Driving 6G Innovation with OpenAirInterface

EURECOM
Sophia Antipolis

Institute for the Wireless Internet of Things at Northeastern

OPEN AIR INTERFACE

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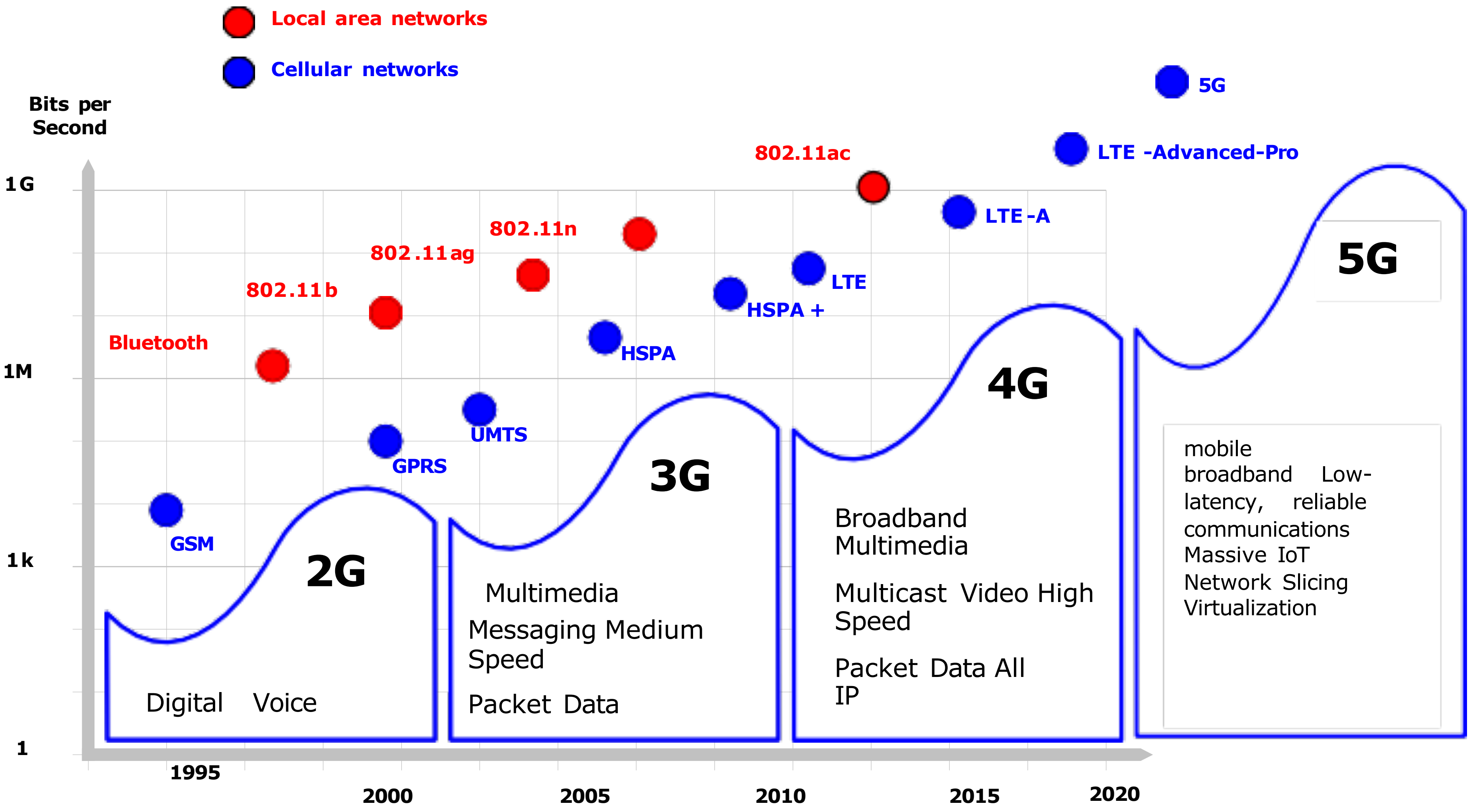
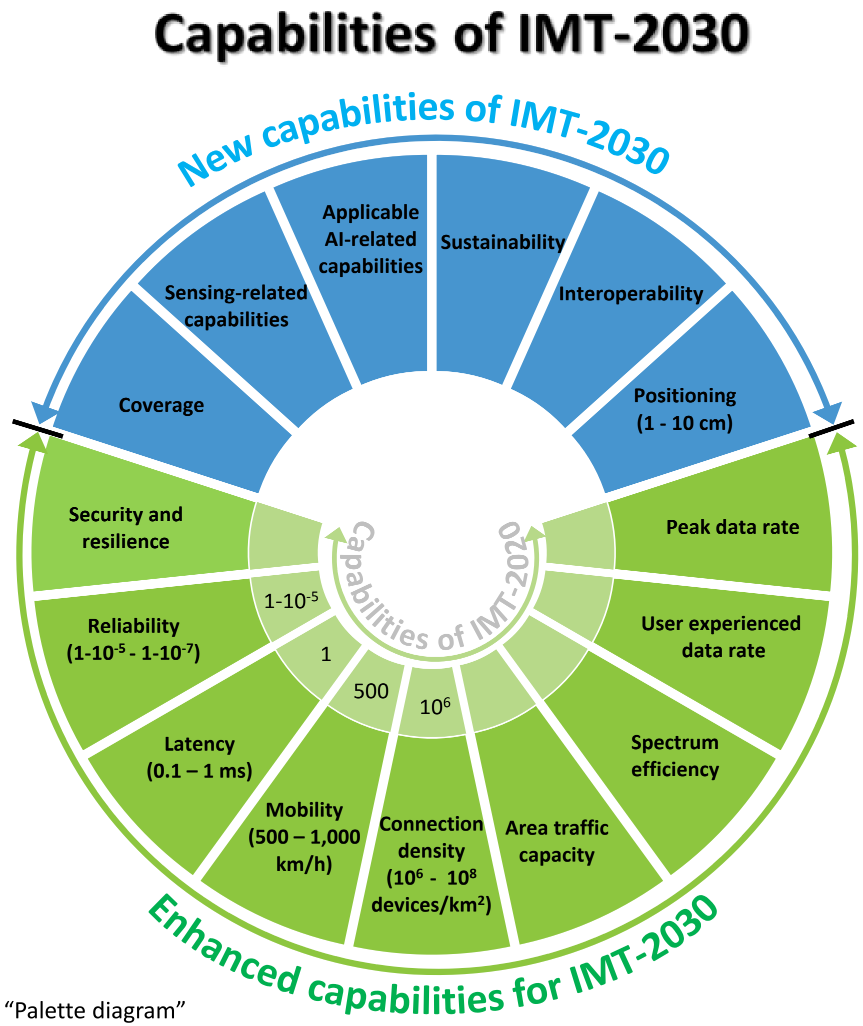
Evolution of Wireless Standards



6G requirements



So called "Palette diagram"

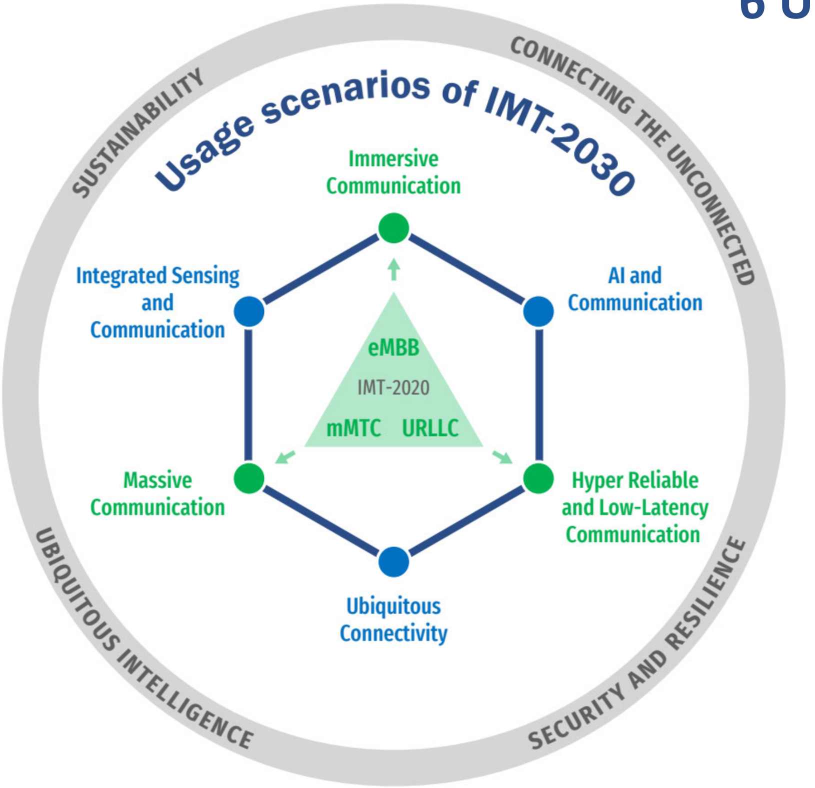
The range of values given for capabilities are estimated targets for research and investigation of IMT-2030.

All values in the range have equal priority in research and investigation.

For each usage scenario, a single or multiple values within the range would be developed in future in other ITU-R Recommendations/Reports.

6G Usage scenarios

Usage scenarios



So called "Wheel diagram"
Source: Document 5/131 and edited in SG 5

6 Usage scenarios

Extension from IMT-2020 (5G)

- eMBB ➡ Immersive Communication
- mMTC ➡ Massive Communication
- URLLC ➡ HRLLC (Hyper Reliable & Low-Latency Communication)

New

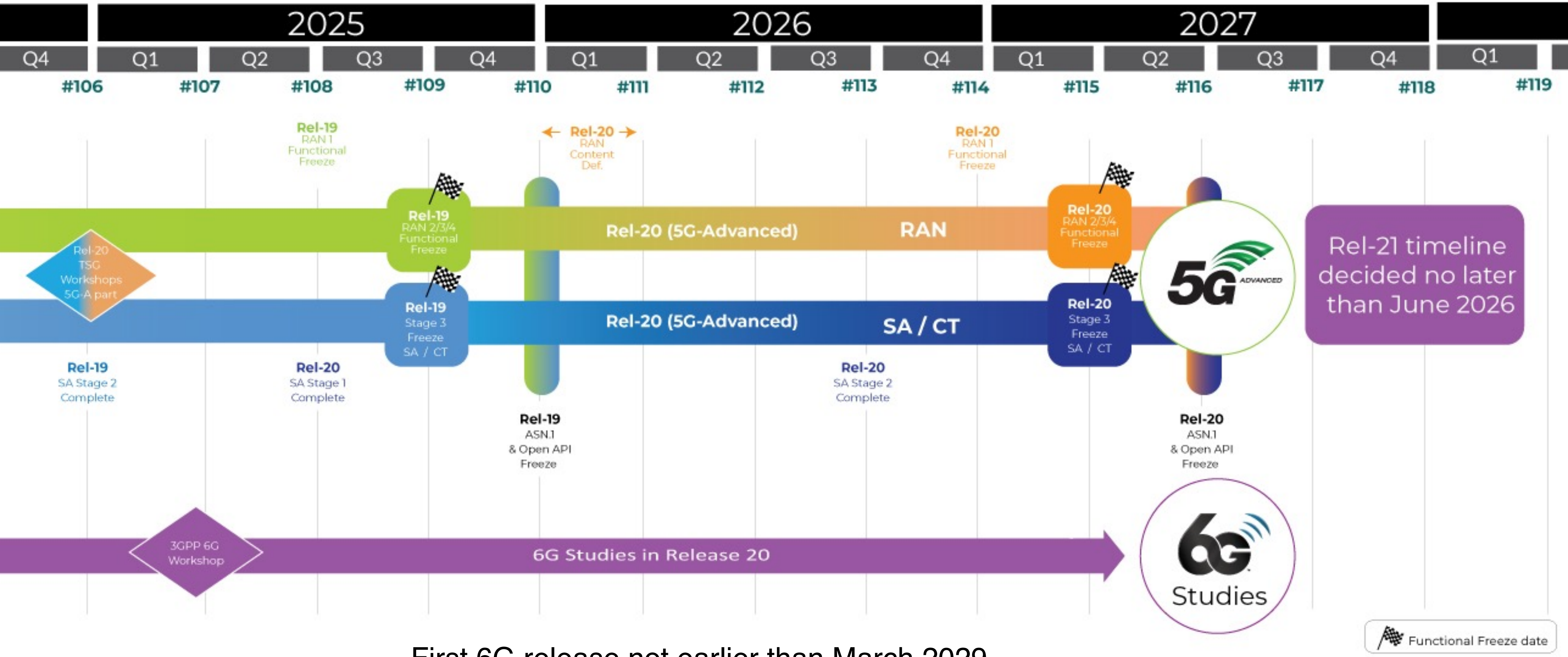
- Ubiquitous Connectivity
- AI and Communication
- Integrated Sensing and Communication

4 Overarching aspects:

act as design principles commonly applicable to all usage scenarios

Sustainability, Connecting the unconnected,
Ubiquitous intelligence, Security/resilience

Release 20 Timeline



First 6G release not earlier than March 2029

Principles for 6G design

- Radio access network
  - Non-backwards compatible (from a UE perspective)
  - Superior coverage than 5G
  - Support for diverse device types
  - Harmonized TN and NTN design
  - Extensible AI/ML framework
- Spectrum
  - 6G should support operation in a wide range of spectrum allocations including FR1 (410 MHz to 7125 MHz), FR2 (24.25 GHz to 71.0 GHz), and upper mid-band FR3 (7.125 GHz to 24.25 GHz).
  - Highly efficient multi-RAT spectrum sharing (MRSS) between 5G and 6G is essential
- Architecture
  - 6G RAN should connect to an evolution of the 5G core network.
  - 6G should support stand-alone operation only
  - 6G should include open interfaces

The road to 6G…

- … is paved with good intentions
- There are many candidate technologies that could become building blocks of 6G
- Most of them have been researched in a contained environment (simulations, simplifications)
- Need to test these algorithms on real systems and at scale
- Today there are many open source tools to build such systems
- Today we are going to focus on OpenAirInterface

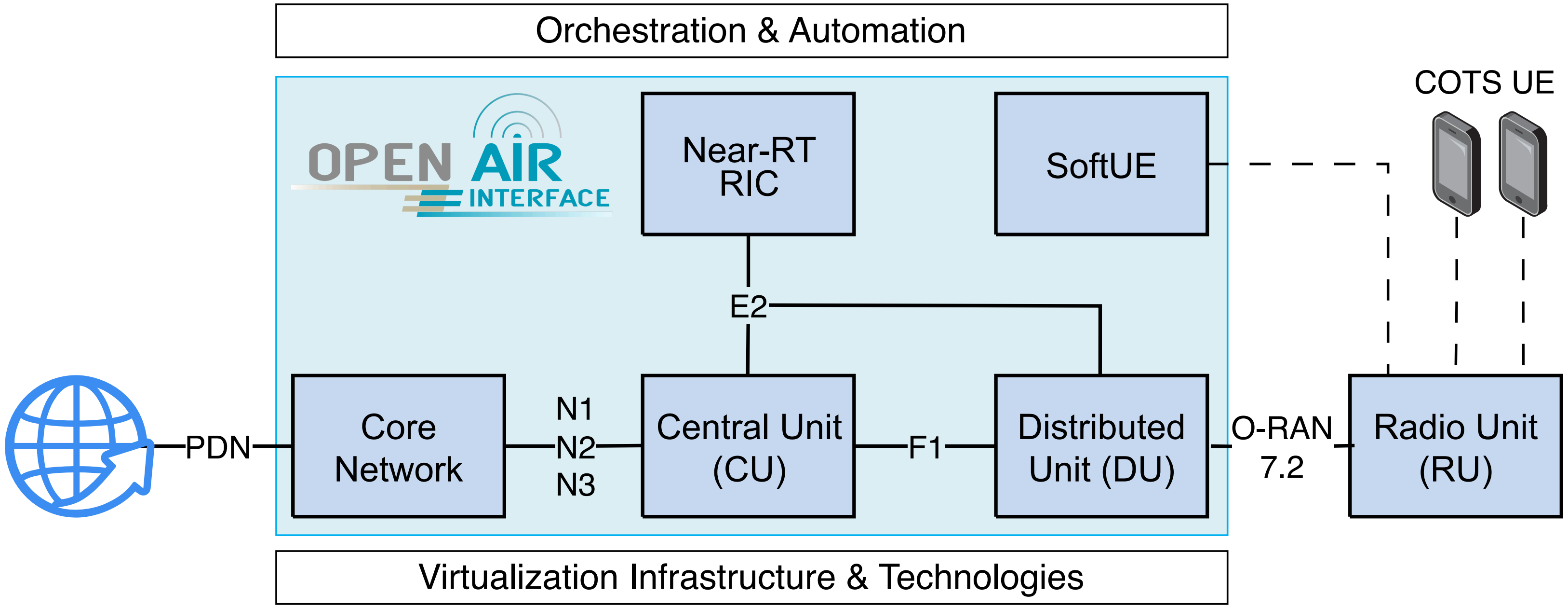
Agenda

- Part 1: Introduction to OpenAirInterface
- Part 2: Sample deployments
- Part 3: Use case: positioning, localization and sensing with OAI
- Discussion and conclusions

What is OpenAirInterface?

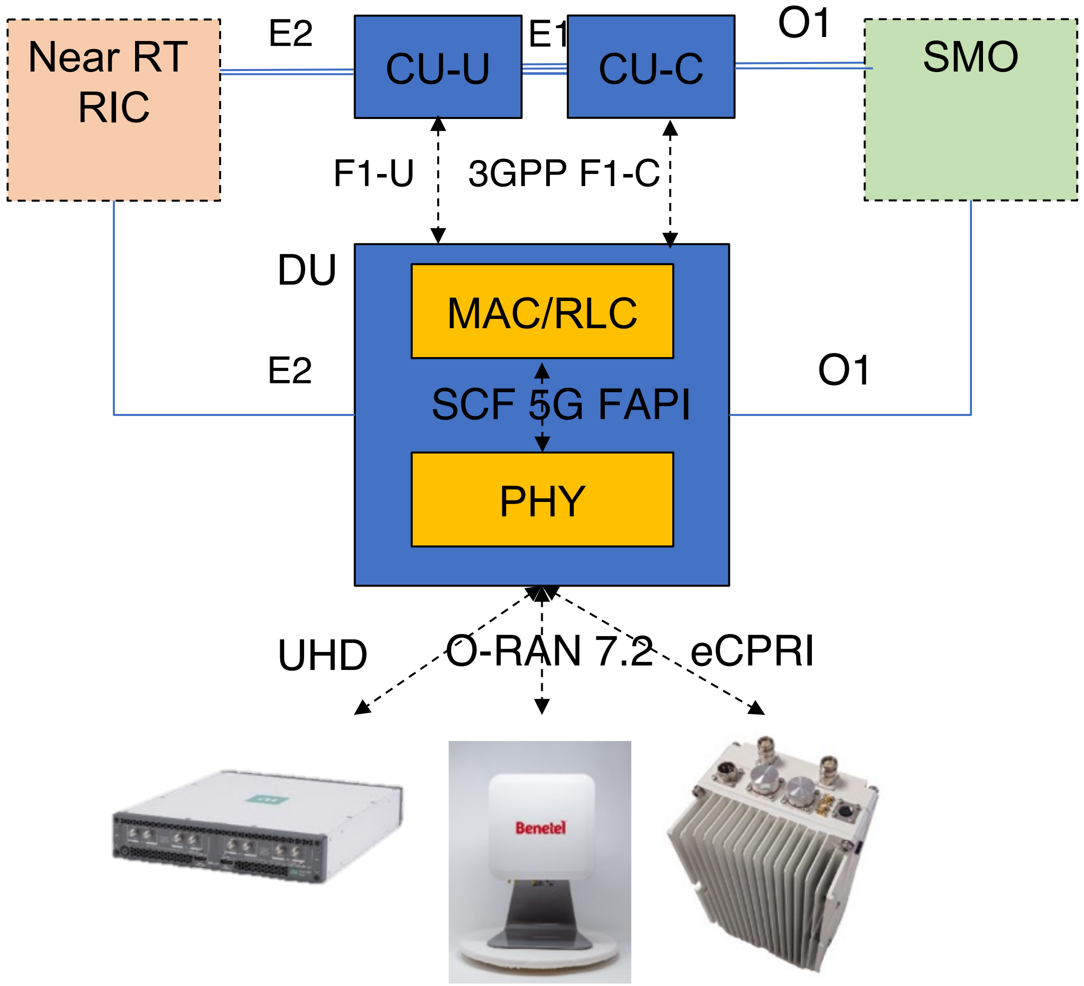
- OpenAirInterface (OAI) is the most complete, open-source implementation of 3GPP 4G/5G RAN and EPC/5GC
- The OAI public license is based on Apache 2.0 but allows patent owners to contribute and keep their patents under 3GPP FRAND rules
- Community driven development supported by the OpenAirInterface Software Alliance and its strategic members

5G Network Architecture



- OpenAirInterface provides virtual network functions (software) for DU, CU, RIC, and most core network functions (AMF, SMF, UPF, etc).
- Runs on x86 and ARM hardware, bare-metal or virtualized (docker, Kubernetes, Open Shift)
- Follows 3GPP and O-RAN specifications

OpenAirInterface RAN

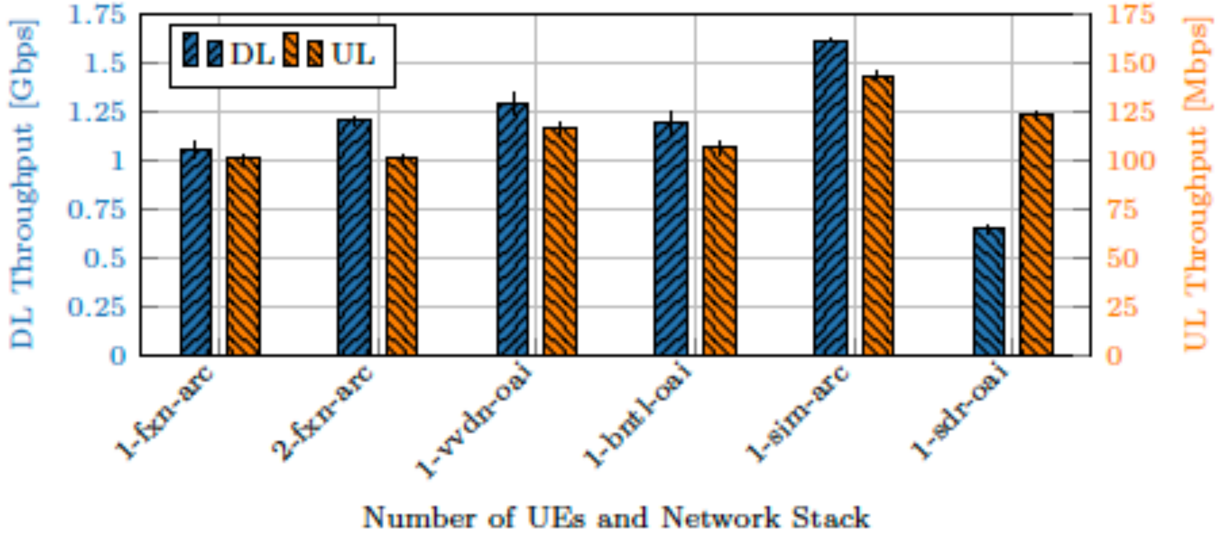


- F1-C and F1-U
  - Multiple DU per CU support
  - F1 handover
- E1 interface
- E2 interface
  - E2 agent interop with OAI FlexRIC and OSC RIC
  - Supports service models KPM v2.03/v3.0 , RC v1.00, and custom
- 5G FAPI
  - Compliant with SCF 5G FAPI 222.10.02
  - OAI L2 tested with Nvidia L1
  - 5G nFAPI
- Look-aside acceleration
  - With Xilinx T2 card
- Fronthaul
  - UHD with USRP (Split 8)
  - eCPRI with AW2S (Split 8)
  - O-RAN 7.2 CUSM-plane (Split 7.2) tested with many RUs
- O1 interface
  - Tested with ONAP

Features

- 5G standalone (SA) and non-standalone (NSA)
- Duplexing: Static TDD, FDD
- Subcarrier spacings: 15 and 30kHz (FR1), 120kHz (FR2)
- Bandwidths: 10, 20, 40, 60, 80, 100MHz, 200MHz (FR2)
- Support for UL transform precoding (SC-FDMA)
- MIMO: 4-layer DL and 2-layer UL
- Highly efficient 3GPP compliant channel encoder and decoder (turbo, LDPC, polar)
- Support for inline and lookaside hardware acceleration
- O-RAN
  - 7.2 C/U/S/M-plane through OSC FHI library
  - E2 agent with KPM v2.03/v3.0 and RC v1.03
  - O1 interface with ONAP
- Support for NTN, RedCap, Localization
- Full list of features: https://gitlab.eurecom.fr/oai/openairinterface5g/-/blob/develop/doc/FEATURE_SET.md

OAI gNB performance

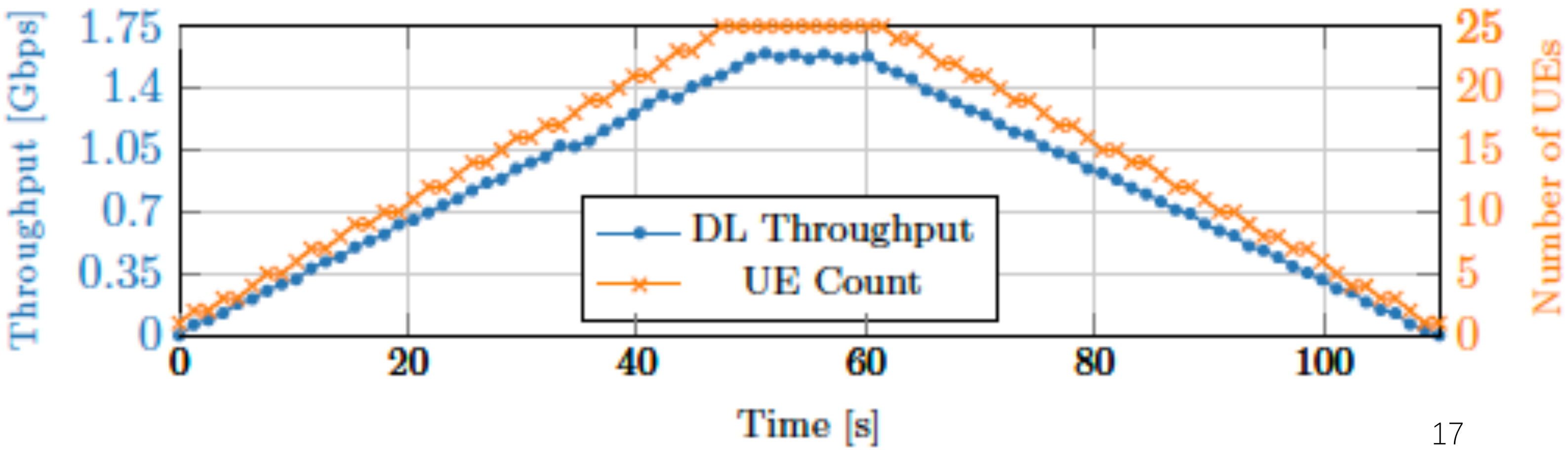


RUs:

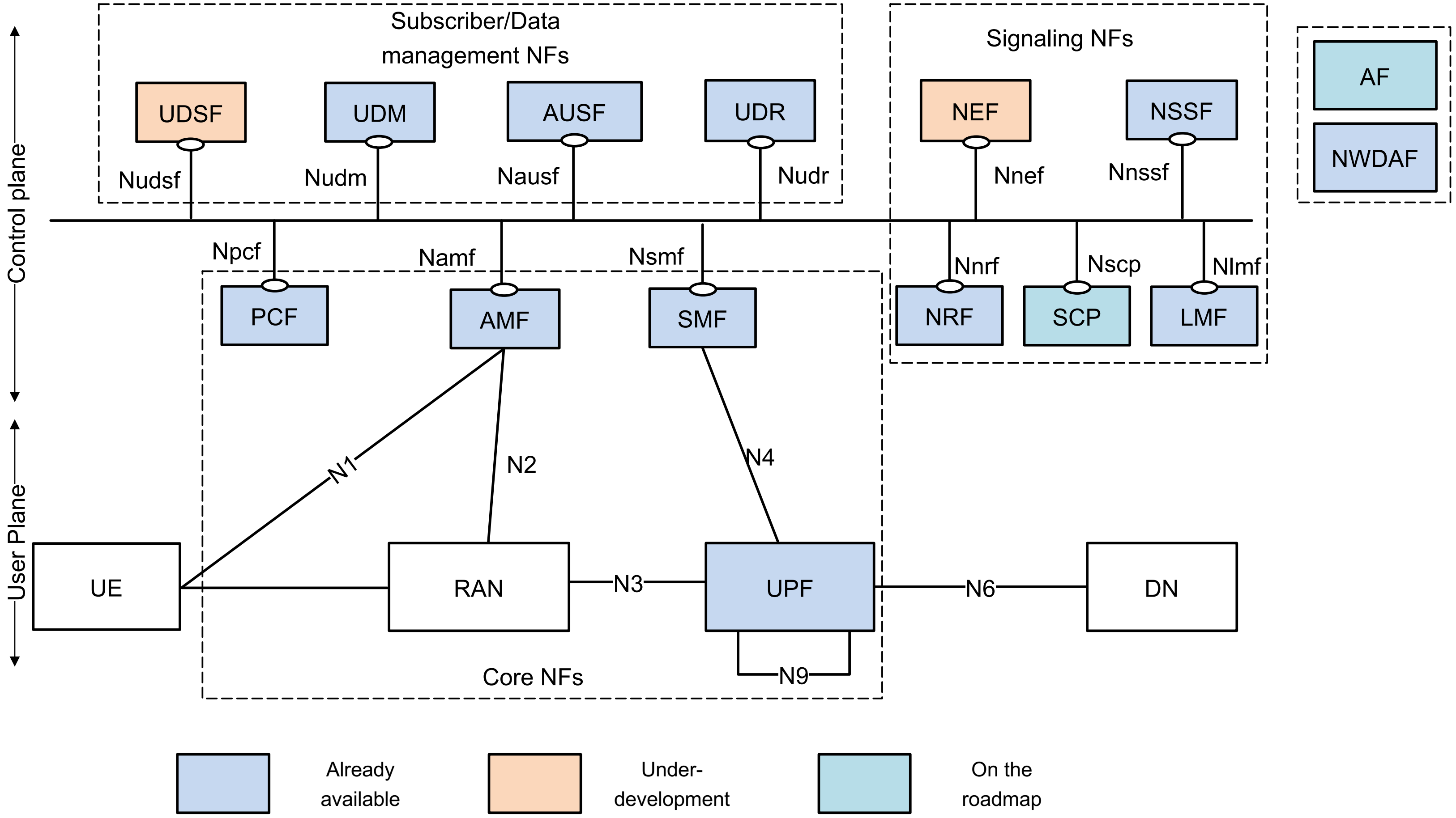
- Foxconn (fxn),
- VVDN (vvdn),
- Benetel (bntl) ,
- Keysight ruSIM (sim),
- USRP (sdr)

DUs:

- OpenAirInterface (oai),
- Nvidia Aerial (arc)



OAI Core Network



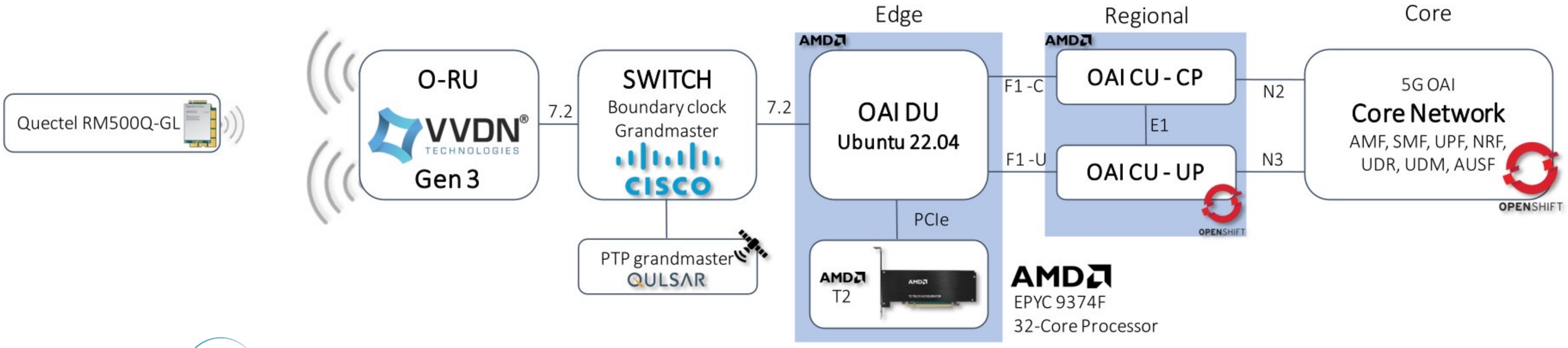
- Access and Mobility Management Function (AMF),
- Session Management Function (SMF), UPF,
- Authentication Server Function (AUSF),
- Unified Data Management (UDM),
- Unified Data Repository (UDR),
- Network Repository Function (NRF),
- Network Slice Selection Function (NSSF),
- Policy Control Function (PCF),
- Network Data Analytics Function (NWDAF),
- Localization Management Function (LMF)
- Network Exposure Function (NEF)
- Unstructured Data Storage Function (UDSF),
- Service Communication Proxy (SCP)
- Application Function (AF)

Core Network recent updates

- NEW: Localization Management Function (LMF)
  - Supports UL TDoA positioning via NRPPa
  - Updated AMF to support NRPPa transfers
- QoS Support for Data plane
  - New implementation of UPF based on eBPF (extended Berkeley Packet Filter), XDP (eXpress Data Path), and TC (Traffic Control)
  - SMF manages QoS rules by handling information from UDM and PCF
- Ethernet-type PDU session (for TSN)
- Improve the Code Quality of 5G CN to Make it Stable and Robust
  - Simplifying the codebase with tools like C++ Request (Lib CPR).
  - Extensive testing with RAN/UE simulators, commercial gNBs, COTS UEs, and professional testers

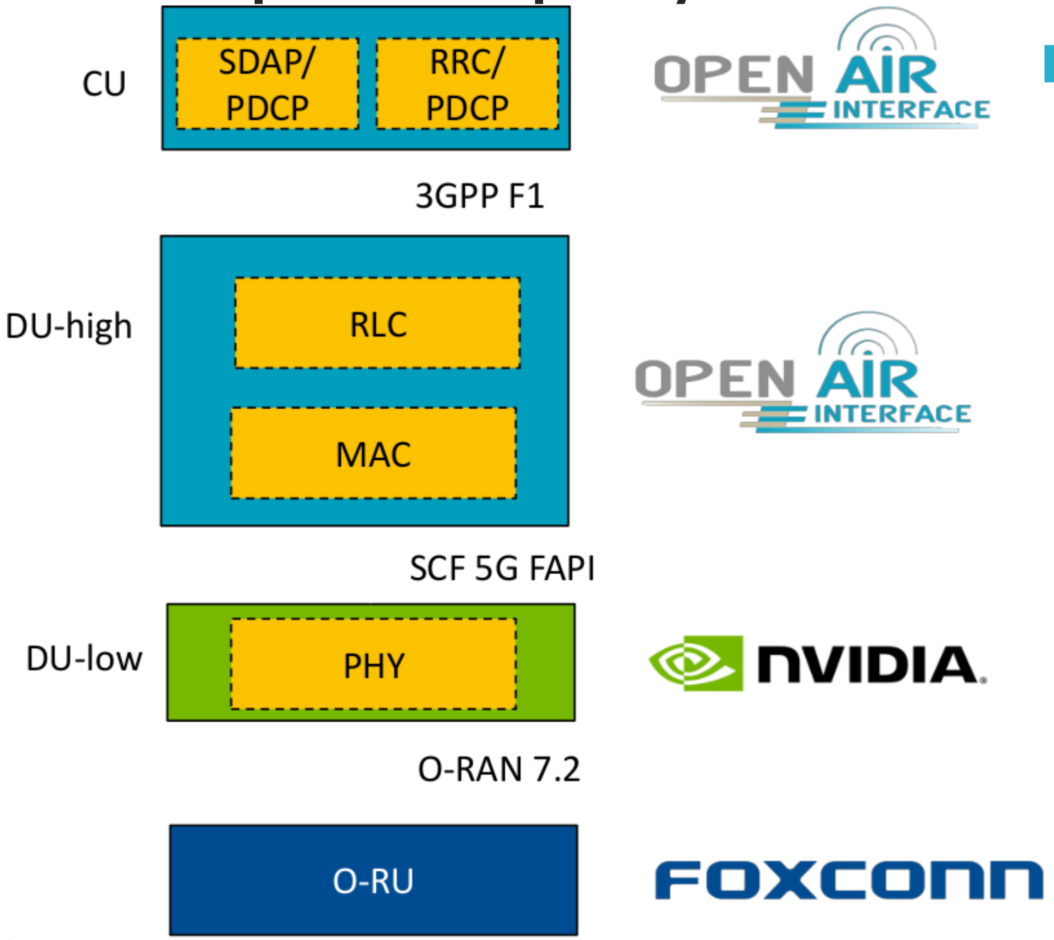
Sample Deployment: O-RAN 7.2 Fronthaul with T2-Telco Card

- OAI 5GC and CU-CP/UP deployed in OpenShift Cluster
- 3GPP F1 and E1 midhaul splits between OAI CU-CP/CU-UP/DU
- O-RAN 7.2 fronthaul split using OSC fronthaul interface library (FHI, E release)
- Optionally: AMD T2 Lookaside Accelerator card
- Integration with O-RUs, 100MHz BW: Benetel, LITEON, VVDN; 500 Mbps throughput in DL



Florian Kaltenberger

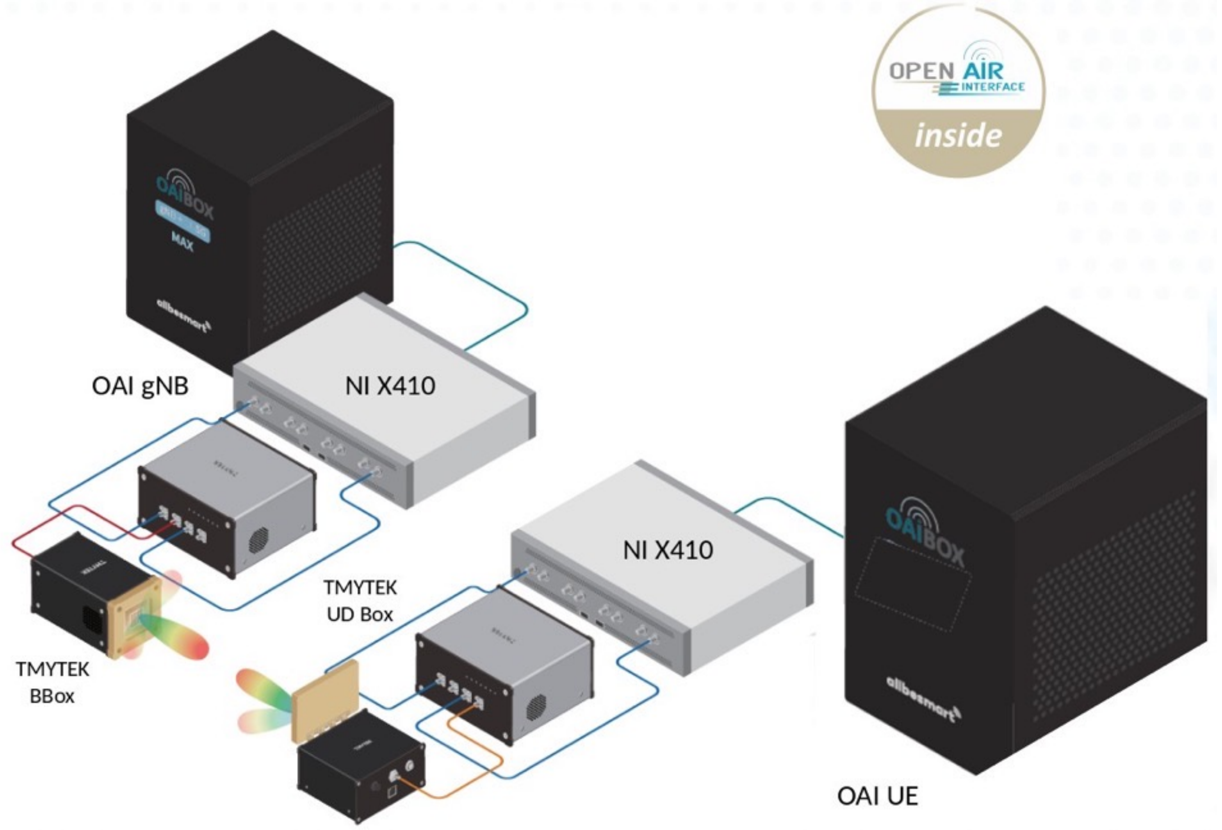
Sample Deployment: Nvidia Aerial ARC Setup



- Nvidia Aerial: GPU used as inline L1 accelerator
- L2/L3 from OpenAirInterface, Interface via SCF 5G FAPI
- DU Layer 1 southbound interface: O-RAN 7.2, Foxconn O-RU
- L1 can support multiple RUs and multiple Dus
- Runs on Grace Hopper or x86 + A100X
- Can leverage Aerial DataLake

Sample Deployment: FR2 SA with USRP and OAI UE

- FR2 Connection establishment with OAI UE
- Using USRP x400 and TMYTEK BBox
- Operating at 28GHz, 100MHz and 200MHz bandwidth
- Demo at MWC 2024: 200Mbps DL/40 UL

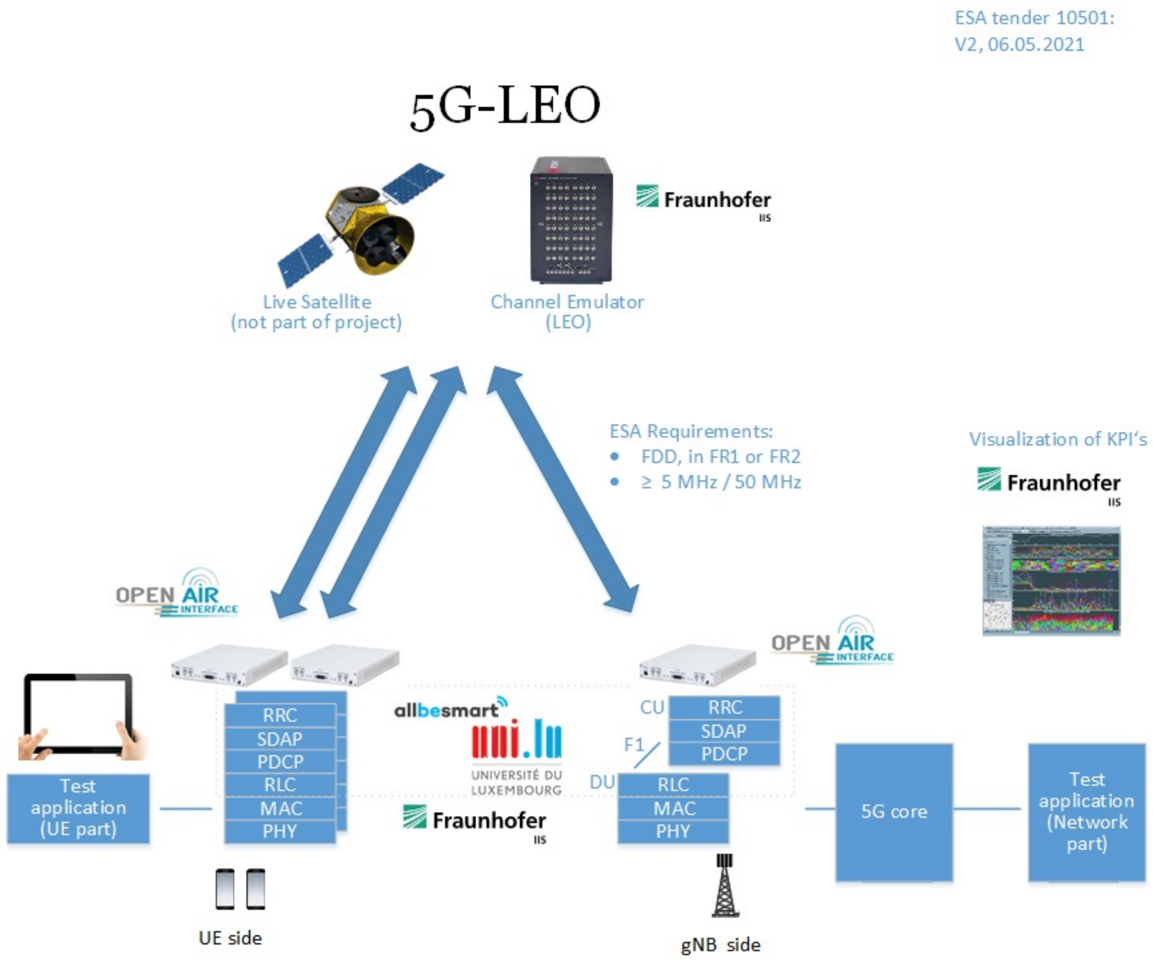


Sample Deployment: LiteOn FR2 O-RU

- Demonstrated at MWC 2025
- LiteOn FR2 O-RU
  - n257 : 26.5 – 29.5GHz
  - Max. 400MHz
  - Internal 8x8 Antenna Array, EIRP 46dBm
  - 2T2R, DL : 256 QAM / UL : 64 QAM
  - O-RAN C/U/S-plane
- UEs
  - Quectel RM530F: For Fixed Wireless Access, supports SU
  - Samsung Galaxy S23 and above: Supports only NR-DC

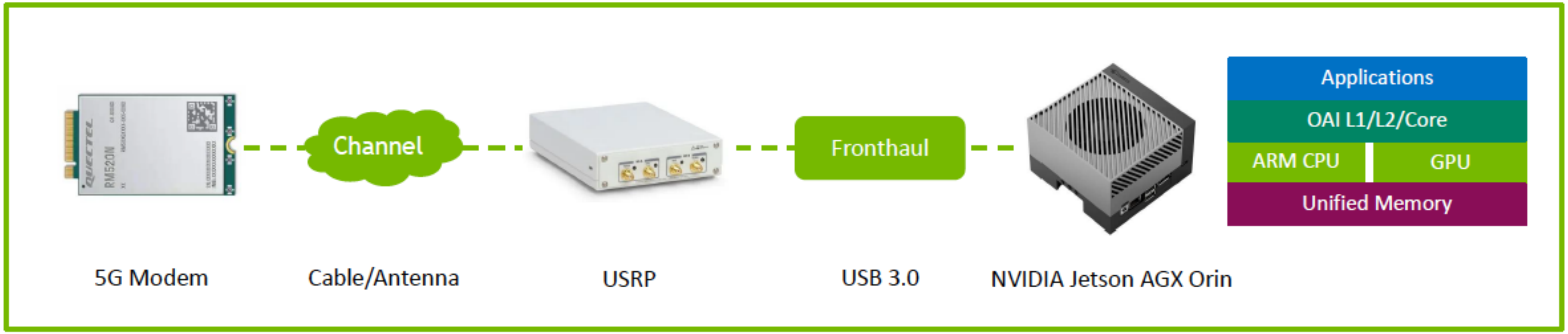
Sample deployment: NTN

- 3GPP Rel 17 support for GEO and LEO deployments
- gNB and UE,
- GEO and LEO channel models in rfsimulator
- Tested with real GEO satellite, LEO channel emulation
- SIB 19
- Continuous frequency offset estimation and compensation



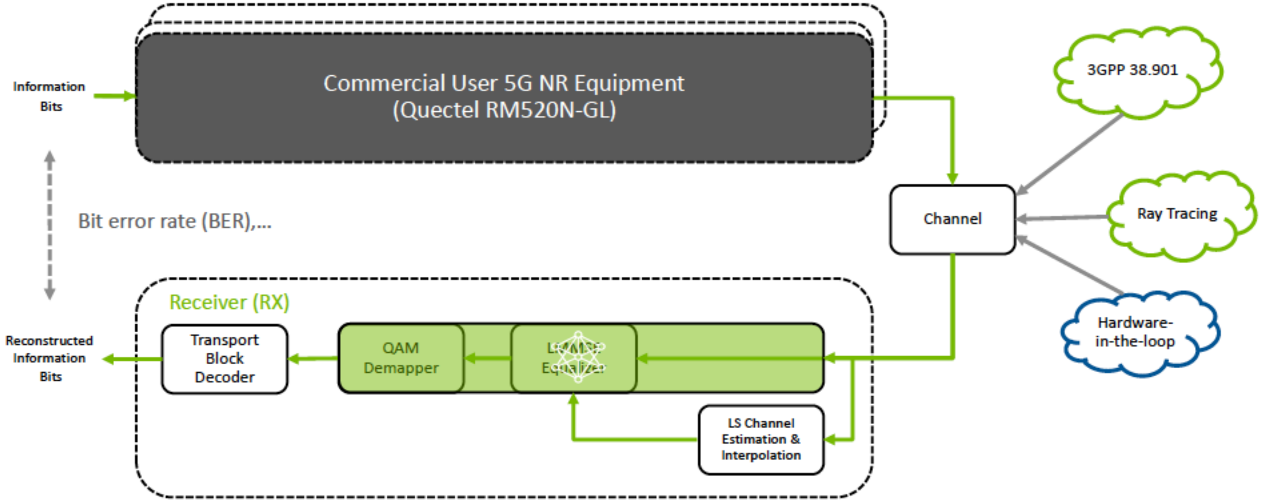
Sample deployment: Sionna Research Kit

- Sionna: GPU-accelerated differentiable open-source library for research on communication systems
    - **Sionna RT: A lightning-fast stand-alone ray tracer for radio propagation modeling**
        - Can be used with rfsim: https://gitlab.eurecom.fr/oai/raytracing-channel-emulator
    - Sionna PHY: A link-level simulator for wireless and optical communication systems
    - Sionna SYS: System-level simulation functionalities based on physical-layer abstraction
    - **Sionna Research Kit: Rapid 5G RAN prototyping, powered by NVIDIA Jetson**



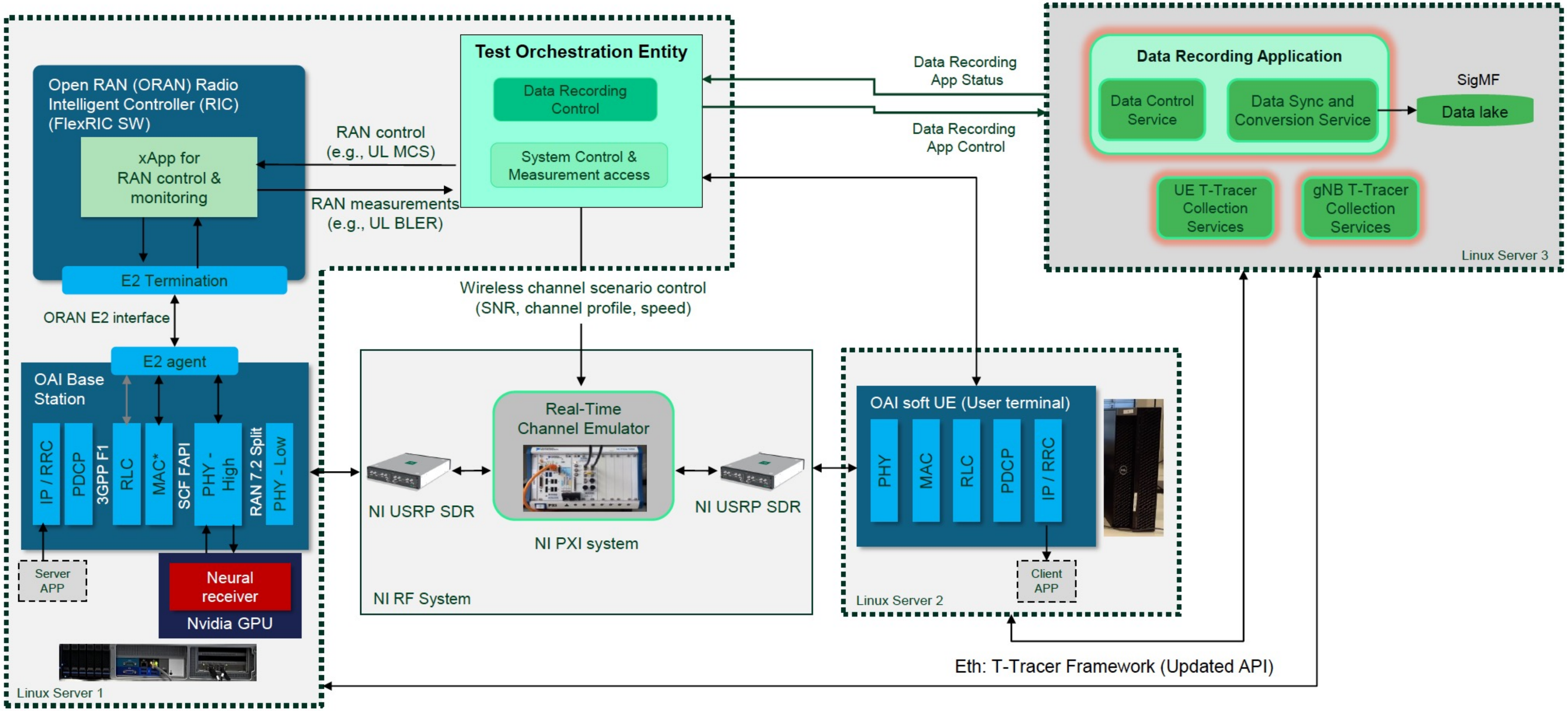
Real-time (Multi-user MIMO) Neural Receiver: Proof of Concept

- Trained with Sionna - deployed in the Research Kit



- Paper https://arxiv.org/abs/2409.02912
- Blogpost https://developer.nvidia.com/blog/real-time-neural-receivers-drive-ai-ran-innovation/
- Code https://github.com/NVlabs/neural_rx

OAI Based Neural Receiver System (NI)

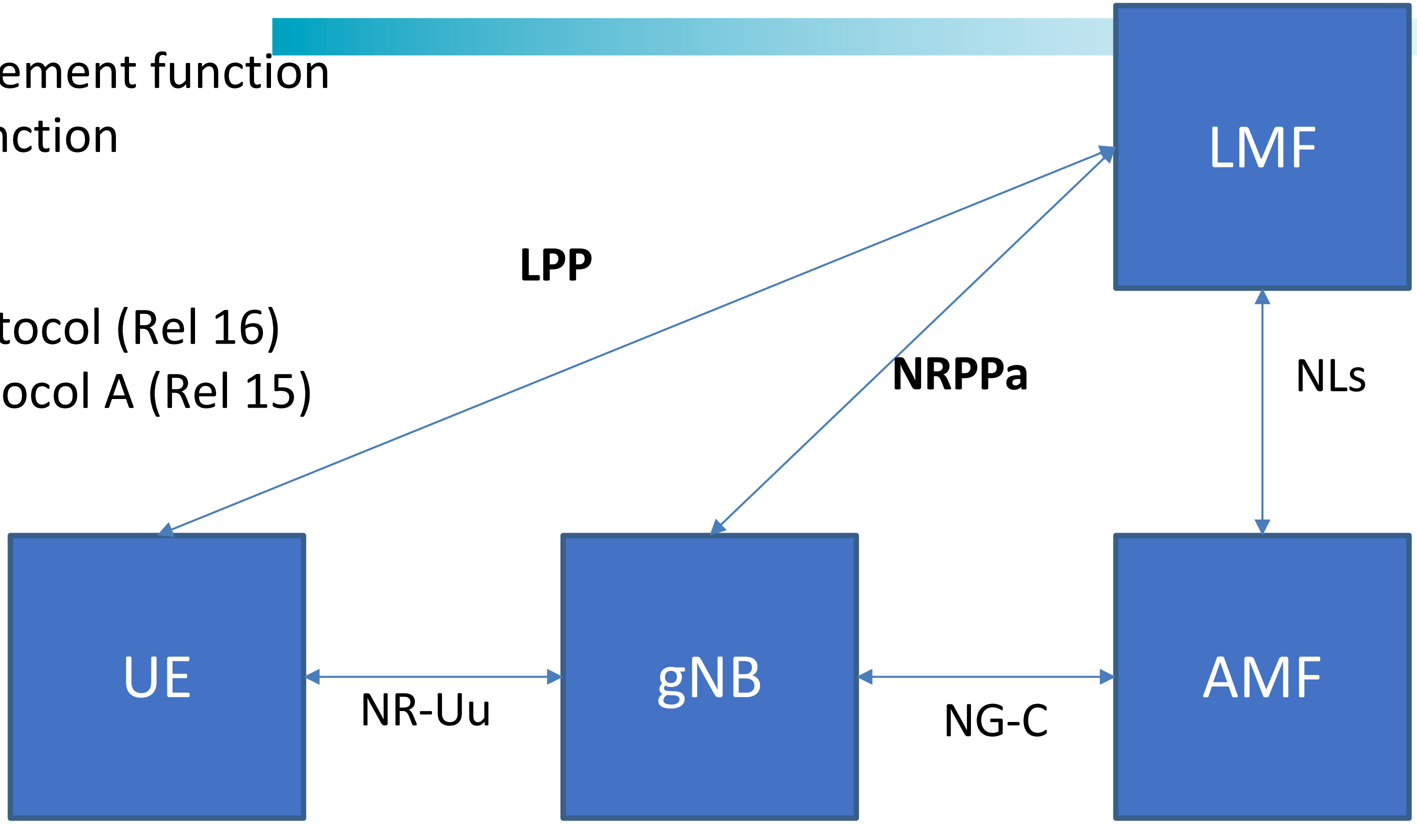


Localization and Sensing

With help from Adeel Malik, Mohsen Ahadi, Rakesh Mundlamuri

Localization Architecture in 5G NR

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)



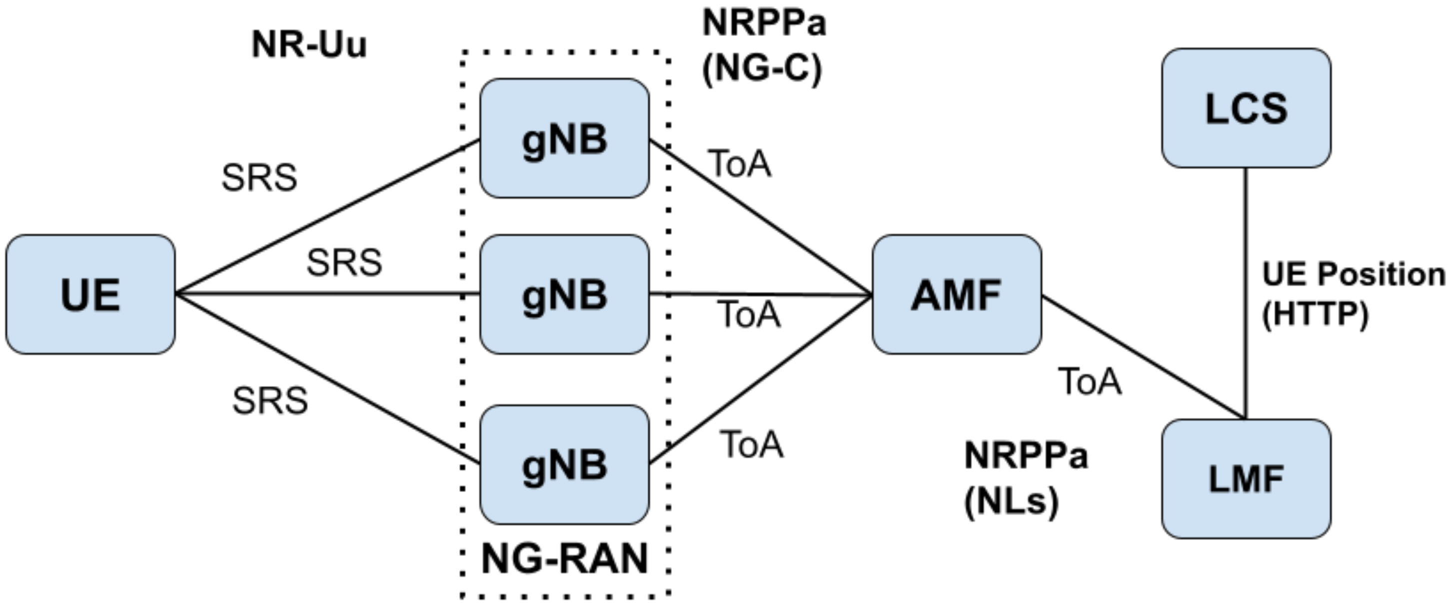
Support for localization in 5G NR

- Network based and UE based localization
- Hybrid positioning using GNSS, Bluetooth, Wifi, other sensors
- Positioning methods that rely only on 5G NR signals (and signaling)
  - Rel 15: Enhanced cell ID, UL-TDoA, UL-AoA
  - Rel 16: DL-TDoA, DL-AoD, Multi-RTT (Round-trip-time)
  - Rel 17: RRC_INACTIVE positioning, on-demand PRS, improvements in accuracy and latency
  - Rel 18: RedCap, Carrier aggregation, low power, sidelink
- mm-wave spectrum attractive for localization
  - High bandwidths → higher accuracy
  - AoA/AoD information can be derived from beam indices
  - Can achieve sub-meter accuracy in theory*

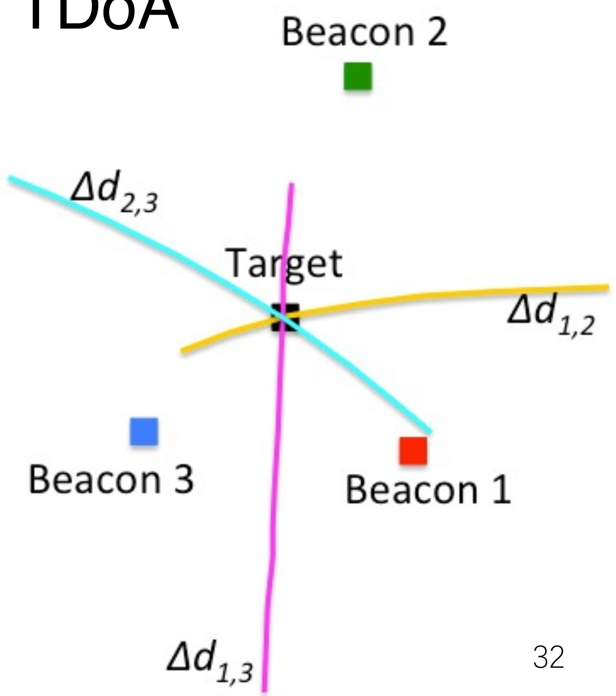
*Ahadi, Mohsen; Kaltenberger, Florian, "5G NR indoor positioning by joint DL-TDoA and DL-AoD," WCNC 2023, IEEE Wireless Communications and Networking Conference, 26-29 March 2023, Glasgow, Scotland, UK

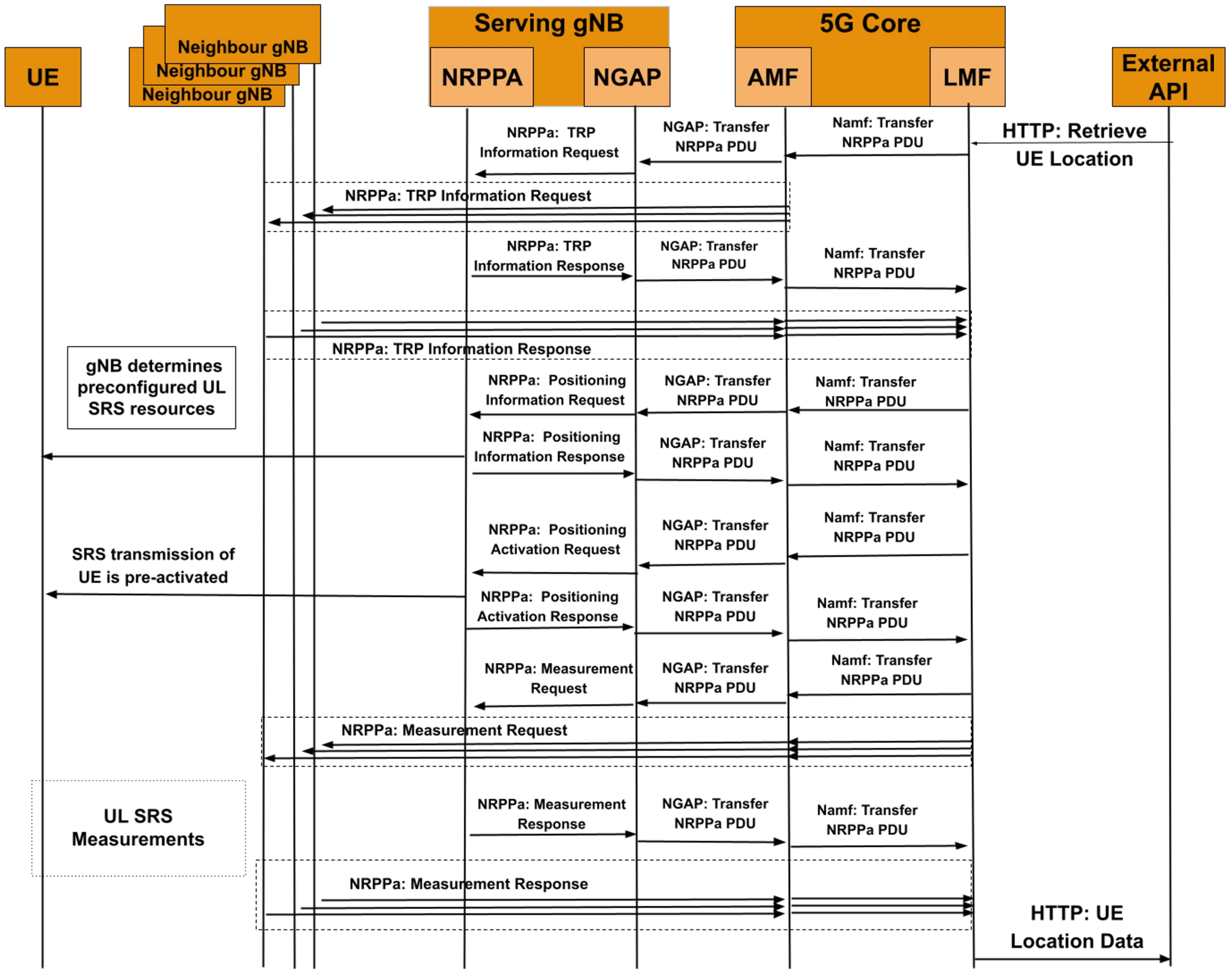
Uplink Time Difference of Arrival (UL-TDoA) Positioning

- UE transmitting UL-Sounding Reference Signal (SRS) to multiple gNBs
- Synchronized gNBs estimate the Time of Arrival (ToA)
- gNBs send ToAs over New Radio Positioning Protocol (NRPPA) to Location Management Function (LMF)
- LMF converts ToAs to TDoAs and estimates the UE coordinates and sends it to an external location service API



TDoA




UE
Neighbour gNB
Neighbour gNB
Neighbour gNB
Serving gNB
NRPPA
NGAP
5G Core
AMF
LMF
External API
HTTP: Retrieve UE Location
Namf: Transfer NRPPa PDU
NGAP: Transfer NRPPa PDU
NRPPa: TRP Information Request
NRPPa: TRP Information Request
NRPPa: TRP Information Response
NGAP: Transfer NRPPa PDU
Namf: Transfer NRPPa PDU
NRPPa: TRP Information Response
gNB determines preconfigured UL SRS resources
NRPPa: Positioning Information Request
NGAP: Transfer NRPPa PDU
Namf: Transfer NRPPa PDU
NRPPa: Positioning Information Response
NGAP: Transfer NRPPa PDU
Namf: Transfer NRPPa PDU
NRPPa: Positioning Activation Request
NGAP: Transfer NRPPa PDU
Namf: Transfer NRPPa PDU
SRS transmission of UE is pre-activated
NRPPa: Positioning Activation Response
NGAP: Transfer NRPPa PDU
Namf: Transfer NRPPa PDU
NRPPa: Measurement Request
NGAP: Transfer NRPPa PDU
Namf: Transfer NRPPa PDU
NRPPa: Measurement Request
UL SRS Measurements
NRPPa: Measurement Response
NGAP: Transfer NRPPa PDU
Namf: Transfer NRPPa PDU
NRPPa: Measurement Response
HTTP: UE Location Data

Implementation of 3GPP UL-TDoA Positioning in OAI

- Contributions to OAI 5G RAN
  - ToA estimation on OAI gNB based on UL SRS and channel estimation
  - Integrating of NRPPa functionalities and PDU transfers to AMF
- Contributions to OAI 5G CORE (AMF AND LMF)
  - Integration of LMF from TU-Dresden
  - NRPPa PDU transfer protocol between gNB-AMF
  - NRPPa PDU transfer protocol between AMF-LMF
  - Integration of Positioning Algorithms on LMF
  - Framework to integrate user-defined Positioning Algorithm
  - Integrating Fraunhofer IIS Positioning as a Service (PaaS) to LMF
- Contribution to Location Service API
  - Initiating positioning procedure from external host machine
  - Accurately mapping antennas and estimated UE positions in a relative cartesian coordinate

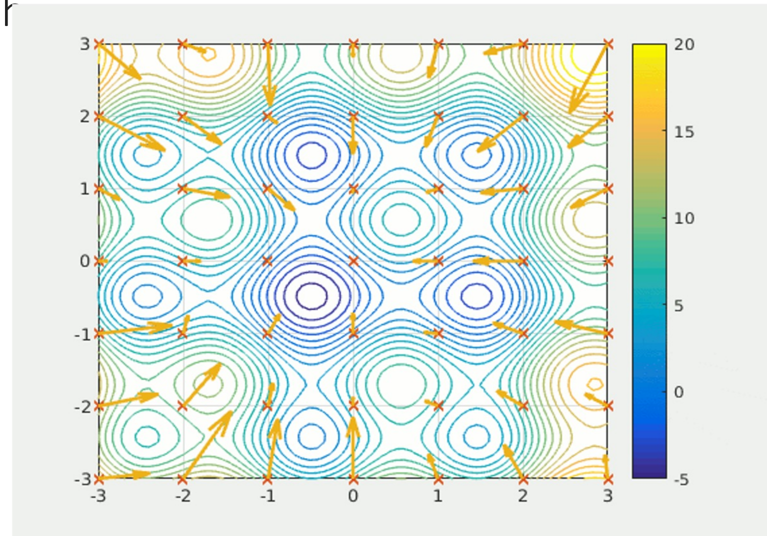
Positioning Estimation Algorithm: Particle Swarm Optimization

- Geometry-based positioning estimation algorithm needs is solution to minimization problem

$$\hat{\mathbf{X}} = \min_{\mathbf{X} \in R^{2\times 1}} \sum_{n}^{N-1} (r_{n1} - (\| \mathbf{a}_n - \mathbf{x} \| - \| \mathbf{a}_1 - \mathbf{x} \|)^2 \quad (3)$$

- Our implementation uses Particle Swarm Optimization:
  - First randomly generates a set of particles in a bounded area and with initial velocity
  - Moves on to pursue the best solution
  - Particles update based on "Individual_best" and "Global_best"
  - Iteratively update the positions and velocities
  - Takes the final "Global_best" as UE's position estimate

$$\mathbf{v}_{k+1}^{i} = w\mathbf{v}_{k}^{i} + c_1 r_1 (\mathbf{p}_{k}^{i} - \mathbf{x}_{k}^{i}) + c_2 r_2 (\mathbf{p}_{k}^{g} - \mathbf{x}_{k}^{g}), \quad (4)$$

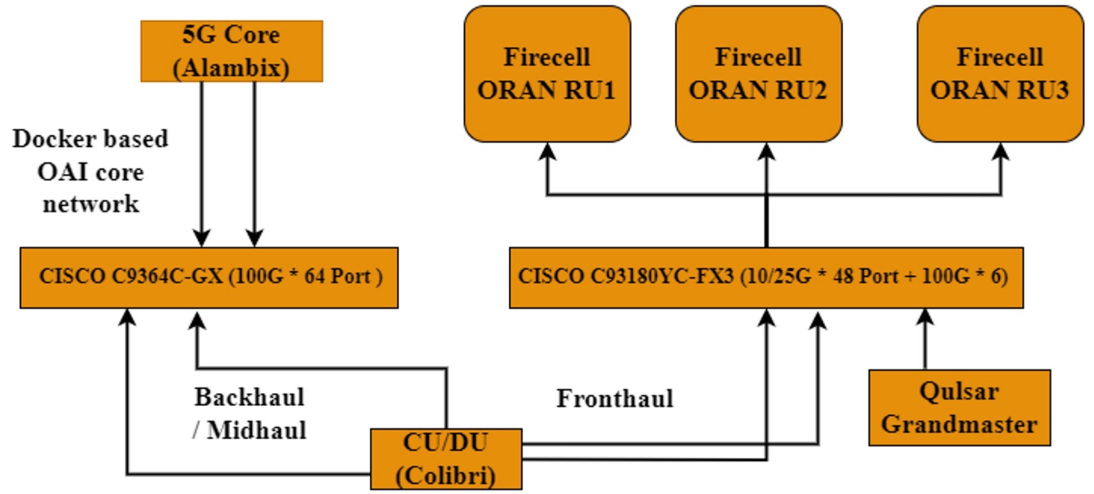


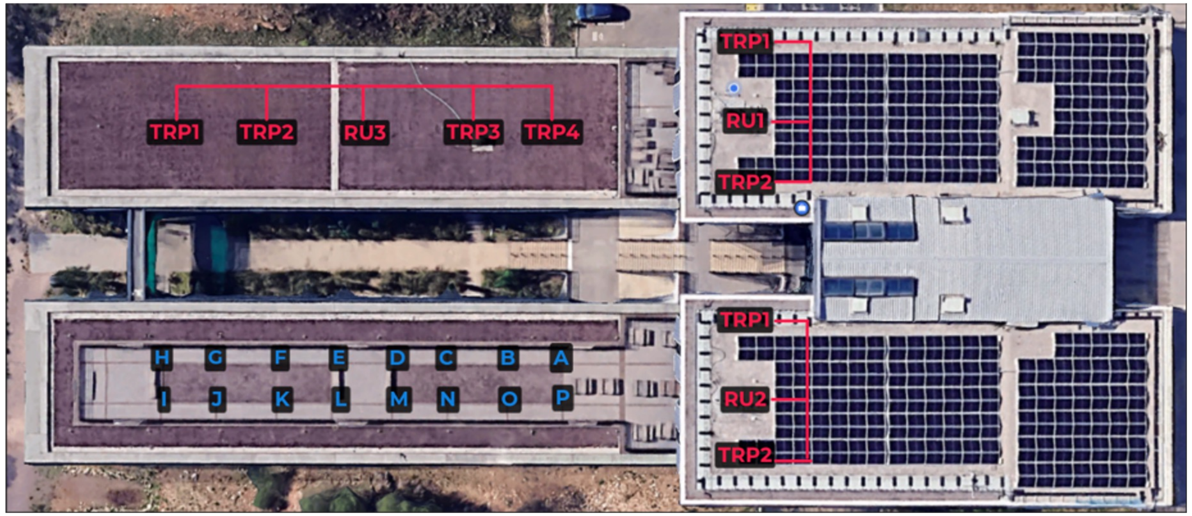
Ahadi, Mohsen; Malik, Adeel; Kaltenberger, Florian; Thienot, Cedric, "**5G NR UL SRS TDoA Positioning by OpenAirInterface,**" IPIN-WiP 2023, 13th International Conference on Indoor Positioning and Indoor Navigation, 25-28 September 2023, Nuremberg, Germany

Firecell GEO-5G Testbed at EURECOM

- 5G Core Network including LMF
- O-RAN architecture with 7.2 split (CU/DU and RU)
- Equipped with 3 Firecell RUs
- Synchronizing RUs with Precision Timing Protocol (PTP)
- Distributing multiple directional antennas on each RU
- 16 testing points A-P accurately positioned by laser equipment

NR Radio Specification	
Band	n77
Occupied Bandwidth(max)	100MHz
Duplex Mode	TDD
Sub Carrier Spacing	30KHz
MIMO	4T4R
RF Output Power per port	250mWatt/ 24dBm
Antennas	Internal/External

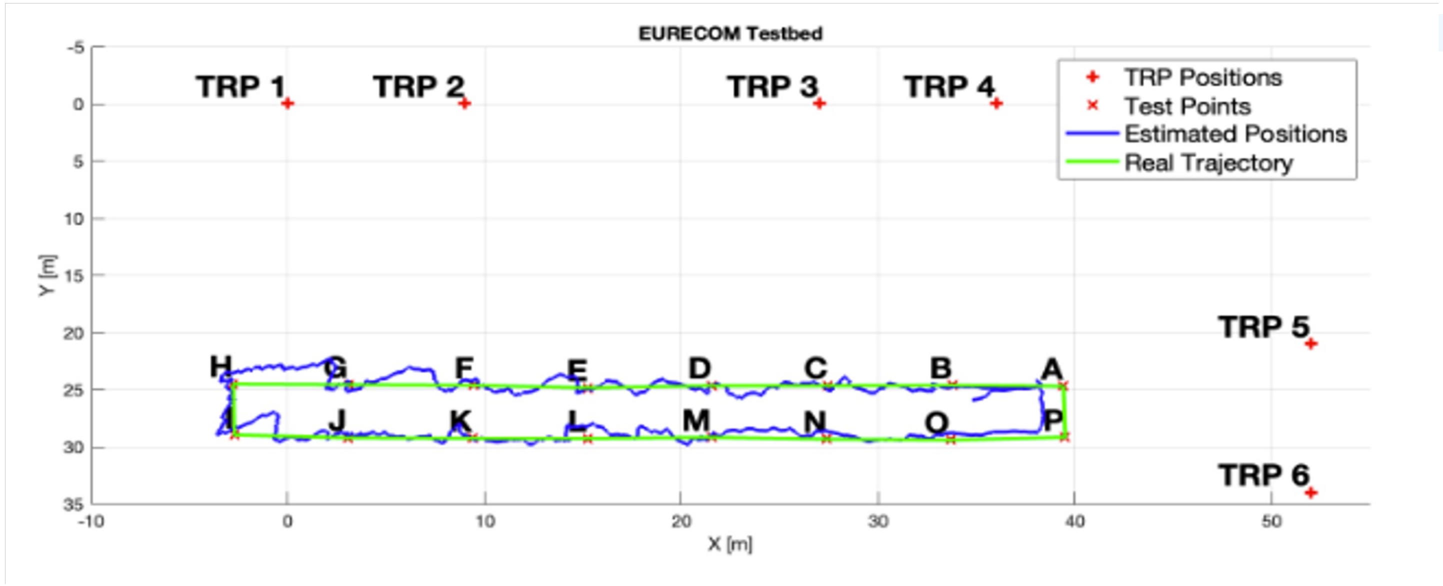






GEO-5G Testbed - Results

Check out the demo video at our poster stand!

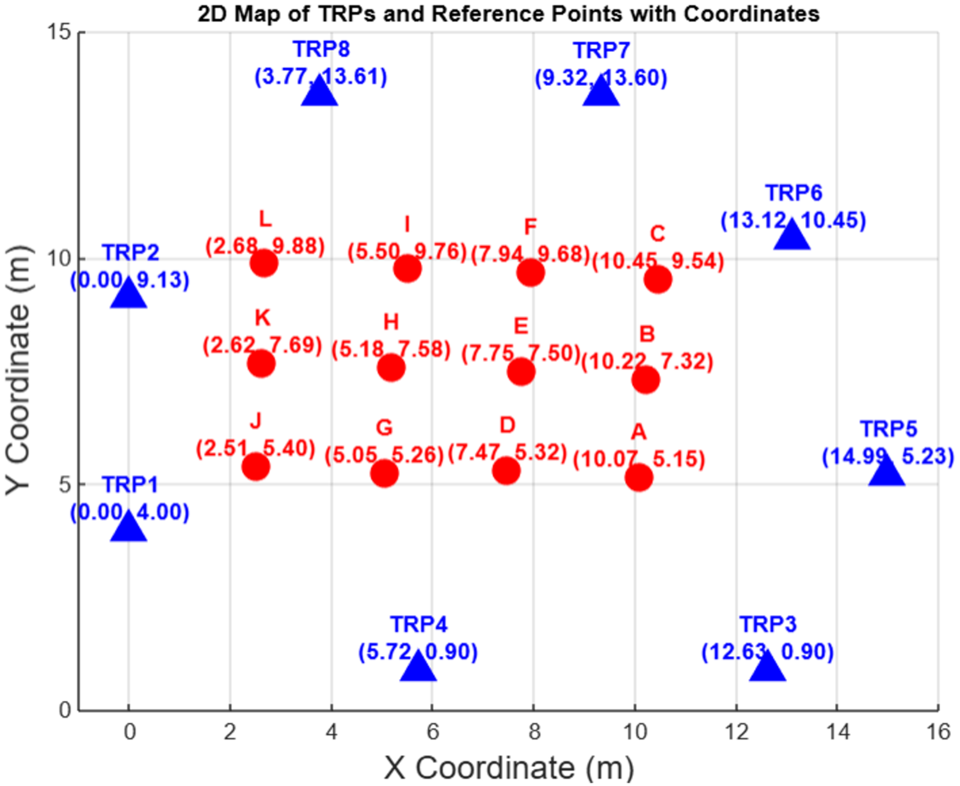


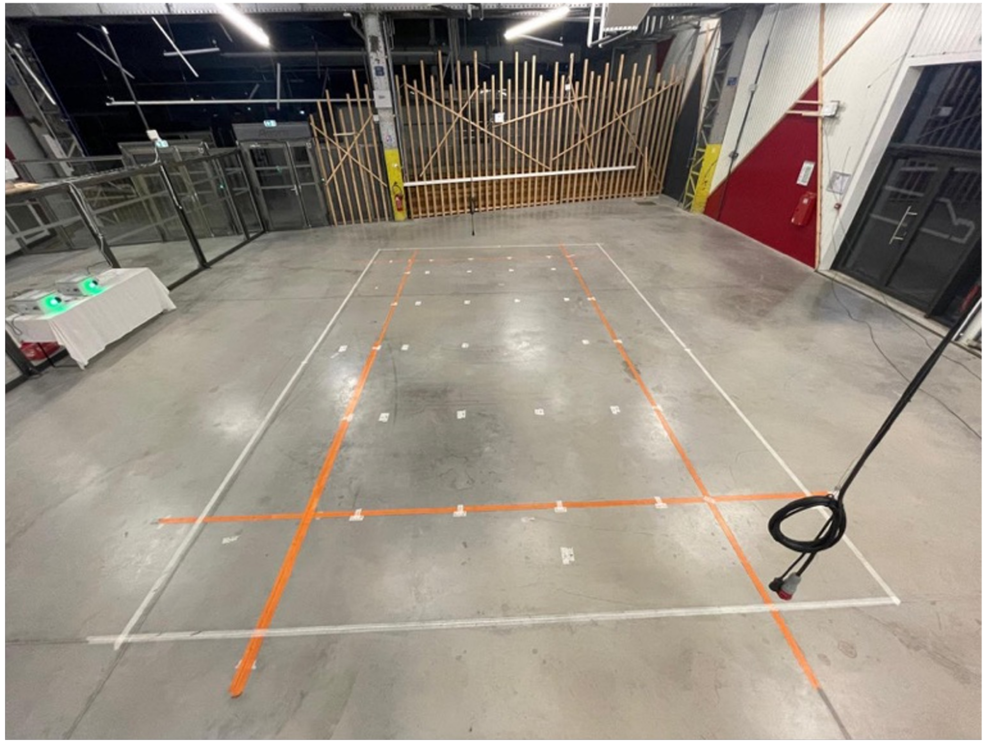
Point	1 RU MAE(m)	2 RUs MAE(m)	Point	1 RU MAE(m)	2 RUs MAE(m)
A	4.77	1.93	I	3.02	0.60
B	4.69	1.80	J	2.32	0.83
C	0.81	1.29	K	3.38	0.82
D	1.30	1.28	L	3.23	1.65
E	2.37	1.61	M	0.34	1.15
F	2.00	1.05	N	4.85	1.43
G	2.27	0.92	O	5.41	1.79
H	3.31	0.60	P	4.12	1.98

TABLE I: Mean Absolute Error (MAE) for both single RU (RU3) and multi-RU (RU2+RU3) setups at points A-P.

Other results – Indoor hall

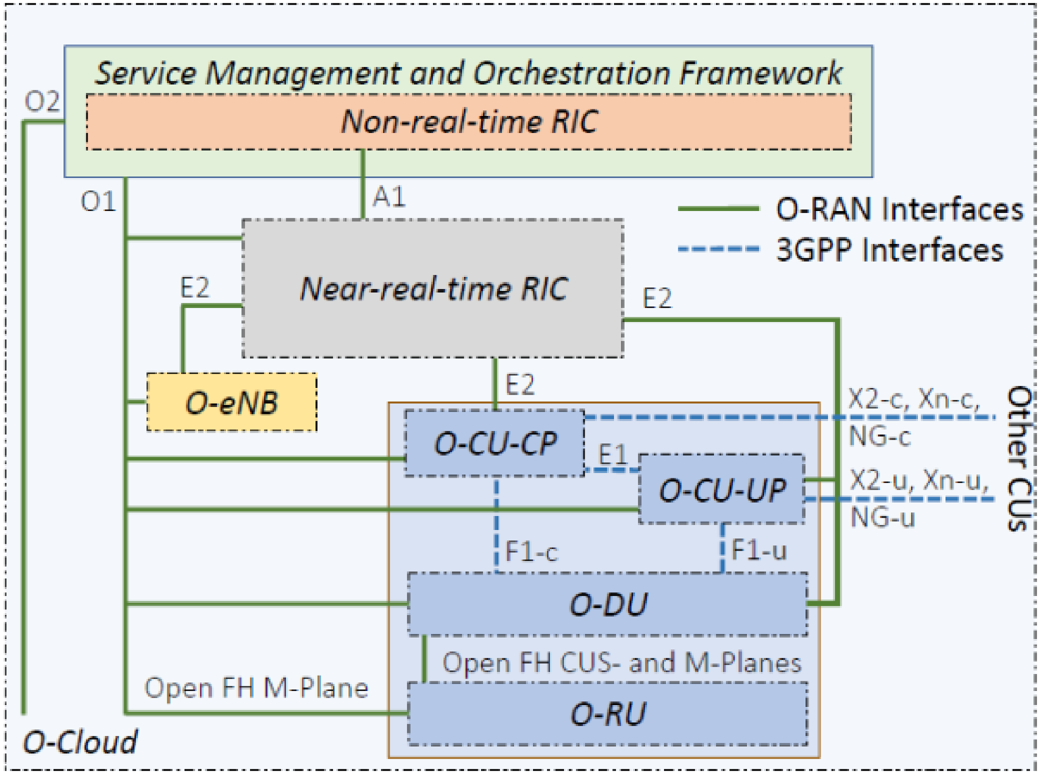
- Preliminary Results from Firecell’s indoor Positioning Testbed Stellantis Factory
  - 70% of the time, the positioning error was below 1.35 meters.
  - 90% of the time, the positioning error was below 1.60 meters.





Positioning based on AI/ML

- 3GPP methods uses RSSI, ToA, TDoA, etc. to localize the UE
- AI/ML models often need a higher dimensional data such as CSI for training and testing
    - No standard protocol in 3GPP carry CSI from gNBs to CN (LMF)
- O-RAN E2 interface can be leveraged for positioning
    - Non-RealTime RIC uses processed CSI for training, Near-RealTime RIC for testing AI/ML models
- SRS can be exported through
    - Lower Layers Control Service model [1]
        - Sends SRS as it comes from the RU
        - No channel estimation
    - Custom Service model
        - Defined by OAI/FlexRIC
        - Re-uses FAPI SRS indication message



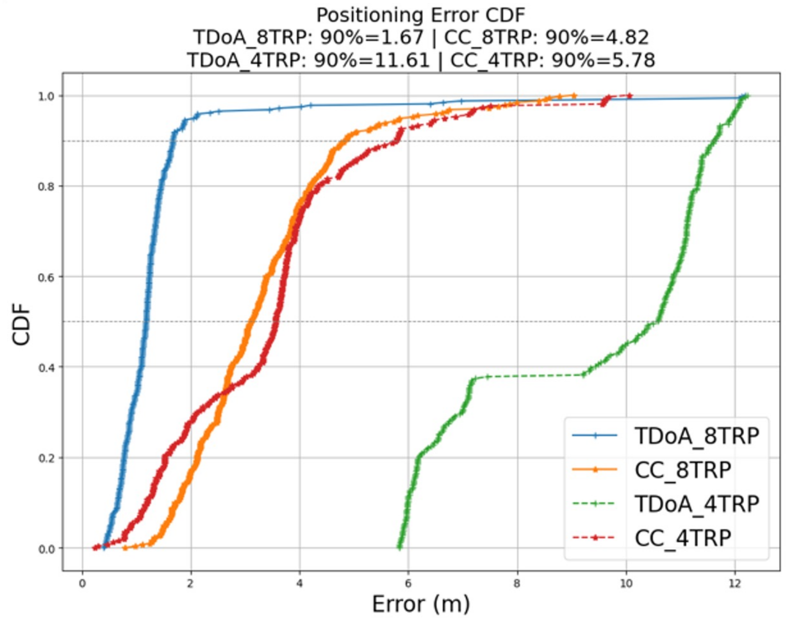
[1] O-RAN.WG3.TS.E2SM-LLC-R004-v01.00, Feb 2025

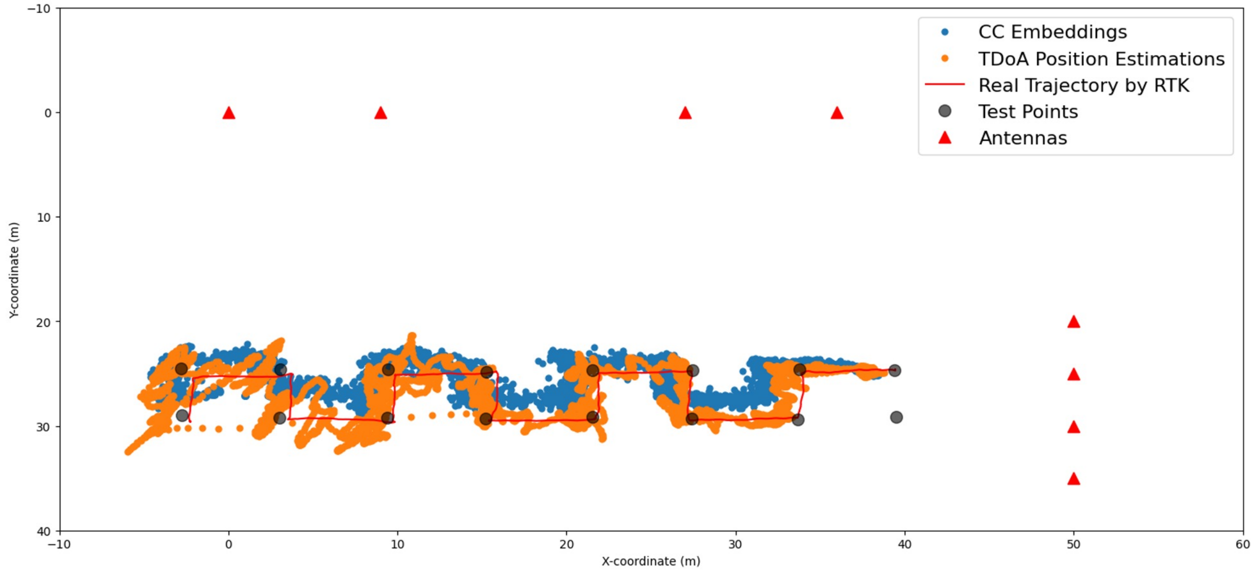
Positioning based on AI/ML

- Algorithms
  - **Fingerprinting:** Assigning each CSI with the UE’s position as label
  - **Channel Charting:** Optimizing a loss function involving CSI and antenna locations with no label
  - NLoS mitigation by learning power distributions and delay spread

Positioning based on AI/ML

- Live test and demo results from EURECOM GEO5G testbed*
- TDoA VS Channel Charting with 2 RUs, 8 non-collinear antennas, mixed LoS/NLoS
- TDoA VS Channel Charting with 1 RU, 4 collinear antennas, mixed LoS/NLoS
- Channel Charting outperforms TDoA in a low antenna and geographically challenging test

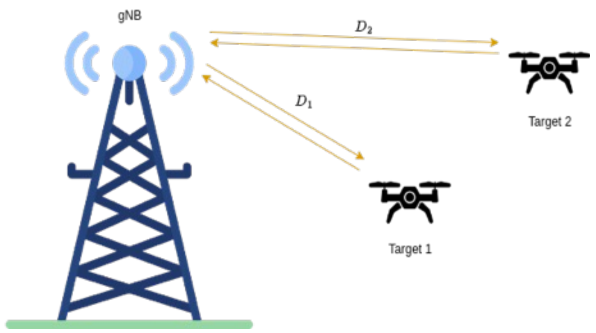


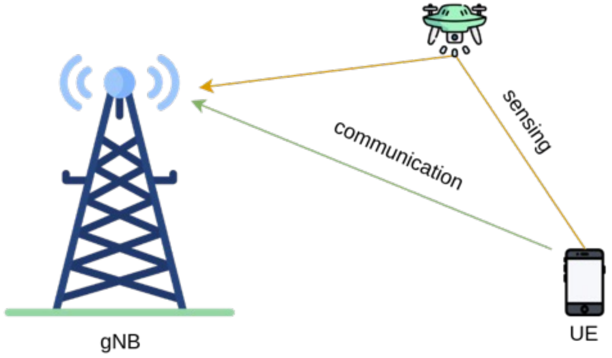


* Not yet using the E2 interface and xAPPs. Simple prototype using MQTT.

Sensing with OAI

- O-RAN SRS/PRS service model can also be used for radar sensing
  - Monostatic
    - Requires full duplex radios
  - Bistatic & Multistatic
    - TX can be UE or other RUs
    - Requires very tight/ over-the-air synchronization

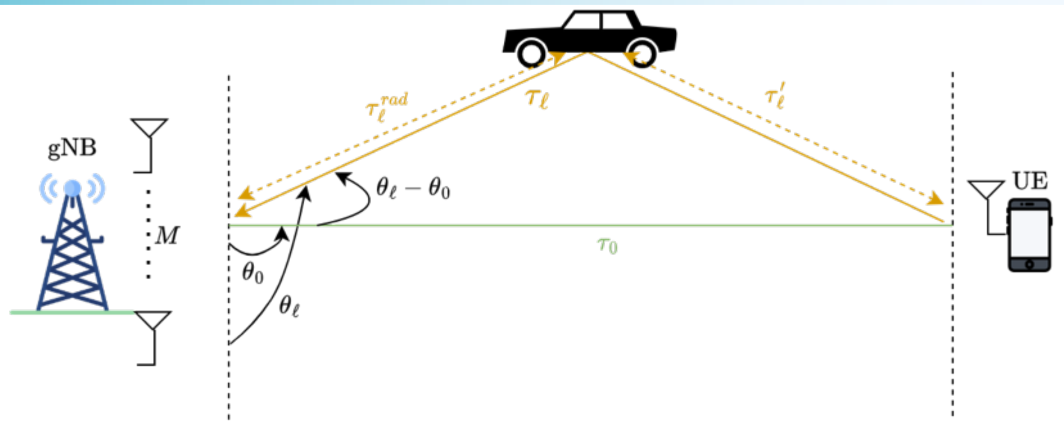


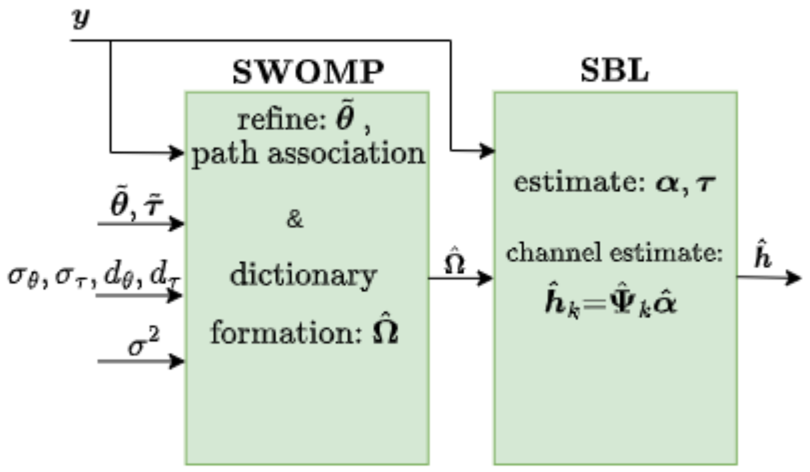


- R.Gangula, T.Melodia, R.Mundlamuri and F.Kaltenberger, " Round Trip Time Estimation Utilizing Cyclic Shift of Uplink Reference Signal", IEEE ICC, 2025.
- R.Mundlamuri, R.Gangula, F.Kaltenberger and T.Melodia, "Novel Round Trip Time Estimation in 5G NR", IEEE Global Communications Conference (GLOBECOM), 2024.
- R. Mundlamuri, "Localization and Sensing in 5G NR and beyond," PhD Thesis, EURECOM, April 2025.

Sensing aided Channel Estimation

- Pilot overhead for channel estimation increases as the number of antennas increase in a MIMO system.
- Proposed a framework to integrate sensing information available at the gNB for channel estimation.
- The proposed framework reduces pilot overhead.
- A two stage SWOMP-SBL algorithm is proposed for channel estimation.
- The proposed algorithm is also robust to the errors present in the sensing information.

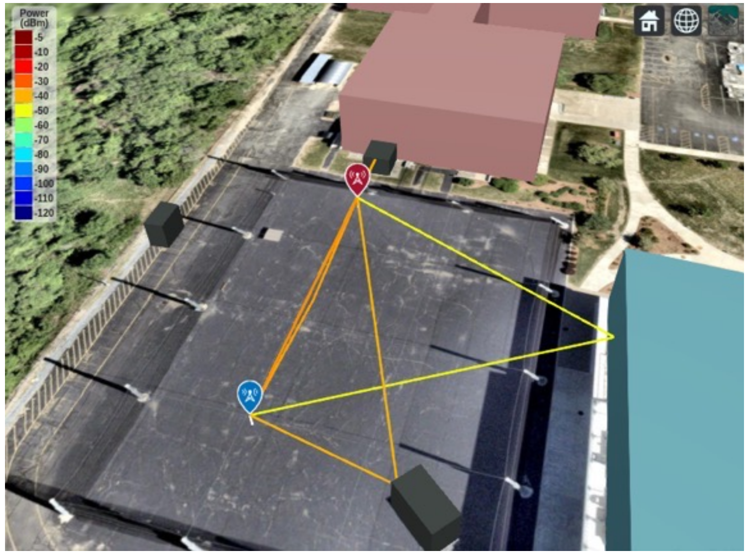




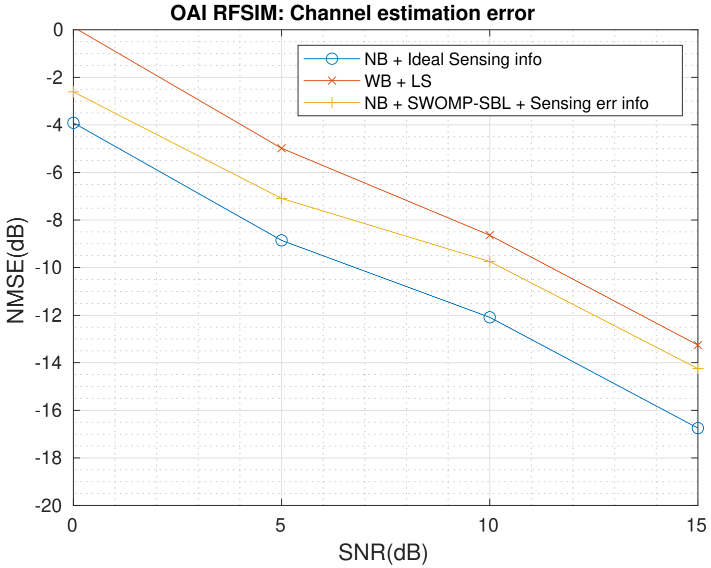
Sensing aided Channel Estimation - Results

- Verified the proposed algorithm using OAI RFSIM considering fixed-point effects.
- Channel from the MATLAB raytracer is applied in the OAI RFSIM.
- Sensing information obtained from Matlab and error model applied
- gNB uses this info for channel estimation (SWOMP-SBL algorithm)
- Reduces the pilot overhead by 97%.

Matlab raytracer



OAI RFSIM



Conclusions

- Sensing is a hot topic for 5G-Advanced and 6G (many use cases)
- Architecture for sensing is likely to be an evolution of 5G positioning architecture
- AI/ML Algorithms well suited for this kind of problems, but require access to full channel state information
- OpenAirInterface is well suited for experimentation in this area

Thank you!

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