      - with $b \ll a$, the averaging parameter for the throughputs
  - This is a two time-scale stochastic approximation type algorithm
    - The index-bias converges to the Lagrange multiplier (LM)

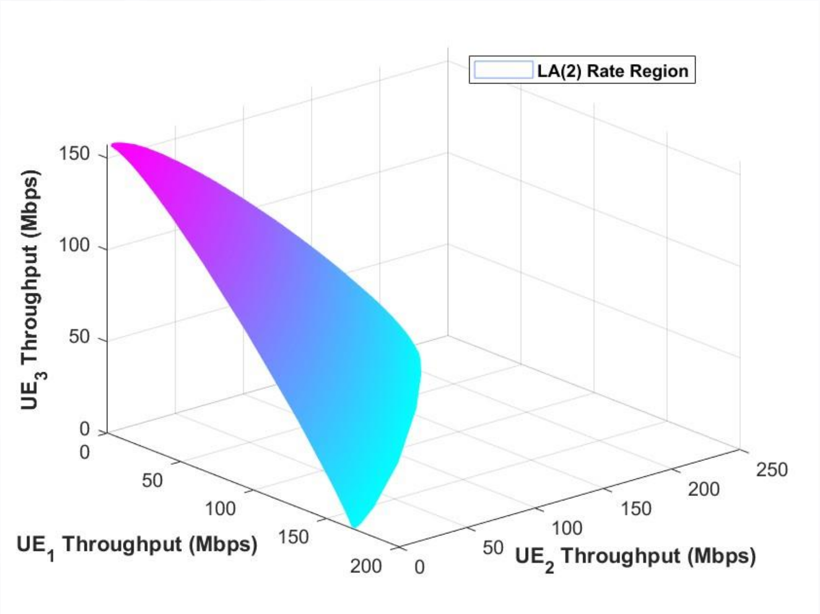
Rate Guarantee with an Arbitrarily Moving UE

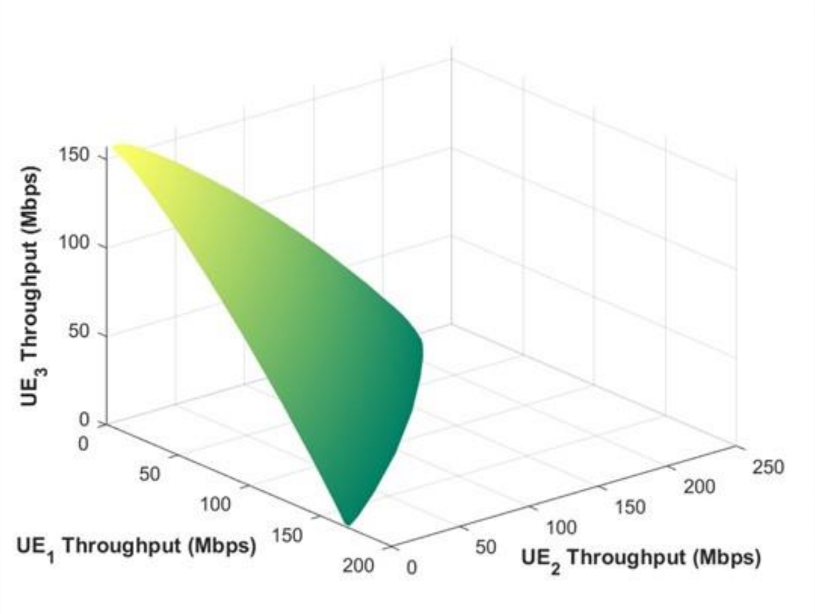


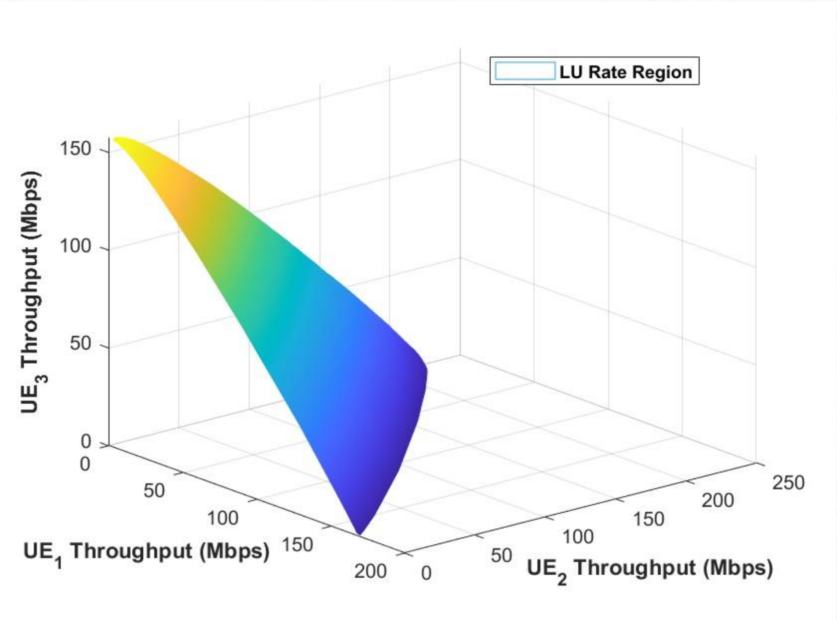
- UE_1 throughput remains at 200 Mbps
  - Except where the rate region cannot accommodate 200 Mbps
- UE_0 throughput varies depending on whatever the rate region boundary accommodates

3 UEs NLoS, One UE with a Rate Guarantee, using PF(LA)-RG-LM

- UE2 is place at ≈ 3 meters from the gNB, NLoS
  - Rate guarantee: 150 Mbps
  - Index-bias estimate: 2.3×10^{-4}
- UE1 and UE3 are placed at ≈ 4 meters from the gNB, NLoS







PF-LA(2) - (UE1,UE2,UE3) = (61,82,68)
RG-LA(2) -(UE1,UE2,UE3) = (34,152,37)

PF-LA(1) - (UE1,UE2,UE3) = (62,80,67)
RG-LA(1) - (UE1,UE2,UE3) = (36,151,37)

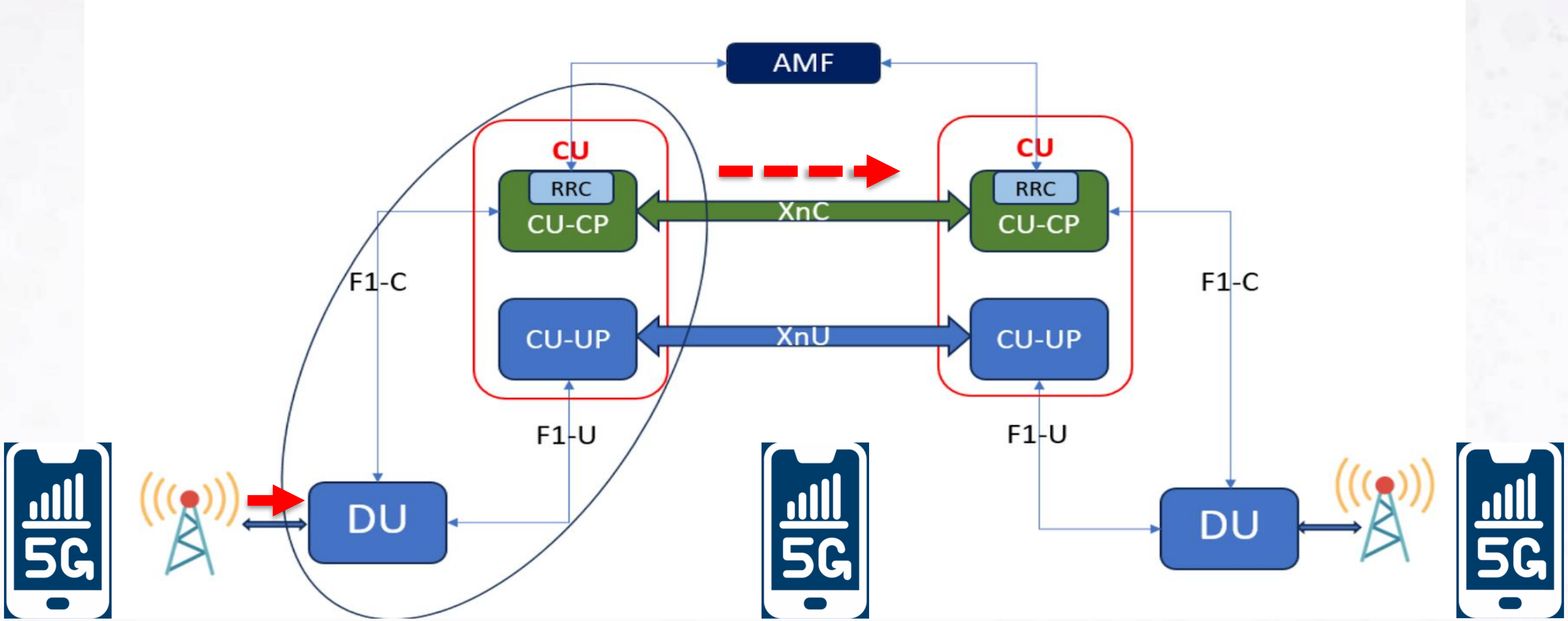
PF-LU - (UE1,UE2,UE3) = (60,75,68)
RG-LU - (UE1,UE2,UE3) = (33,149,35)

- **Loss adaptive PF scheduling yields 3-4 % improvement in total throughput**

Demo of GBR Scheduler implemented in the private 5G setup in our 5G lab

https://www.linkedin.com/posts/ios-mcn_gbr-on-ios-mcn-setup-activity-7218237246141812737-vjCE?utm_source=li_share&utm_content=feedcontent&utm_medium=g_dt_web&utm_campaign=copy

Xn-Handover

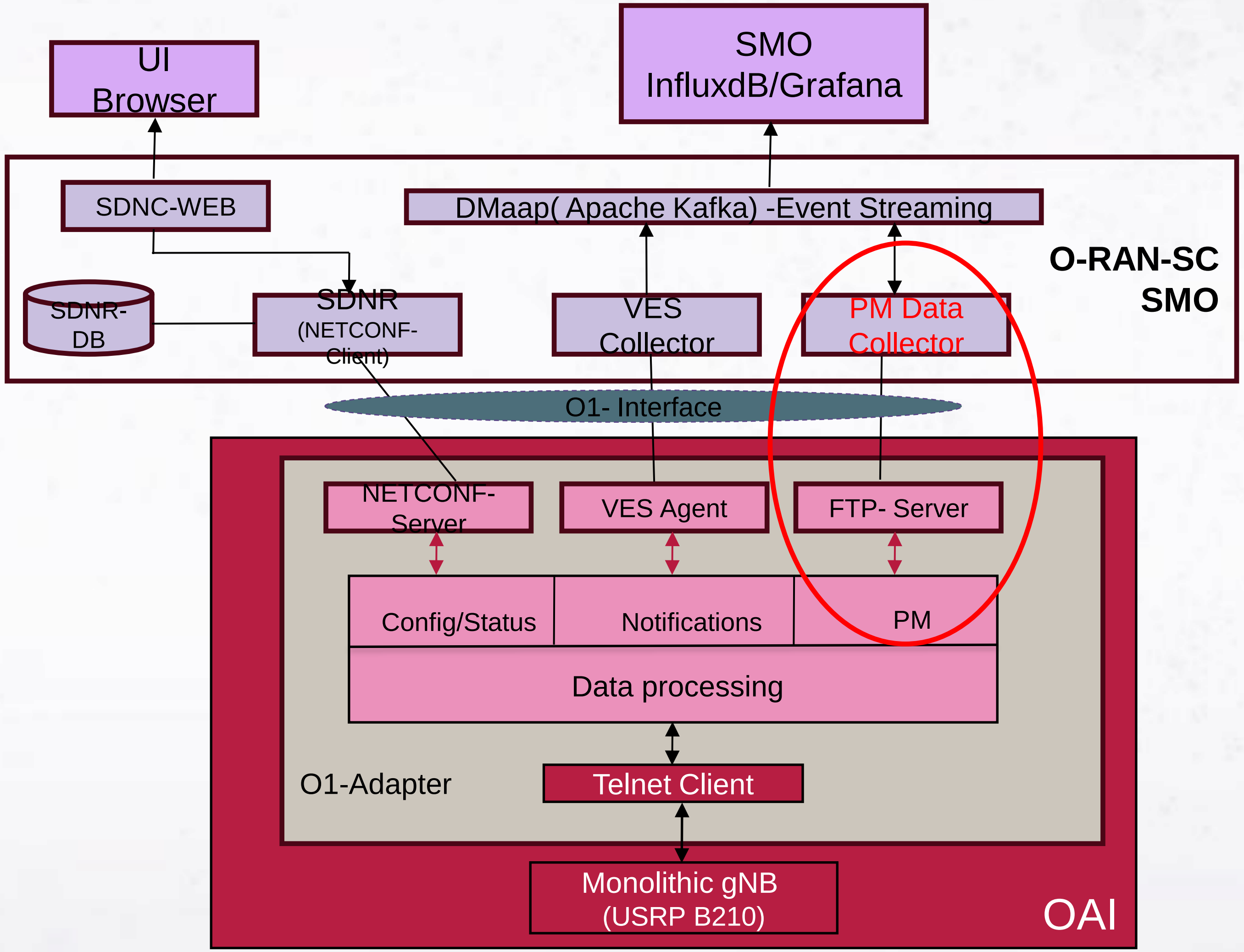


Xn-Handover (Xn-HO):

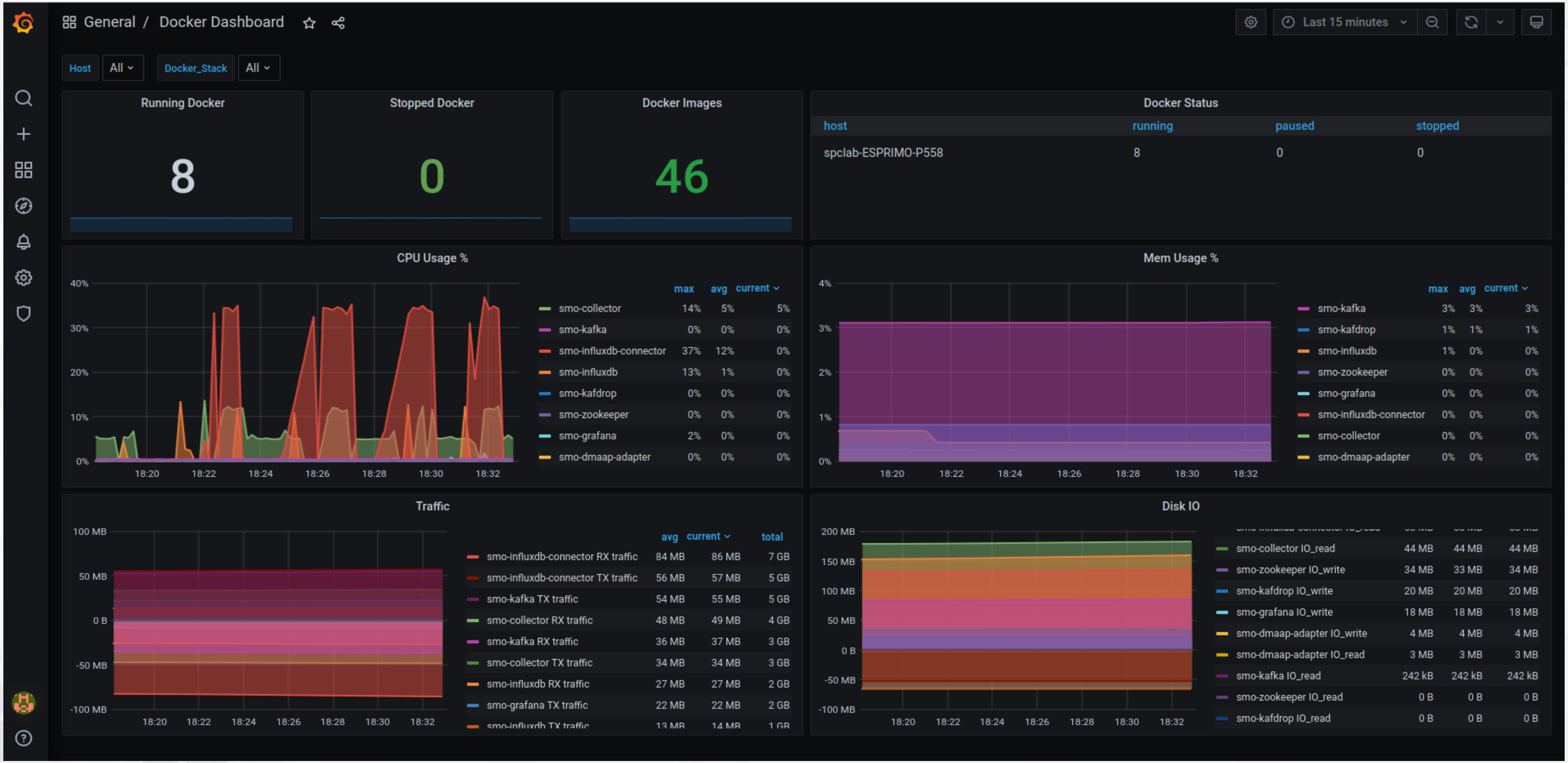
- **Handover from Source gNB to Target gNB depending upon BW, Power, etc.**
- **Complete profile of a UE is transferred**

Non-RT RIC Architecture

- Sample RIC to demo infrastructure for config and controls
- Implement an SMO framework (provision for AI/ML integration)
  - R1 Interface
  - A1 interface
  - O1 interface
- R1 services:
  - one-one, one-many, pub-sub, routed etc.,



SMO: Resource Utilization Grafana



OAI Enhancements

- OAI code tested with commercial 5G UEs, 9 Nos.
- 9 out of 10 UEs are live streaming from YouTube


```
2024-07-18 19:39:15.%f +0530 monitor - INFO - ***file_content***{
        "event":        {
                "measurementFields":    {
                        "DRB.MeanActiveUeDl":   10,
                        "DRB.MaxActiveUeDl":    10,
                        "DRB.MeanActiveUeUl":   10,
                        "DRB.MaxActiveUeUl":    10,
                        "RRU.PrbTotDl": 7,
                        "DRB.UEThpDl":  5194,
                        "DRB.UEThpUl":  132
                },
                "commonEventHeader":    {
                        "domain":       "pm_data",
                        "startEpochMicrosec":   1721311750,
                        "reportingEntityName":  "rama",
                        "eventId":      "spclab",
                        "lastEpochMicrosec":    1714641000646236,
                        "sequence":     356
                }
        }
}
```

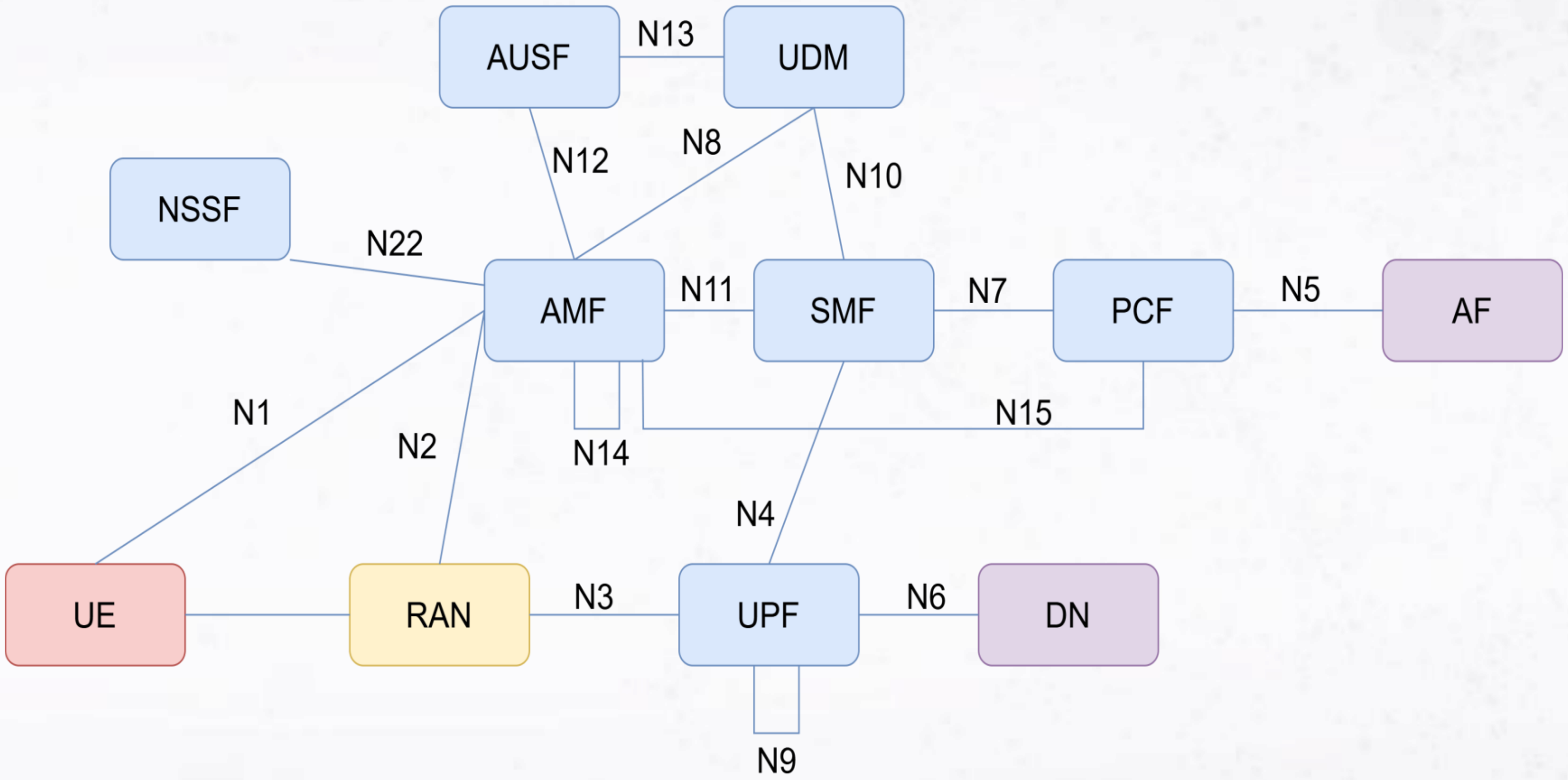
Part II

- 5G System Architecture
- Overview of OAI Codebase

Part II: 5G System Architecture and OAI Codebase

Overall Architecture

- 5G Design choices
  - Dividing monolithic element into smaller Network Functions
  - Virtualization

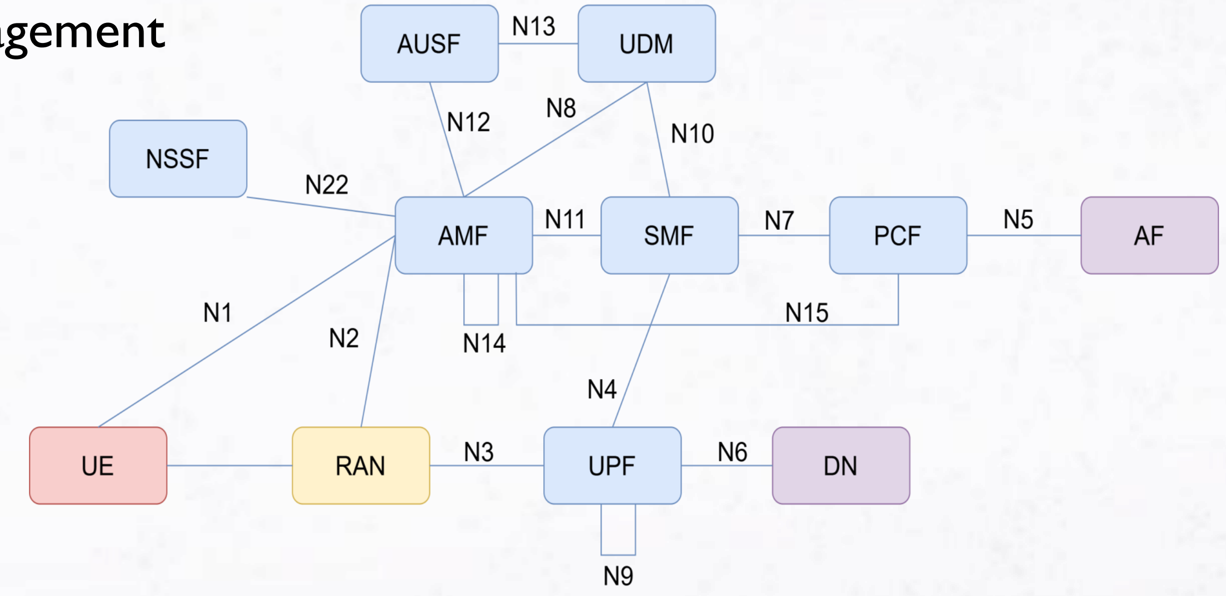


AUSF: Authentication Server Function
AMF: Access and Mobility Management Function
PCF: Policy Control Function
UDM: Unified Data Management

AF: Application Function
DN: Data Network SMF: Session Management Function
UPF: User Plane Function
NSSF: Network Slice Selection Function

Core Network (CN) Functions

- Access and Mobility management Function (AMF)
  - Termination of RAN control plane interface (N2) and NAS (N1)
  - Registration management and Connection management
  - Access authentication and authorization
- Session Management Function (SMF)
  - Session establish, modification and release
  - UE IP address management
- Authentication Service Function (AUSF)
  - UE authentication
- User Plane Function (UPF)
  - Packet routing and forwarding
  - QoS handling for user plane
  - User-plane part of policy rule enforcement



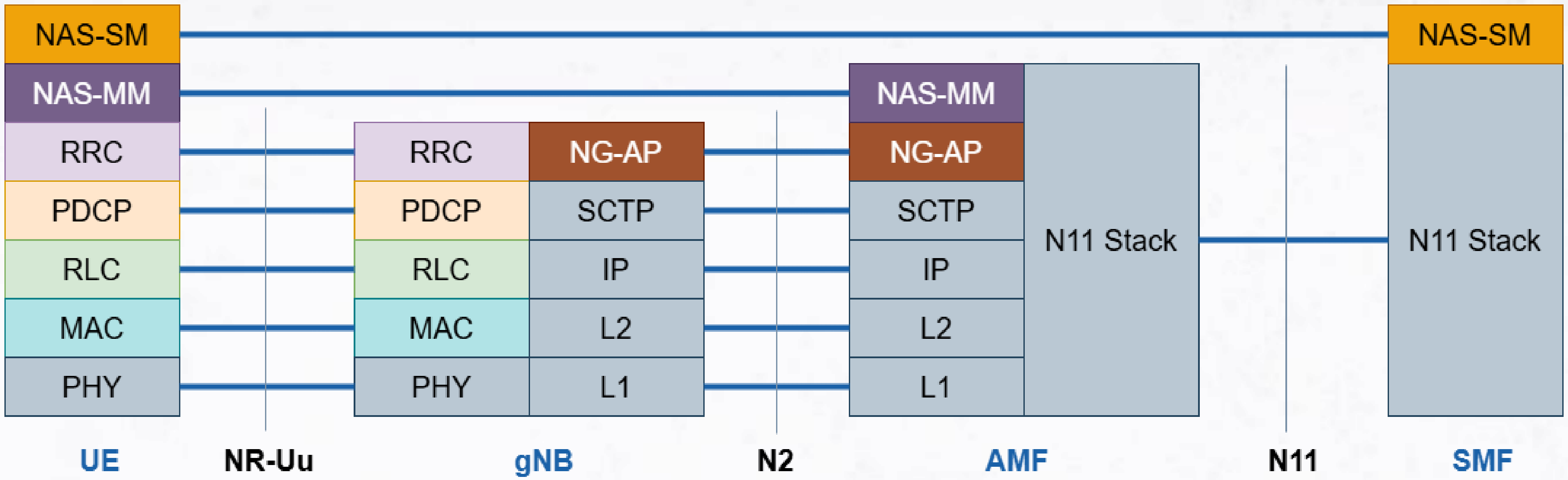
OAI 5G CN

- Main repository https://gitlab.eurecom.fr/oai/cn5g
- Each NF has its own repository
  - Example: https://gitlab.eurecom.fr/oai/cn5g/oai-cn5g-amf
    oai-cn5g-amf is meant for AMF NF
  - Documentation available in /docs folder
- All OAI 5G CN NFs are dockerized

```
docker compose pull
  Pulling mysql              ... done
  Pulling oai-nrf            ... done
  Pulling oai-udr            ... done
  Pulling oai-udm            ... done
  Pulling oai-ausf           ... done
  Pulling oai-amf            ... done
  Pulling oai-smf            ... done
  Pulling oai-upf            ... done
  Pulling oai-traffic-server ... done
```

- MySQL database in the backend stores the subscriber data

Protocol Stack: Control Plane

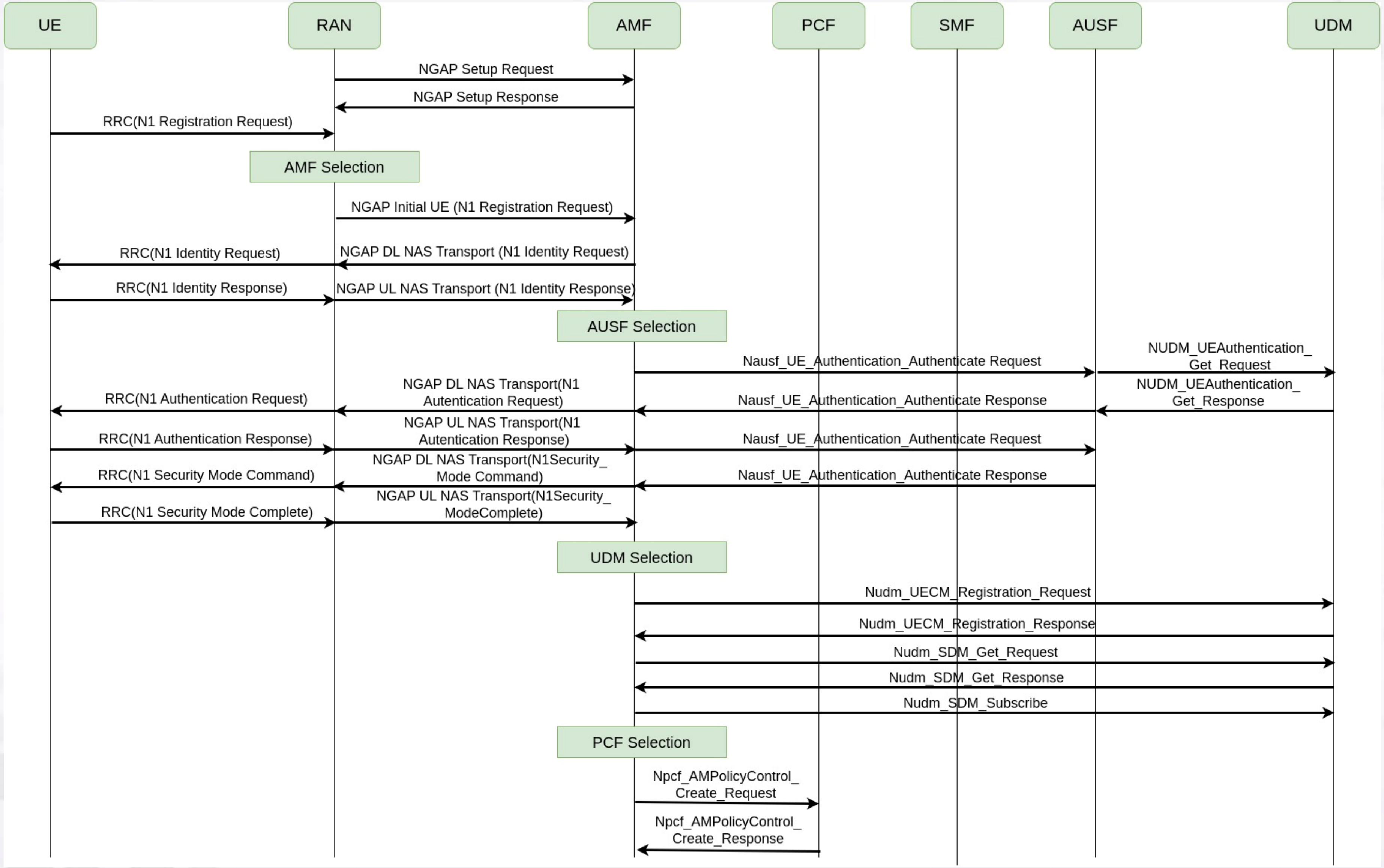


Registration & Session management

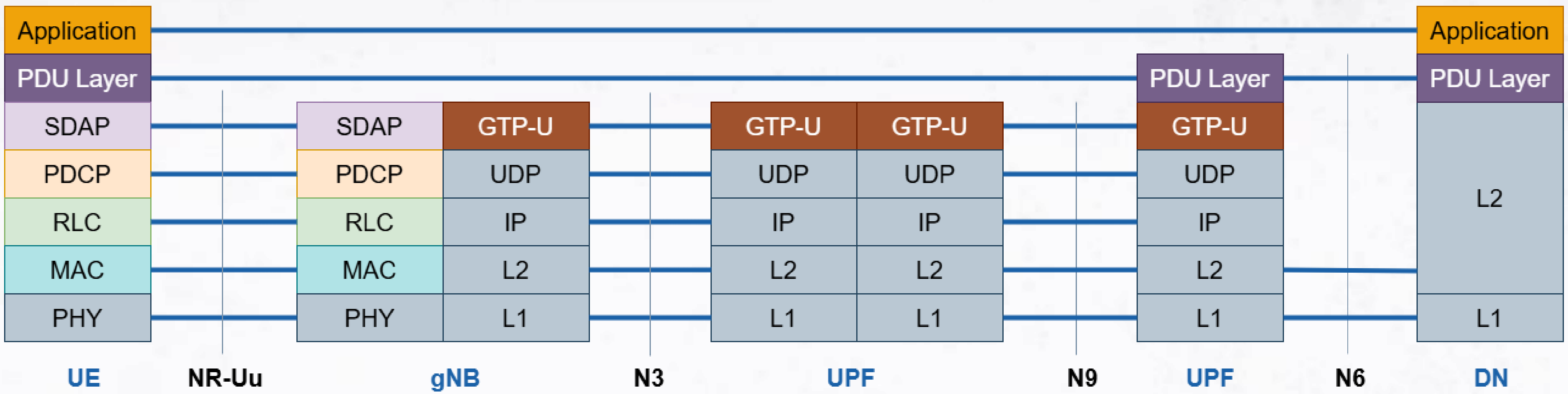
Non-**A**ccess **S**tratum: Functional layer to exchange control plane messages between UE and CN

- Establishment and management of communication sessions (NAS-SM)
- Mobility management (NAS-MM)
- Example NAS messages: UE attach and registration, authentication etc…

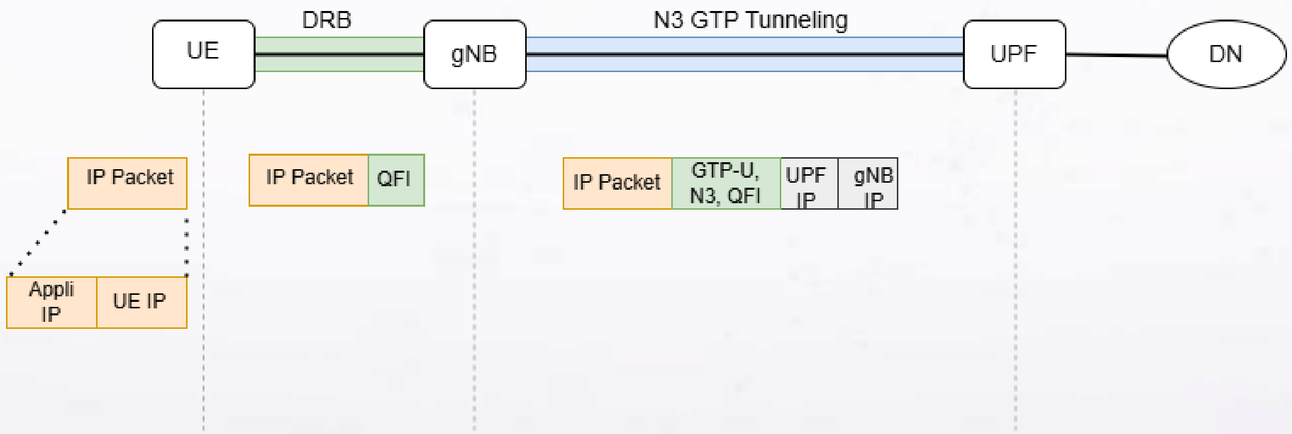
UE Registration Call Flow



User plane

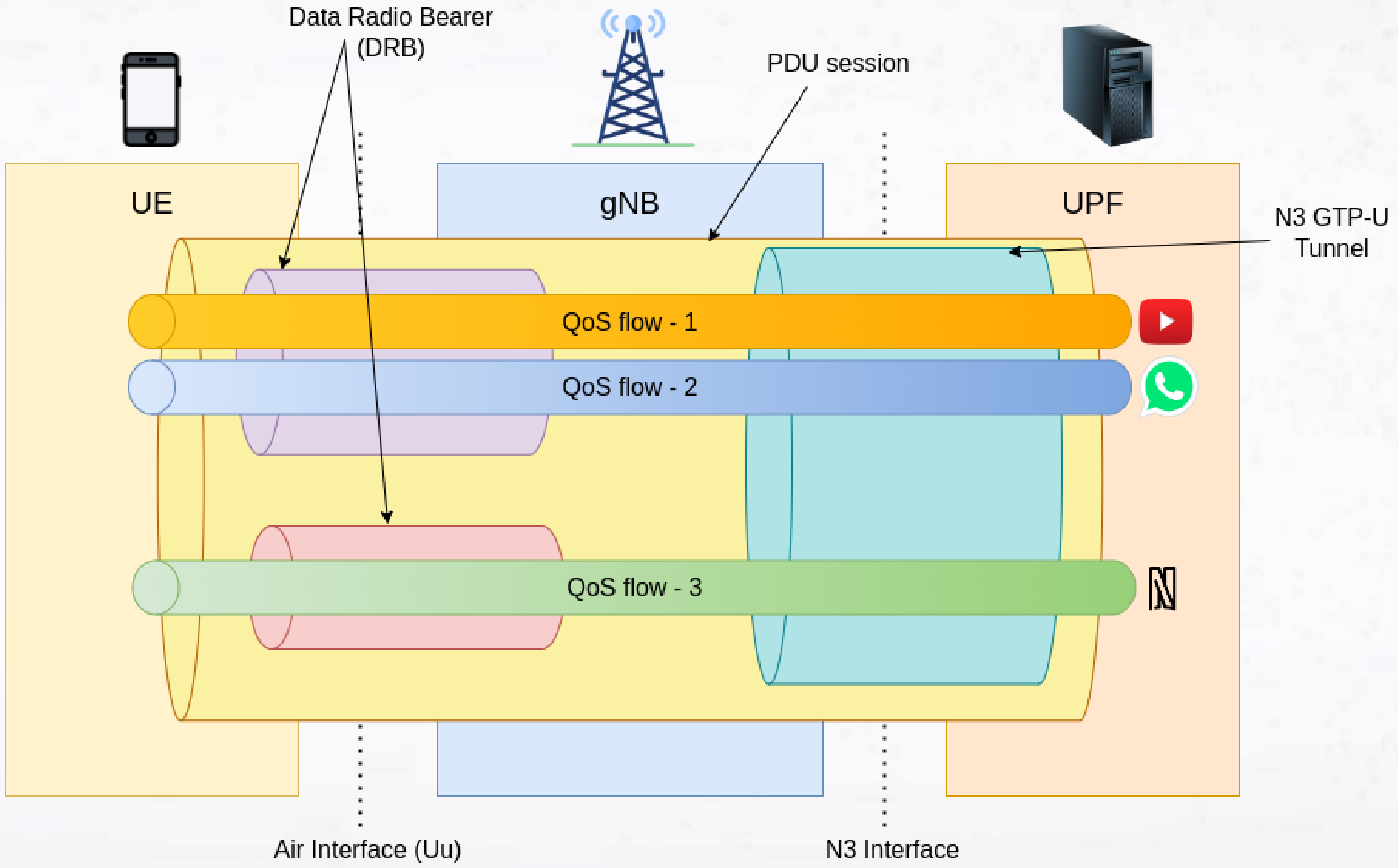


PDU Session

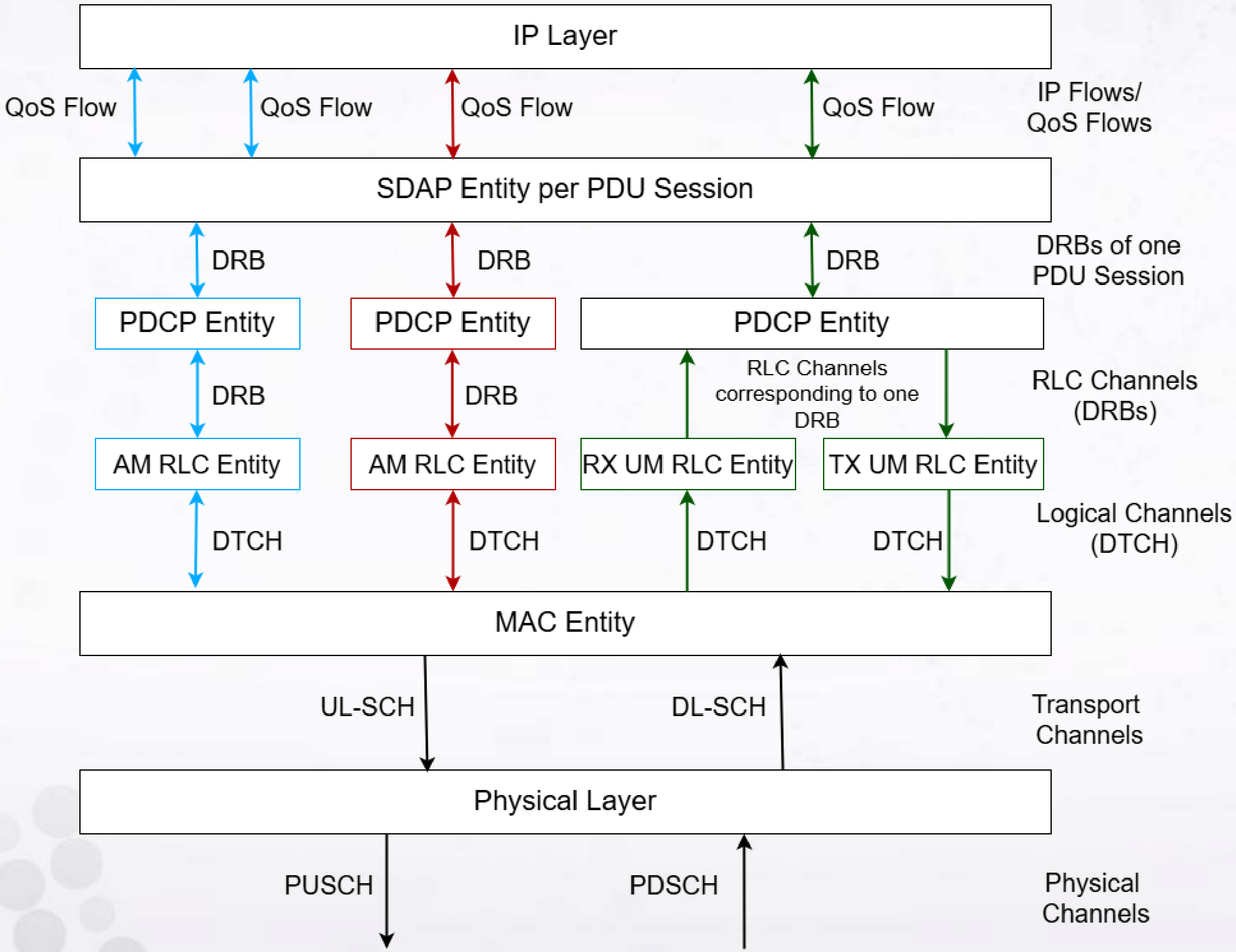


IP connection

PDU session QoS Flows



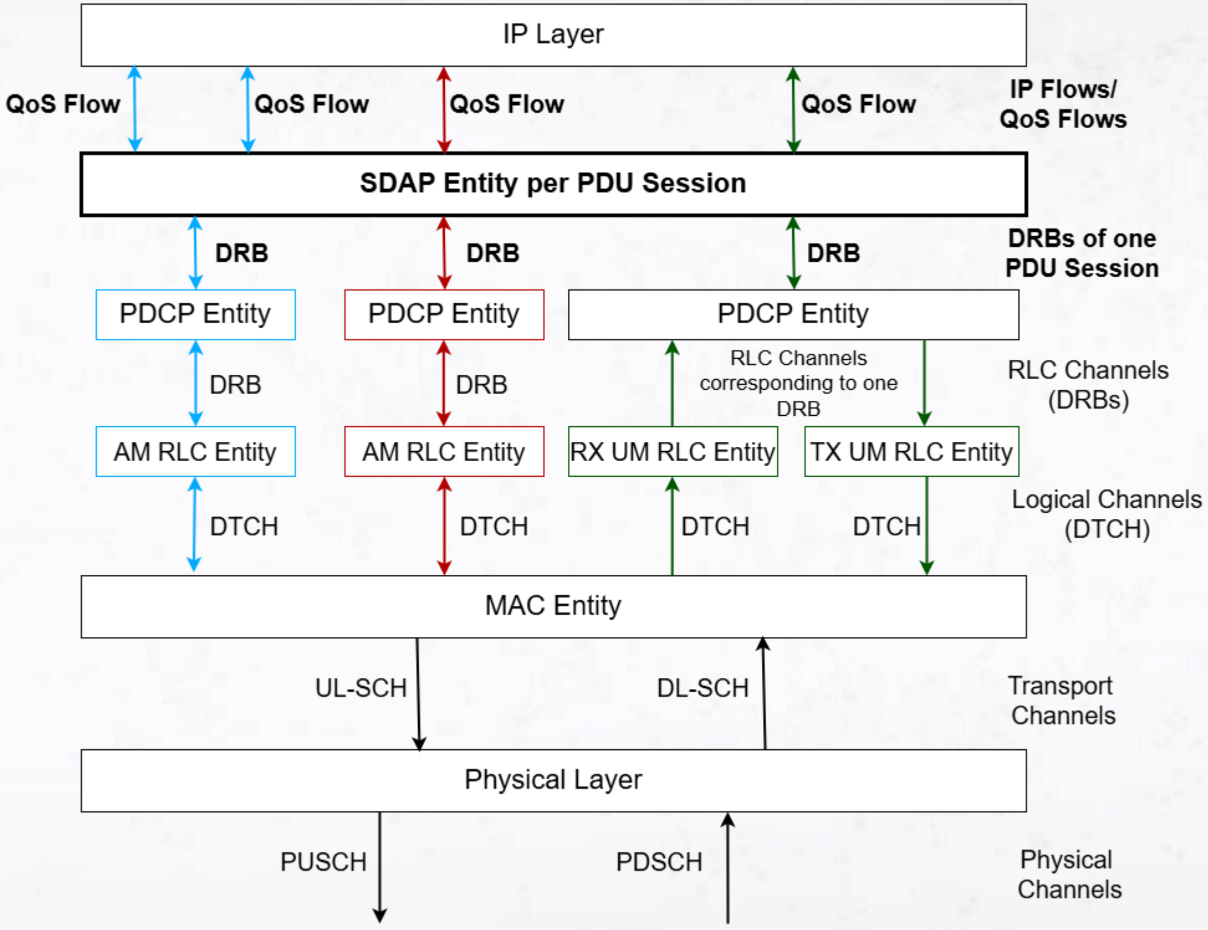
User Plane RAN Protocol Stack



SDAP

Service Data Adaption Protocol [3GPP TS 37.324]

- Mapping between QoS flows and data radio bearers
- Marking QoS flow ID in both UL and DL packets
- One SDAP per PDU session
- SDAP entity establishment and release are managed by RRC



SDAP

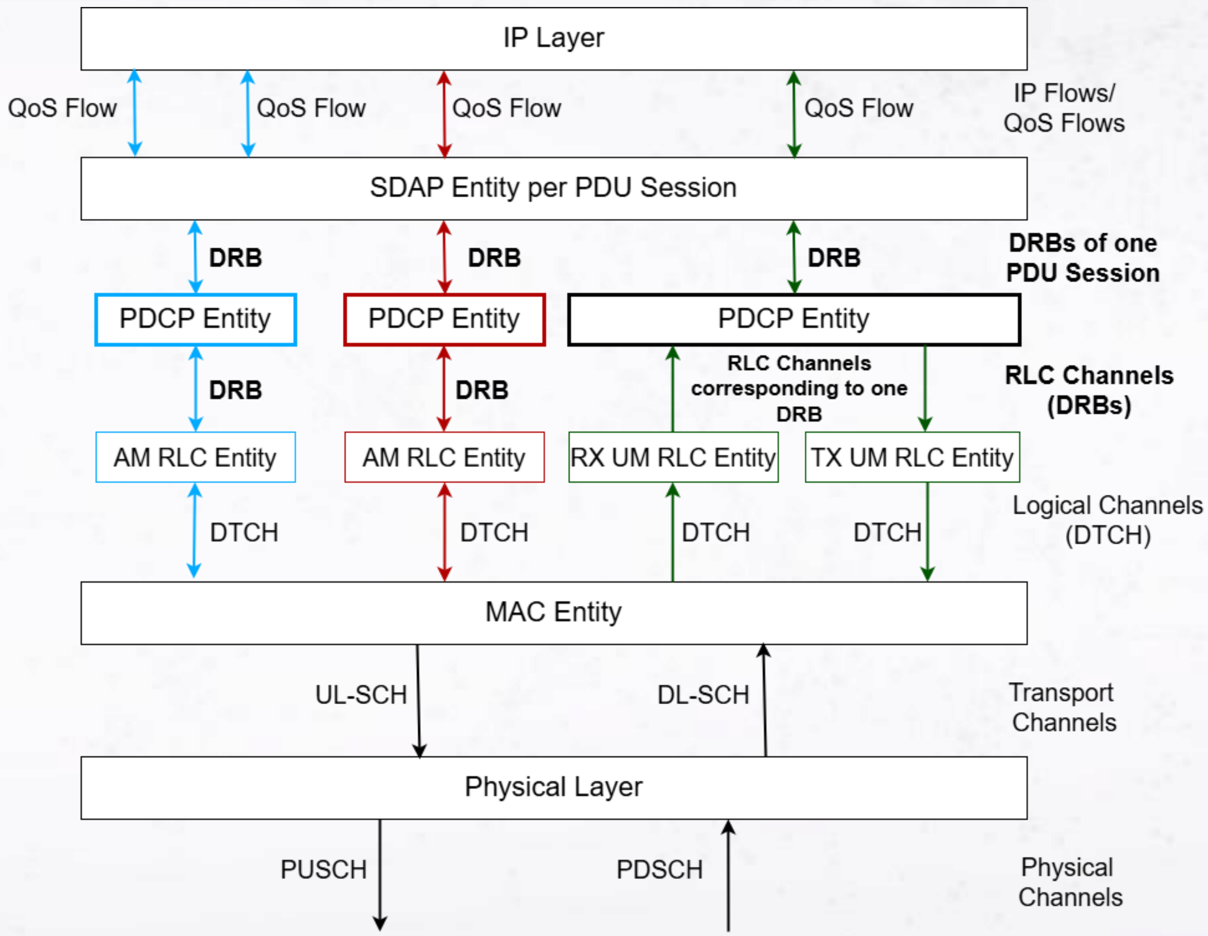
```
typedef struct nr_sdap_entity_s {
  ue_id_t ue_id;
  rb_id_t default_drb;
  int pdusession_id;
  qfi2drb_t qfi2drb_table[SDAP_MAX_QFI];

  void (*qfi2drb_map_update)(struct nr_sdap_entity_s *entity, uint8_t qfi, rb_id_t drb,
  void (*qfi2drb_map_delete)(struct nr_sdap_entity_s *entity, uint8_t qfi);
  rb_id_t (*qfi2drb_map)(struct nr_sdap_entity_s *entity, uint8_t qfi);

  nr_sdap_ul_hdr_t (*sdap_construct_ctrl_pdu)(uint8_t qfi);
  rb_id_t (*sdap_map_ctrl_pdu)(struct nr_sdap_entity_s *entity, rb_id_t pdcp_entity, in
```

/openair2/SDAP/nr_sdap/

PDCP

Packet Data Convergence Protocol [3GPP TS 38.323]

- Mapping radio bearers to RLC channels
- RLC entity mapped to a unique PDCP entity
- Functionalities
  - •Header compression and decompression using the ROHC protocol
  - •Ciphering and deciphering
  - •Integrity protection and integrity verification
  - •Out-of-order delivery
  - •Duplicate discarding ……...



PDCP

```c
typedef struct nr_pdcp_entity_t {
  nr_pdcp_entity_type_t type;

  /* functions provided by the PDCP module */
  void (*recv_pdu)(struct nr_pdcp_entity_t *entity, char *buffer, int size);
  int (*process_sdu)(struct nr_pdcp_entity_t *entity, char *buffer, int size,
                     int sdu_id, char *pdu_buffer, int pdu_max_size);
  void (*delete_entity)(struct nr_pdcp_entity_t *entity);
  void (*release_entity)(struct nr_pdcp_entity_t *entity);
  void (*suspend_entity)(struct nr_pdcp_entity_t *entity);
  void (*reestablish_entity)(struct nr_pdcp_entity_t *entity,
                             const nr_pdcp_entity_security_keys_and_algos_t *param
  void (*get_stats)(struct nr_pdcp_entity_t *entity, nr_pdcp_statistics_t *out);

  /* set_security: pass -1 to parameters->integrity_algorithm / parameters->cipher
   *               to keep the corresponding current algorithm and key
```

```c
typedef struct nr_pdcp_sdu_t {
  uint32_t                   count;
  char                       *buffer;
  int                        size;
  nr_pdcp_integrity_data_t msg_integrity;
  struct nr_pdcp_sdu_t       *next;
} nr_pdcp_sdu_t;
```

```c
nr_pdcp_entity_t *new_nr_pdcp_entity(
    nr_pdcp_entity_type_t type,
    int is_gnb,
    int rb_id,
    int pdusession_id,
    bool has_sdap_rx,
    bool has_sdap_tx,
    void (*deliver_sdu)(void *deliver_sdu_data, struct nr_pdcp_entity_t *entity,
                        char *buf, int size,
                        const nr_pdcp_integrity_data_t *msg_integrity),
    void *deliver_sdu_data,
    void (*deliver_pdu)(void *deliver_pdu_data, ue_id_t ue_id, int rb_id,
                        char *buf, int size, int sdu_id),
```

openair2/LAYER2/nr_pdcp

PDCP

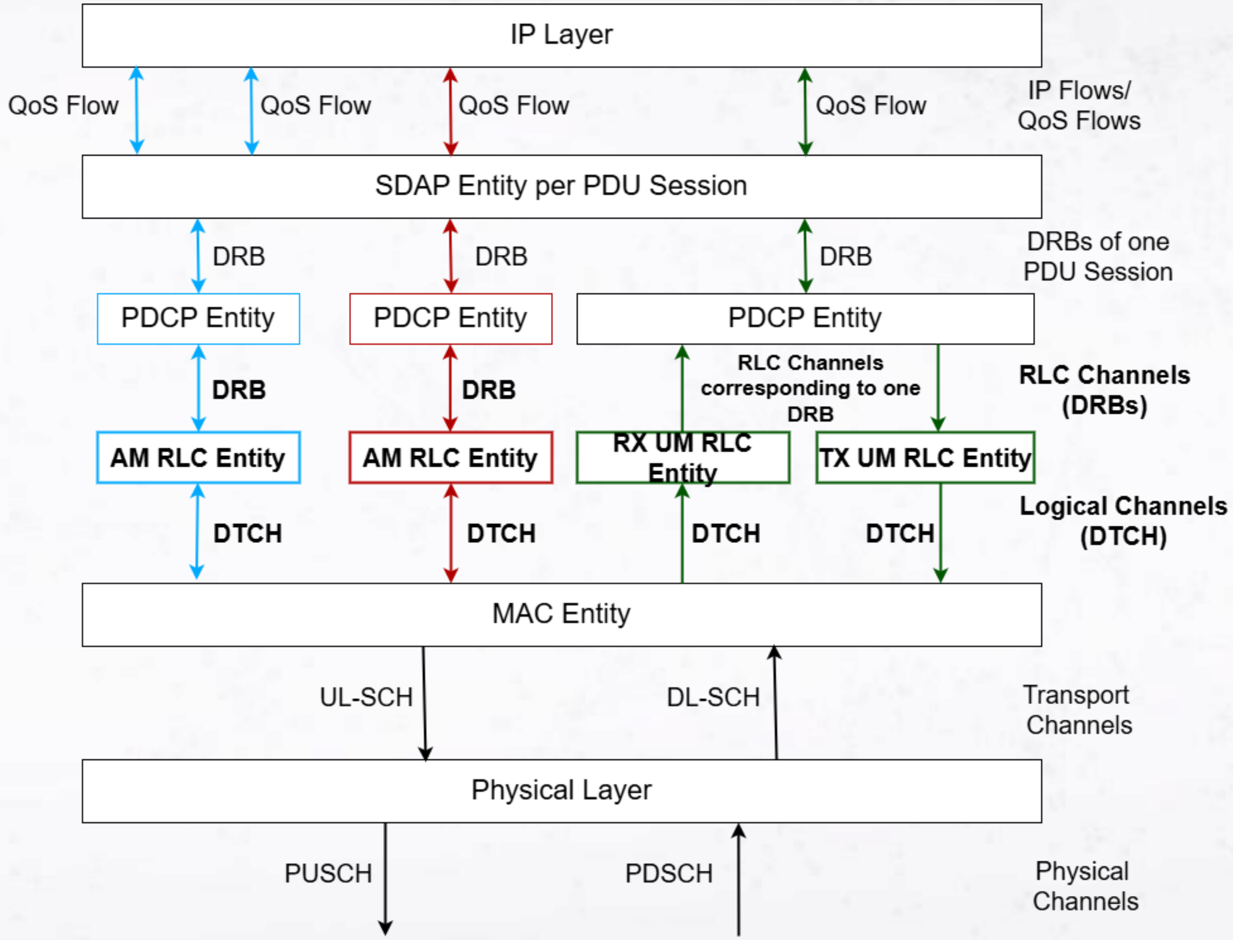
```
typedef void nr_pdcp_ue_manager_t;

typedef struct nr_pdcp_ue_t {
  ue_id_t ue_id;
  nr_pdcp_entity_t *srb[3];
  nr_pdcp_entity_t *drb[MAX_DRBS_PER_UE];
} nr_pdcp_ue_t;
```

UE context at the PDCP layer

RLC

Radio Link Control [3GPP TS 38.322]

- Mapping RLC channels to Logical channels
- One-to-one mapping between RLC channel and logical channel
- Sequence numbering, Error correction (ARQ), Segmentation and Buffering
- Different modes
  - Un-Acknowledge Mode (UM)
  - Acknowledge Mode (AM)



OAI RLC

```c
typedef struct nr_rlc_entity_t {
  /* functions provided by the RLC module */
  void (*recv_pdu)(struct nr_rlc_entity_t *entity, char *buffer, int size);
  nr_rlc_entity_buffer_status_t (*buffer_status)(
      struct nr_rlc_entity_t *entity, int maxsize);
  int (*generate_pdu)(struct nr_rlc_entity_t *entity, char *buffer, int size);

  void (*recv_sdu)(struct nr_rlc_entity_t *entity, char *buffer, int size,
                   int sdu_id);

  void (*set_time)(struct nr_rlc_entity_t *entity, uint64_t now);

  void (*discard_sdu)(struct nr_rlc_entity_t *entity, int sdu_id);
```

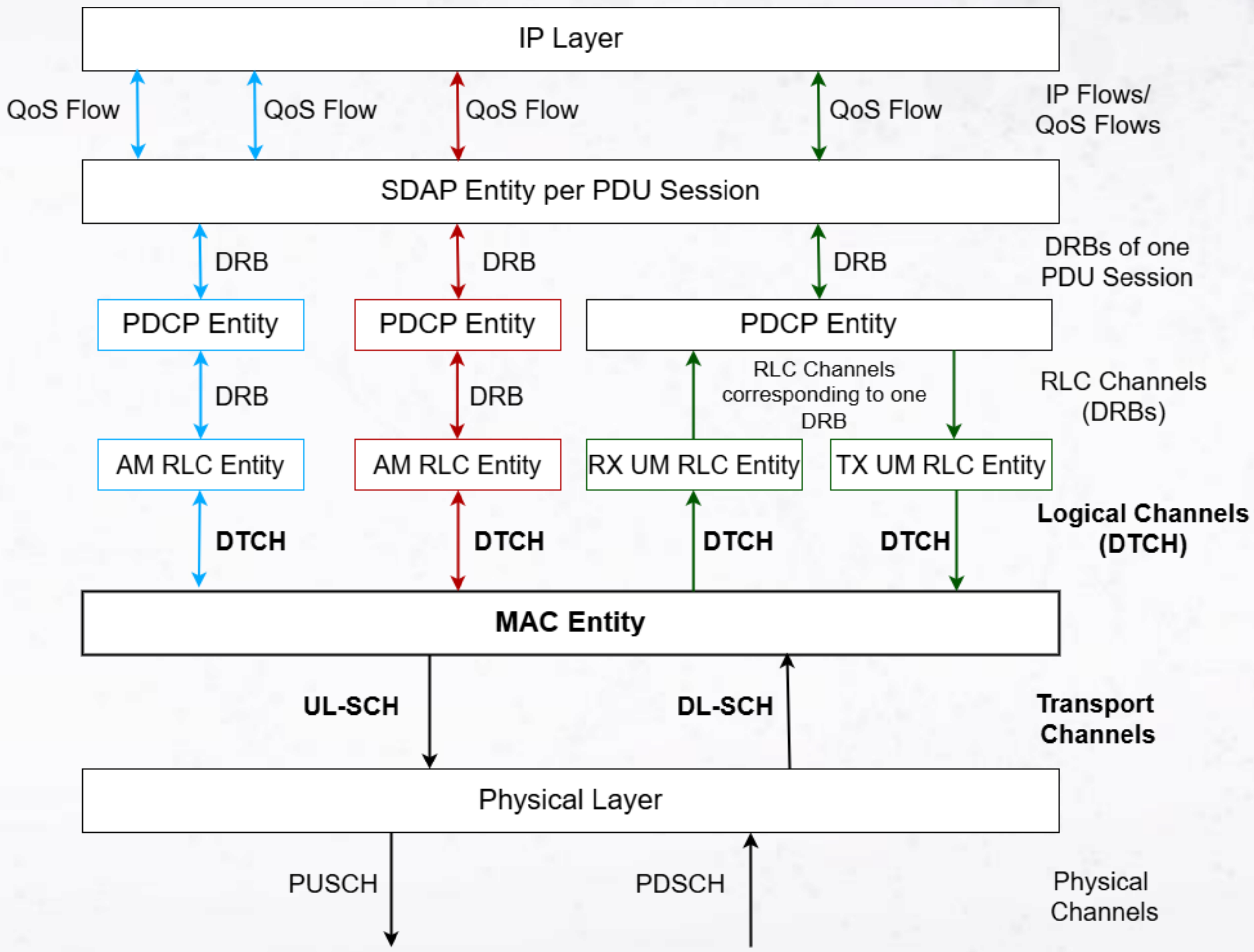
openair2/LAYER2/nr_rlc

```c
typedef struct nr_rlc_rb_t {
  nr_rlc_rb_type type;
  union {
    int srb_id;
    int drb_id;
  } choice;
} nr_rlc_rb_t;

typedef void (*rlf_handler_t)(int rnti);

typedef struct nr_rlc_ue_t {
  int ue_id;
  nr_rlc_entity_t *srb0;
  nr_rlc_entity_t *srb[3];
  nr_rlc_entity_t *drb[MAX_DRBS_PER_UE];
  nr_rlc_rb_t lcid2rb[32];
  rlf_handler_t rlf_handler;
} nr_rlc_ue_t;
```

MAC

Medium Access Control [3GPP TS 38.321]

- Mapping Logical channels to Transport channels
- Multiplexing of transport channels and forming the Transport Block (TB)
- UE scheduling
- Error correction through HARQ
- Maintaining UE synchronization
- Adaptive modulation (mcs), power control



MAC SCHEDULING

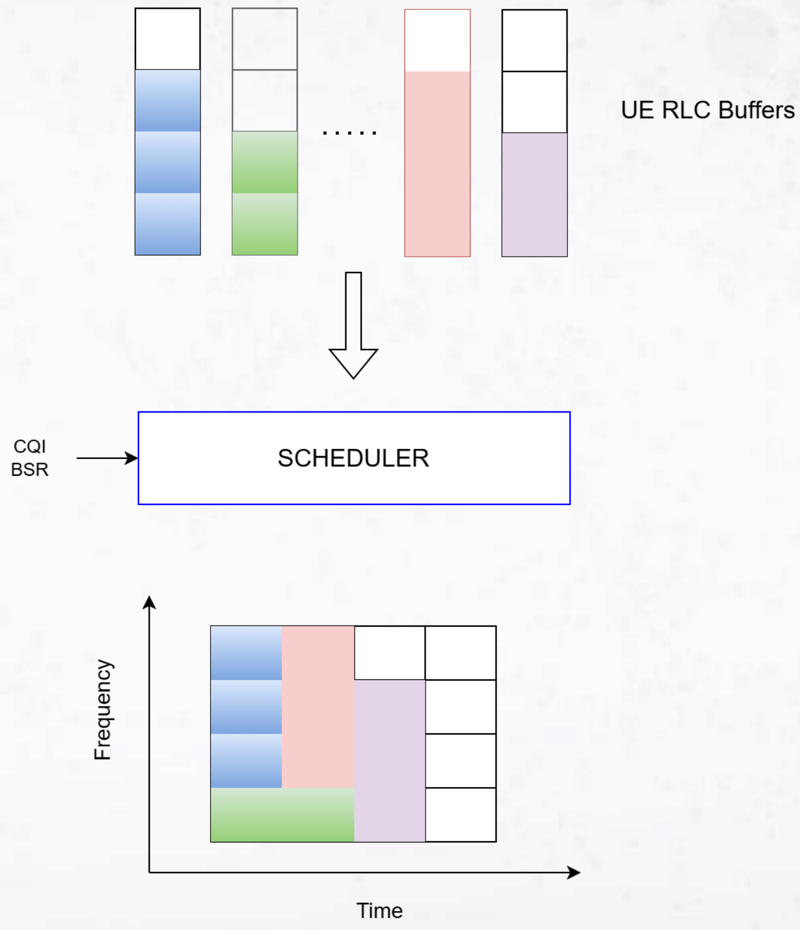
- Which UE gets
  - What PRBs?
  - Which MCS
- Criterion
  - Channel quality
  - Buffer status reports

- Round-Robin scheduling
  - Schedule UEs in rotating manner
- Channel-aware scheduling
  - Max-throughput

$$UE_{i^*} = arg\max_i R_i$$

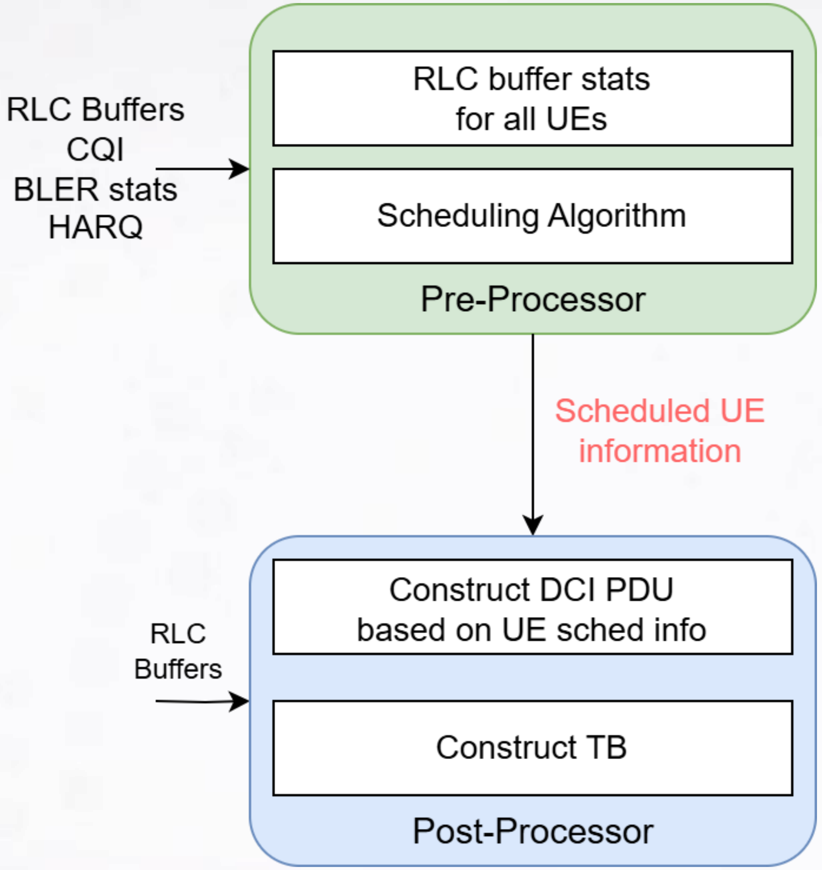
  - Proportional fair

$$UE_{i^*} = arg\max_i \frac{R_i}{\overline{R_i}}$$



Multi-user scheduling

OAI MAC



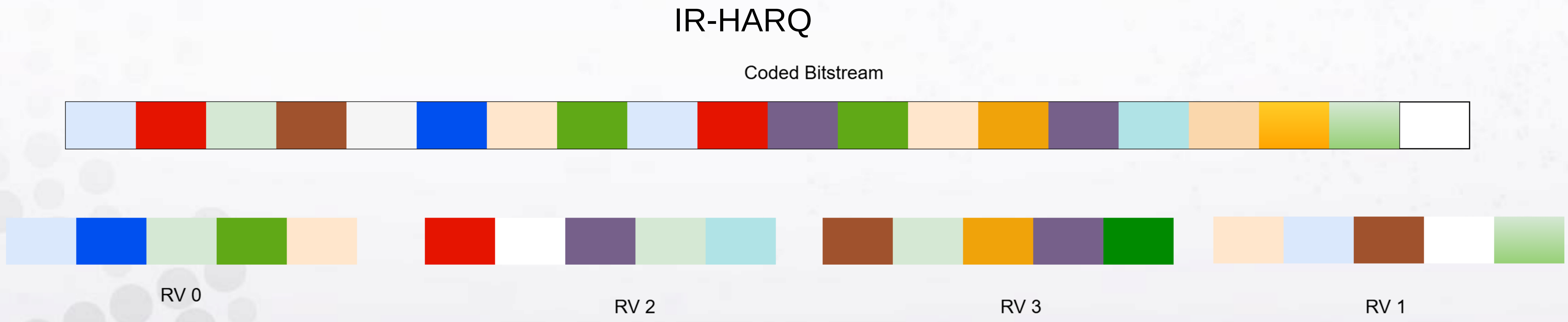

```
nr_mac->pre_processor_ul(module_id,
frame, slot);

gNB_mac->pre_processor_dl(module_id,
frame, slot);
```

openair2/LAYER2/NR_MAC_gNB/gNB_scheduler.c
openair2/LAYER2/NR_MAC_gNB/gNB_scheduler_ulsch.c
openair2/LAYER2/NR_MAC_gNB/gNB_scheduler_dlsch.c

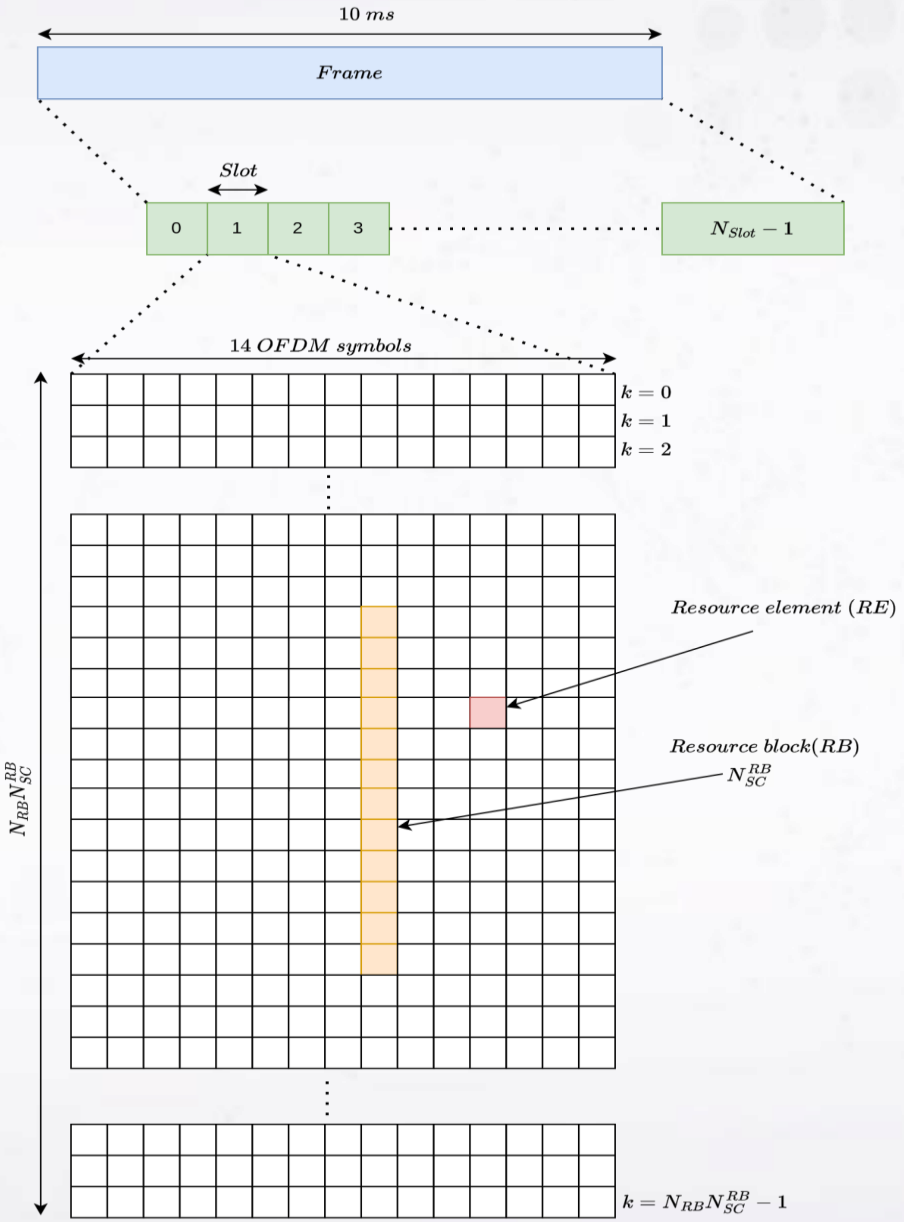
https://gitlab.eurecom.fr/oai/openairinterface5g/-/blob/develop/doc/MAC/mac-usage.md

Error Correction

- Error correction at Transport Block (TB) level
  - Channel Coding
  - Incremental Redundancy HARQ
- Multi-rate Rate LDPC codes for data channels (PDSCH, PUSCH)



Physical Layer



Physical Channels

Downlink

Physical Broadcast Channel (PBCH)
Physical Synchronization Signal (PSS)
Secondary Synchronization Signal (SSS)

Physical Downlink Shared Channel (PDSCH)
Physical Downlink Control Channel (PDCCH)

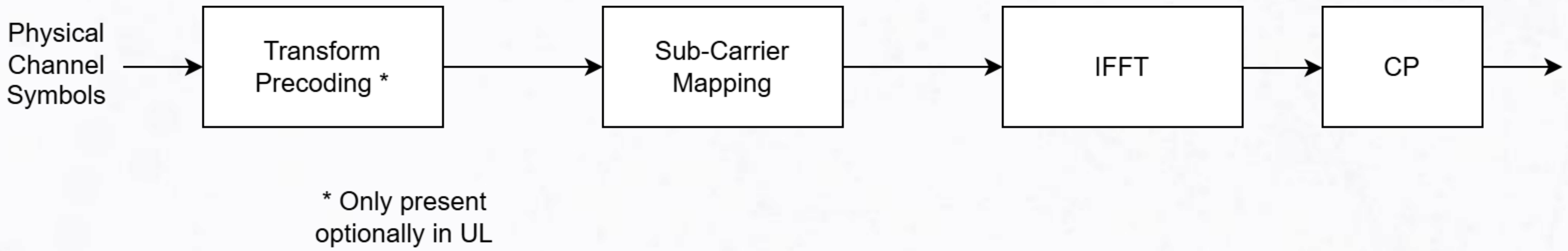
Demodulation Reference Signal (DMRS)
Channel State Information Signal (CSI-RS)
Positioning Reference Signal (PRS)

Uplink

Physical Uplink Shared Channel (PUSCH)
Physical Uplink Control Channel (PUCCH)

Sounding Reference Signal (SRS)
Demodulation Reference Signal (DMRS)

OFDM TX Block



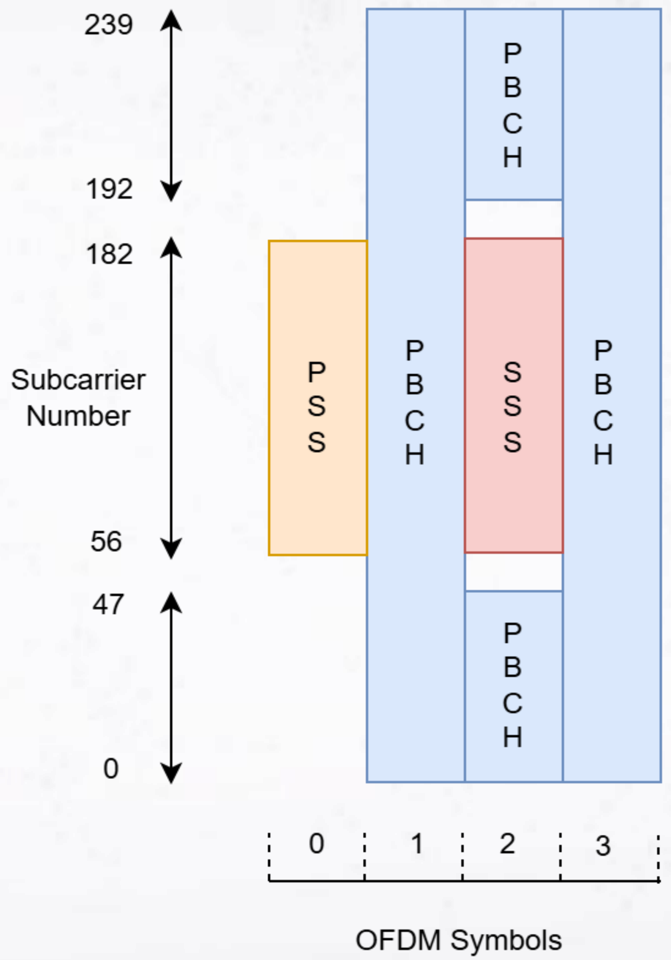
Initial Access

Downlink Synchronization

- **S**ynchronization **S**ystem **B**lock
- Cell-id, Frame and Symbol boundary

Master Information Block

- Mandatory system information that is broadcasted by the gNB
- Frame number, Subcarrier spacing
- System Information Block parameters



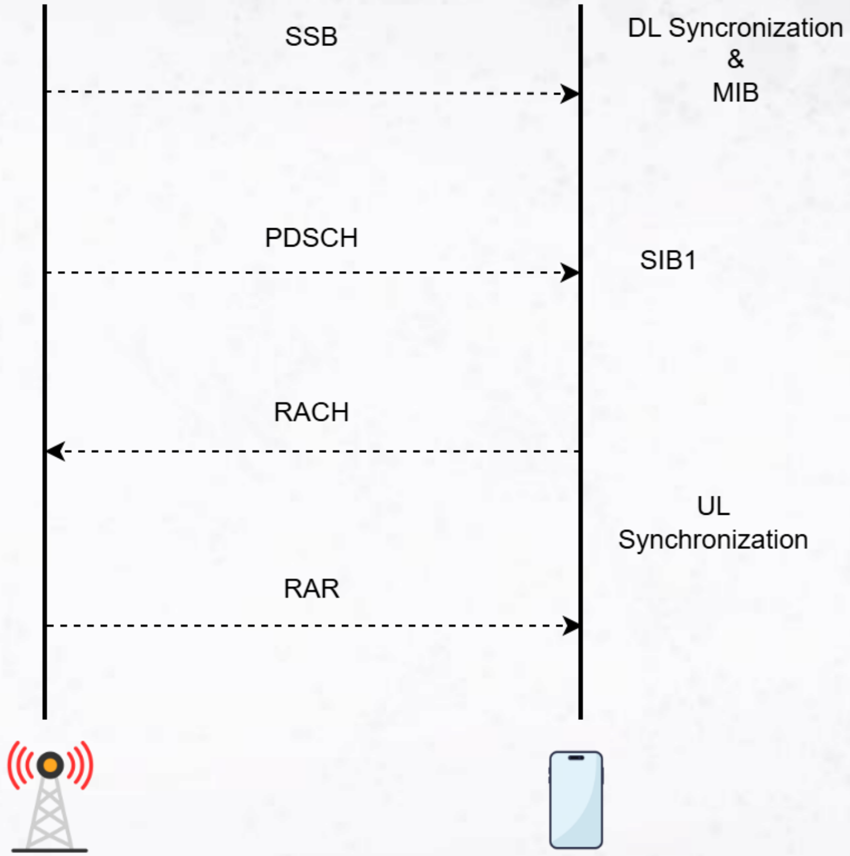
Initial Access

System Information Block

- SIB1, SIB2, …, SIB9
- SIB1 carries basic and essential information
  - Uplink and Downlink configuration, SSB scheduling information, TDD pattern etc..
  - Required for initial access and for acquiring other SIBs
  - Transmitted over DLSCH/PDSCH, and it is cell-specific

Uplink Synchronization

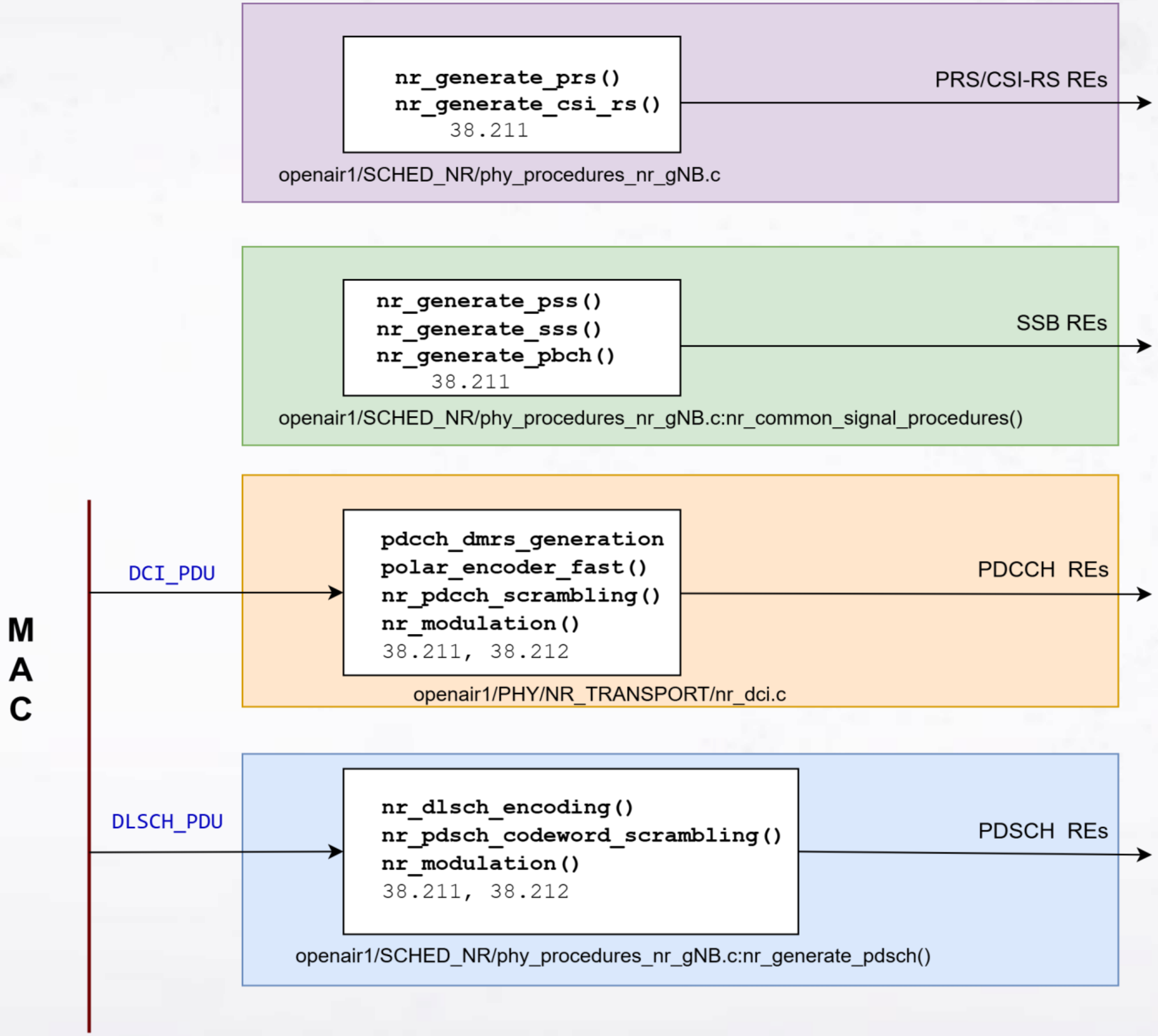
- Random Access Channel (RACH)



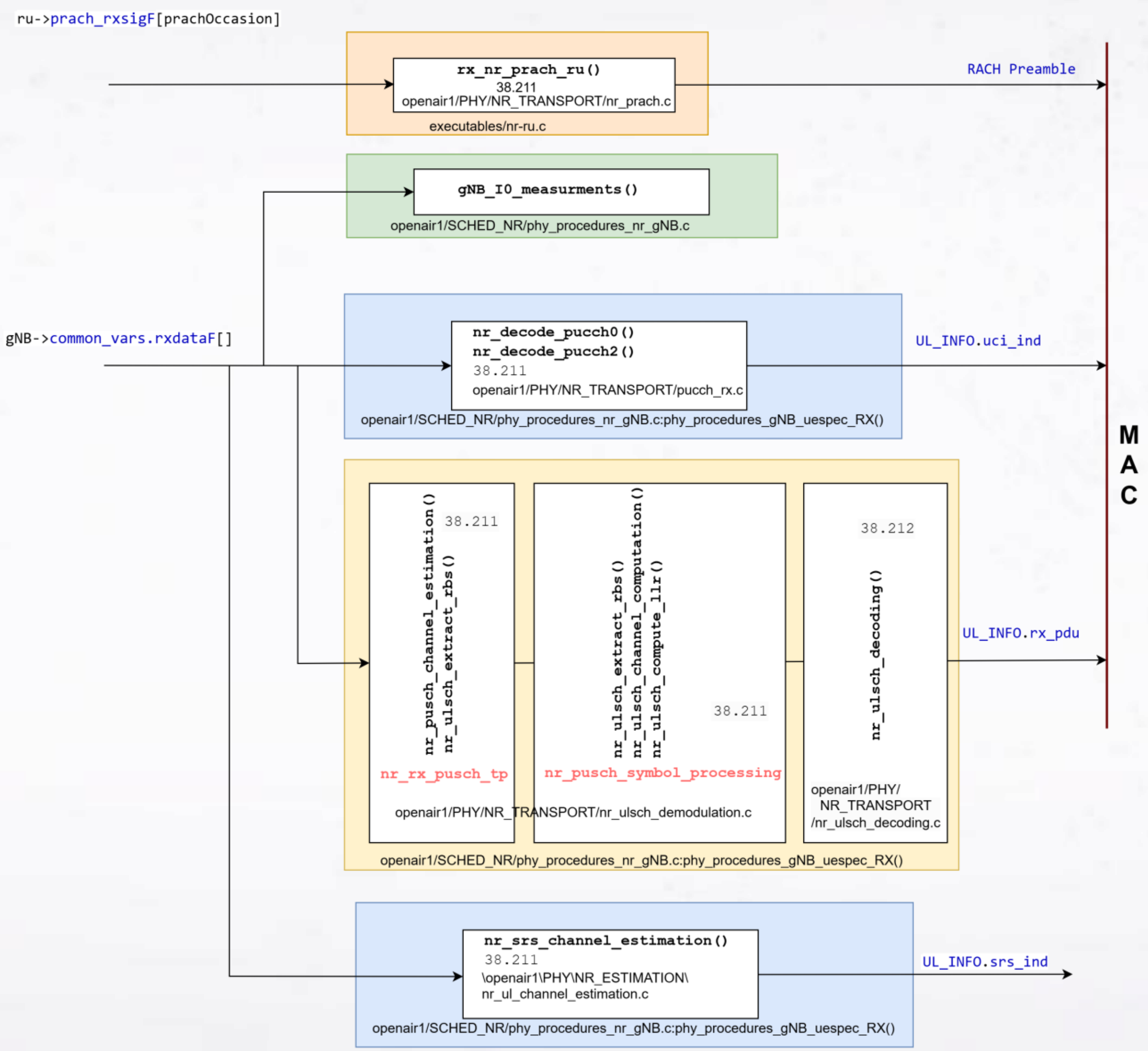
Control and Data Channels

- Control channels carrying Downlink (Uplink) Control Information D(U)CI
- Control info consist of
  - Scheduling information for DL traffic and signaling (PDSCH)
  - Scheduling information for UL traffic and signaling (PUSCH)
- Power control information
- PDCCH uses Polar Coding
- PUSCH and PDSCH use IR-HARQ+ Rate matching +LDPC coding

L1 TX Procedures



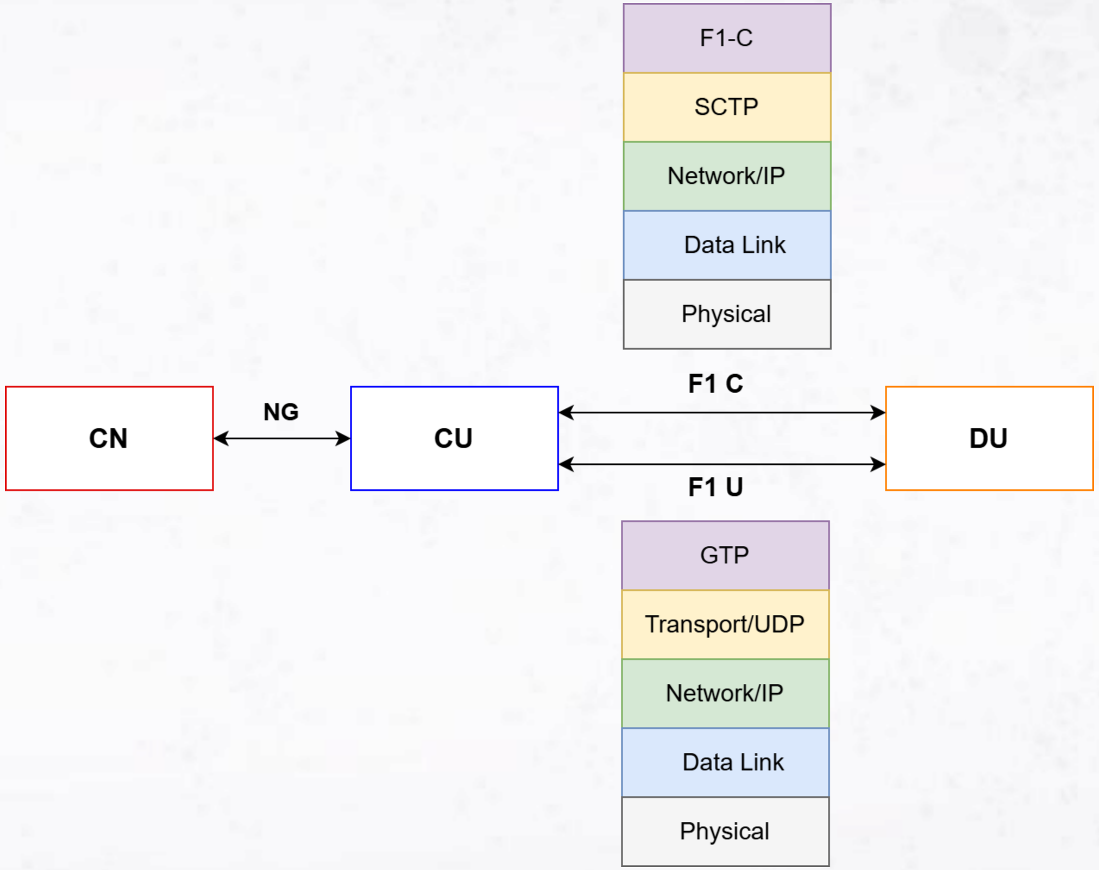
L1 RX Procedures



OAI Functional Splits

CU-DU Split

- Central Unit
  - RRC, PDCP, SDAP
- Distributed Unit
  - RLC, MAC, PHY
- F1 Interface [3GPP TS 38.470-474]
- Control Plane (F1-C)
- User Plane (F1-U)
- https://gitlab.eurecom.fr/oai/openairinterface5g/-/tree/develop/doc/F1AP



CU-DU Split

BACKUP SLIDES