



OAI-Based Wireless Digital Twin with SDR Channel Emulator

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Challenges in 6G R&D

- Limitations of Real-World OTA Experiment:
 - High Cost (CAPEX for **full-stack testbeds**)
 - Time-consuming Radio **Licensing** (at least in Japan)
 - Lack of **Reproducibility** (weather, transient blockages)

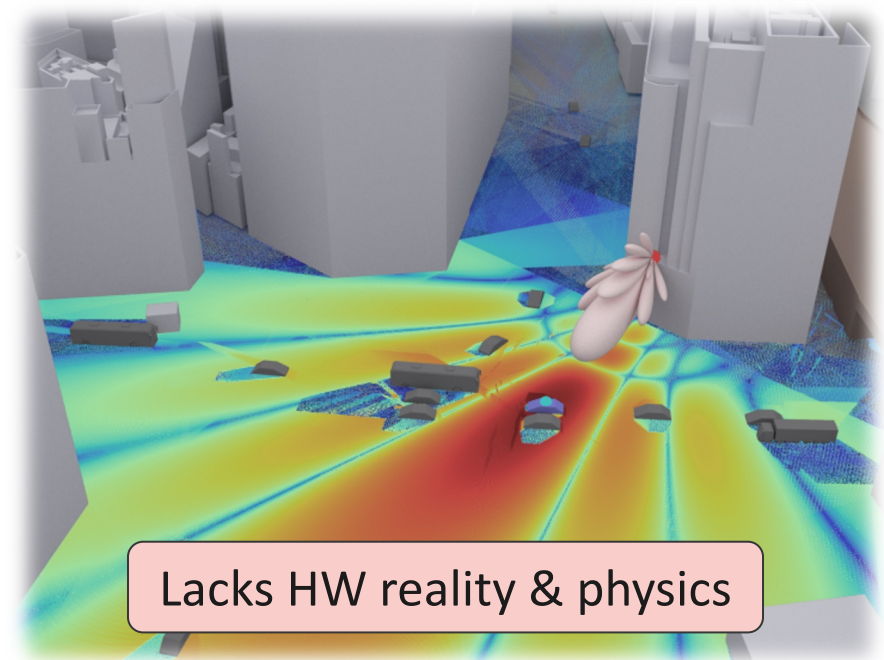
Real-World



Bridging the
Reality Gap



Simulation



● OAI covers the widest scope as a single project

- 5G Core Network (**5GC**)
- Radio Access Network (**RAN**)
- User Equipment (**UE**)
- **OTA** experiment with RF devices (SDRs/O-RUs)
- **O-RAN** compliant
- **Radio Propagation**
 - 3GPP Channel Model (P)
 - Site-specific (✓)
 ... can be supported by integrating 3rd-party OSS (like AODT/Sionna RT/Opal/...)

OSS Project	5GC	RAN	UE	OTA	Prop.	O-RAN
OAI	✓	✓	✓	✓	P	✓
srsRAN	P	✓	P	✓	-	P
OCUDU	-	✓	-	✓	-	✓
free5GC	✓	-	-	-	-	-
Open5GS	✓	-	-	-	-	-
Magma	✓	-	-	-	-	-
AETHER	✓	✓	-	-	-	✓
UERANSIM	-	✓	✓	-	-	-
Aerial/Sionna	-	P	-	-	✓	-
O-RAN SC	-	✓	-	-	-	✓
5G-LENA (ns-3)	P	✓	✓	-	P	-
Simu5G (OMNeT++)	P	✓	✓	-	P	-

✓	Supported
P	Partially supported
-	Not supported

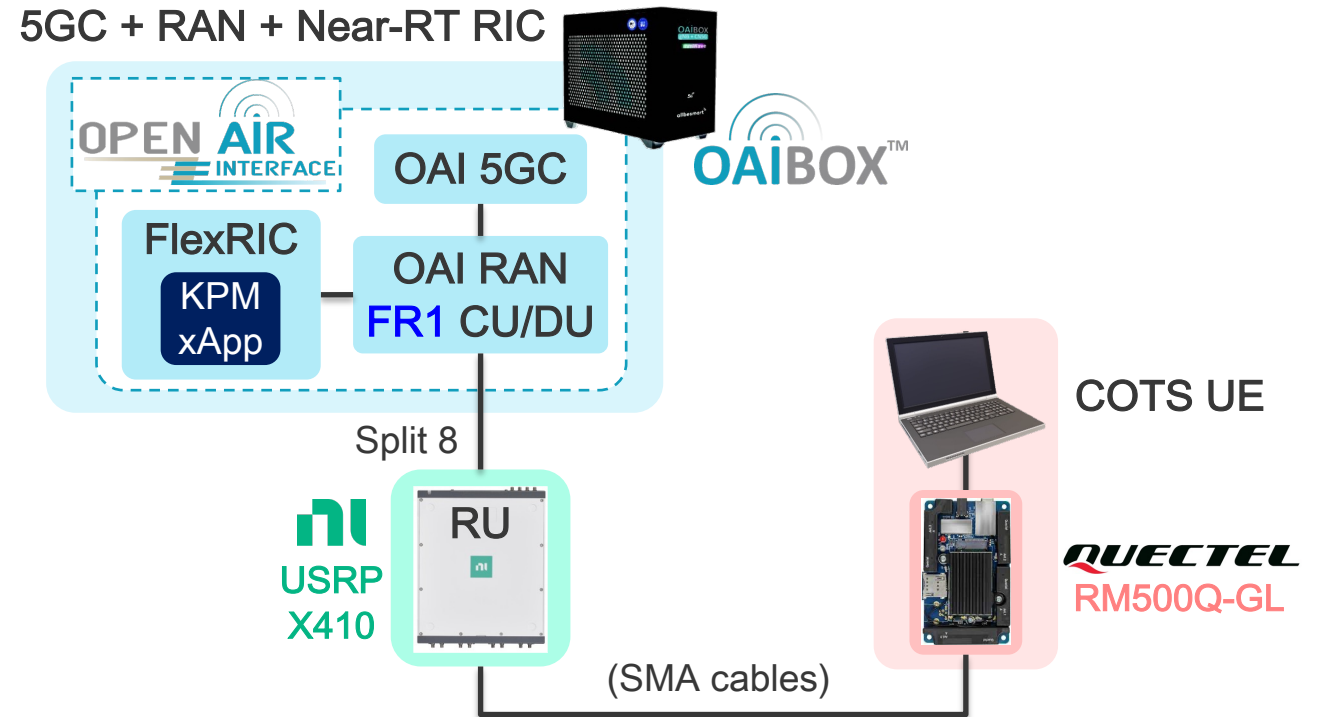
● Cable-Connected Setup

– OAI Software Stack

- 5GC
- RAN
- FlexRIC

– Radio Devices

- USRP X410 as gNB SDR
- COTS UE (Quectel 5G UE module)
- SMA cables



● OTA Setup

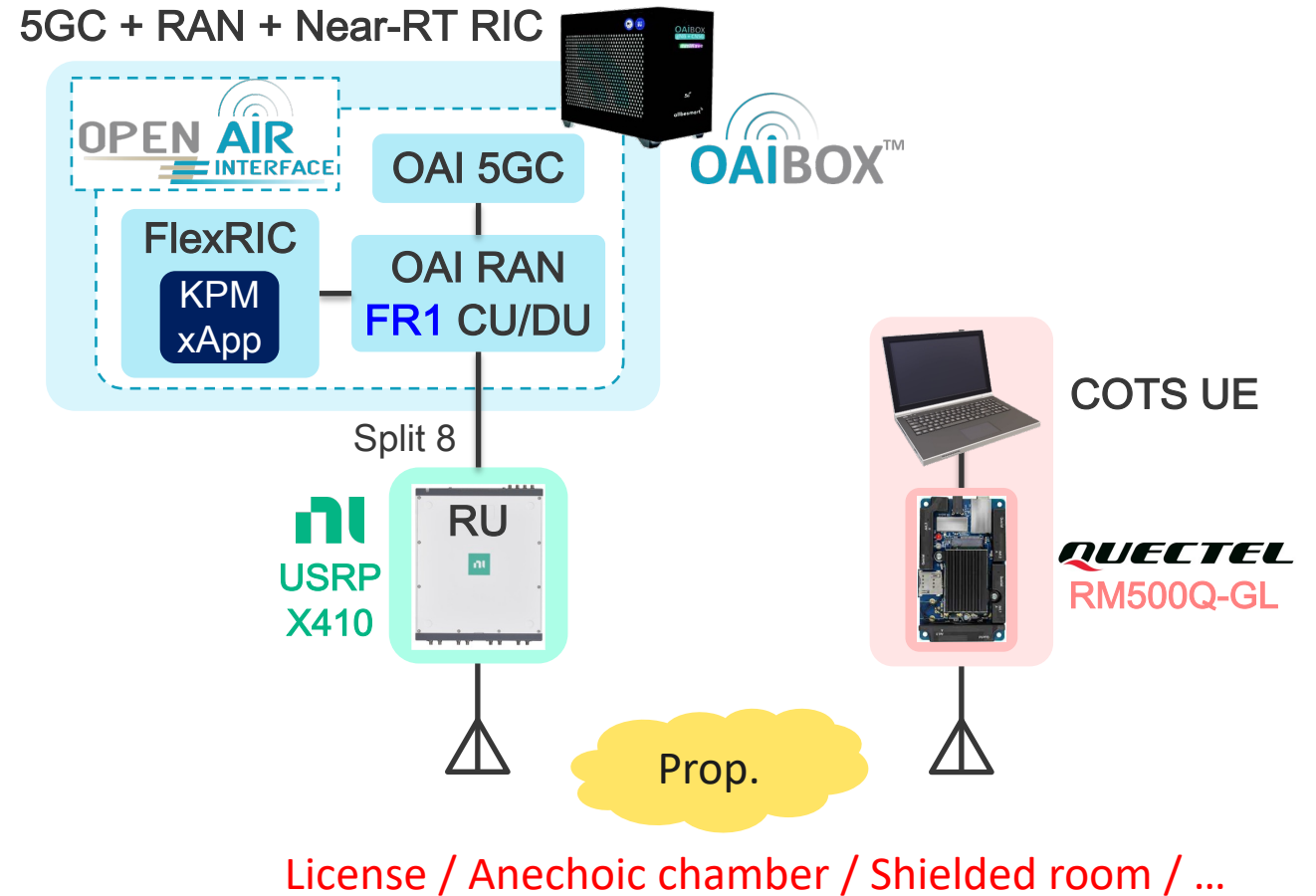
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- Antenna

– Radio Propagation



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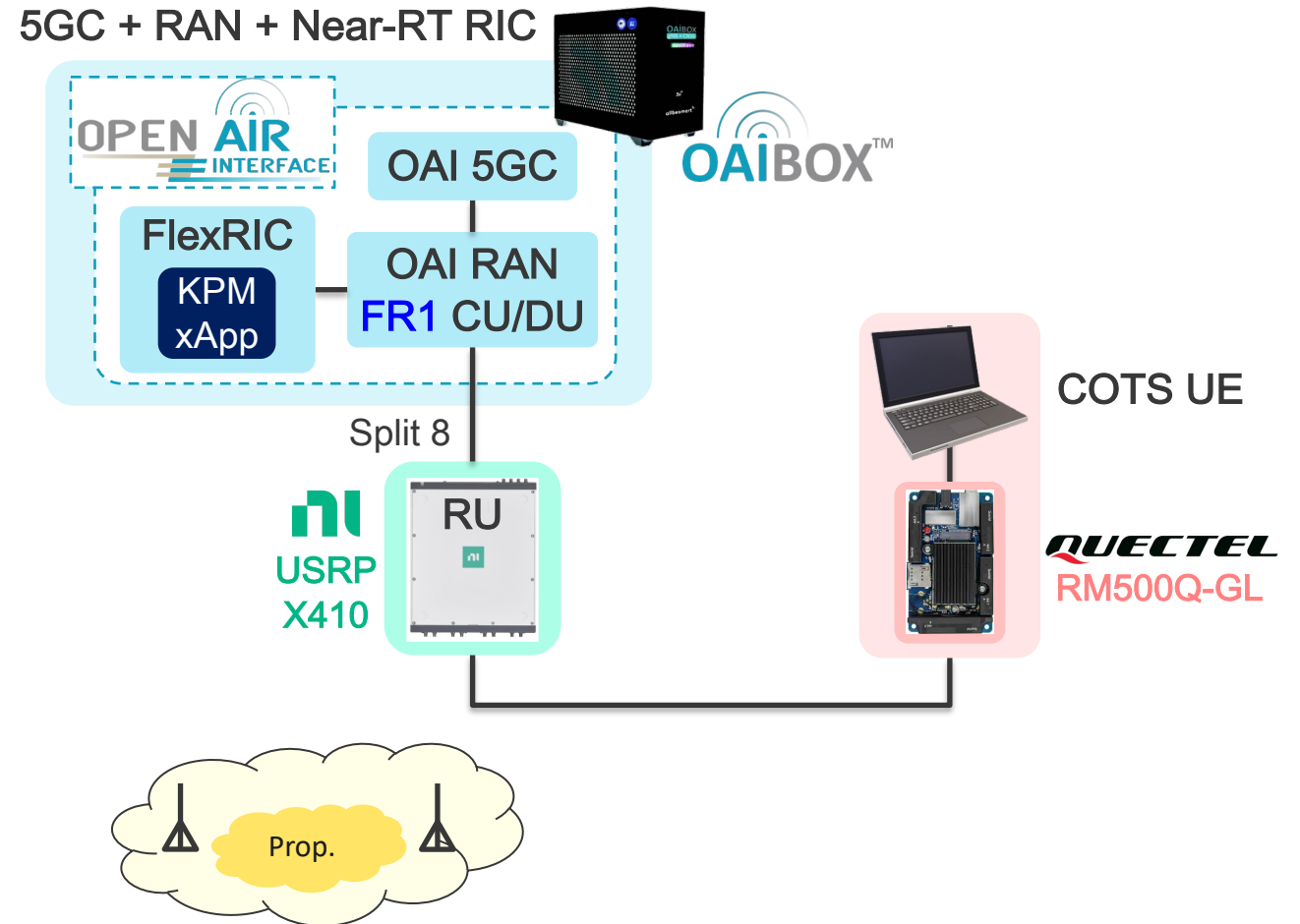
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● OTA Setup

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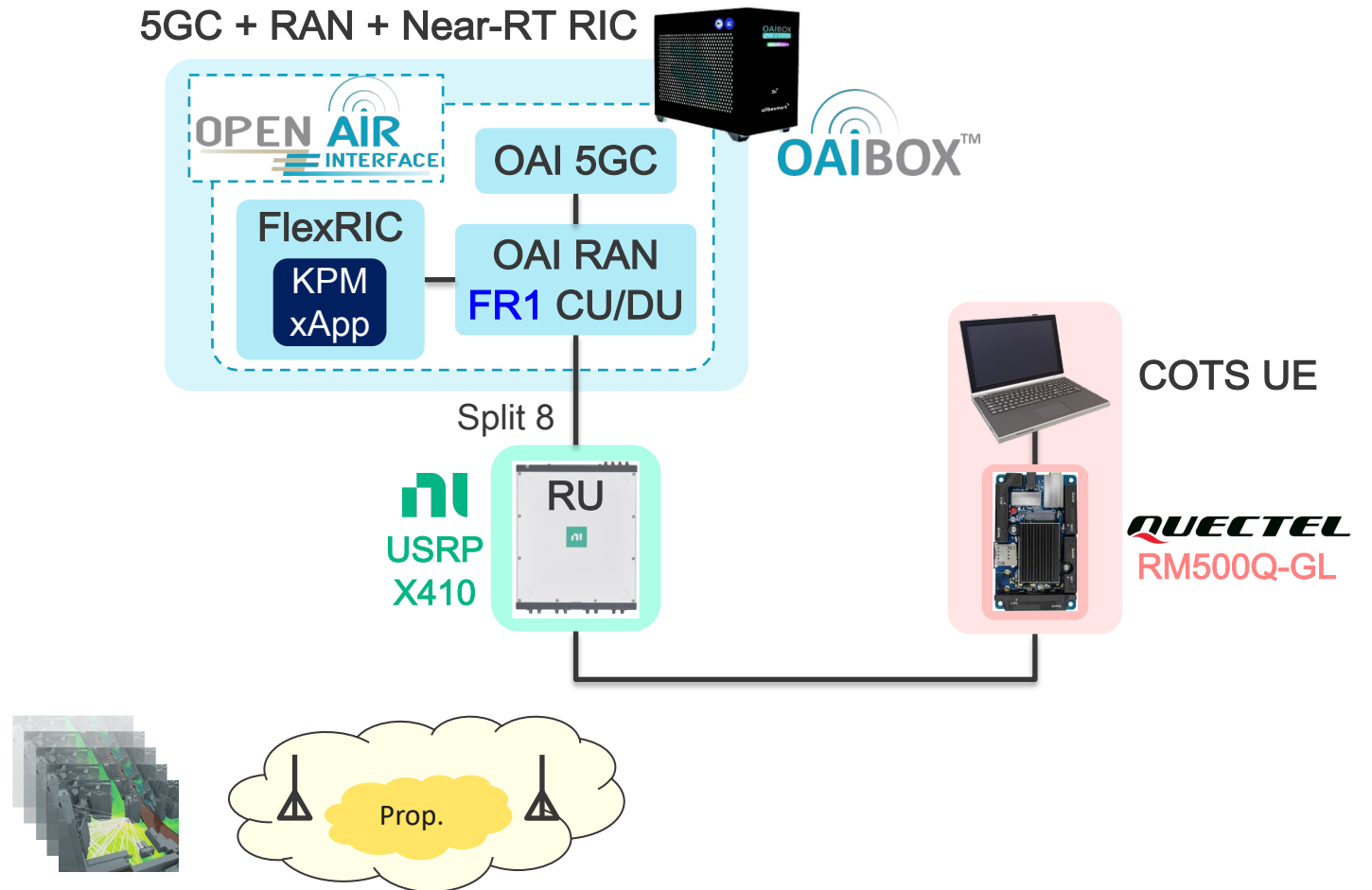
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- Pre-compute dynamic radio prop. scenarios via ray tracing.



● OAI-Based Wireless Digital Twin

– OAI Software Stack

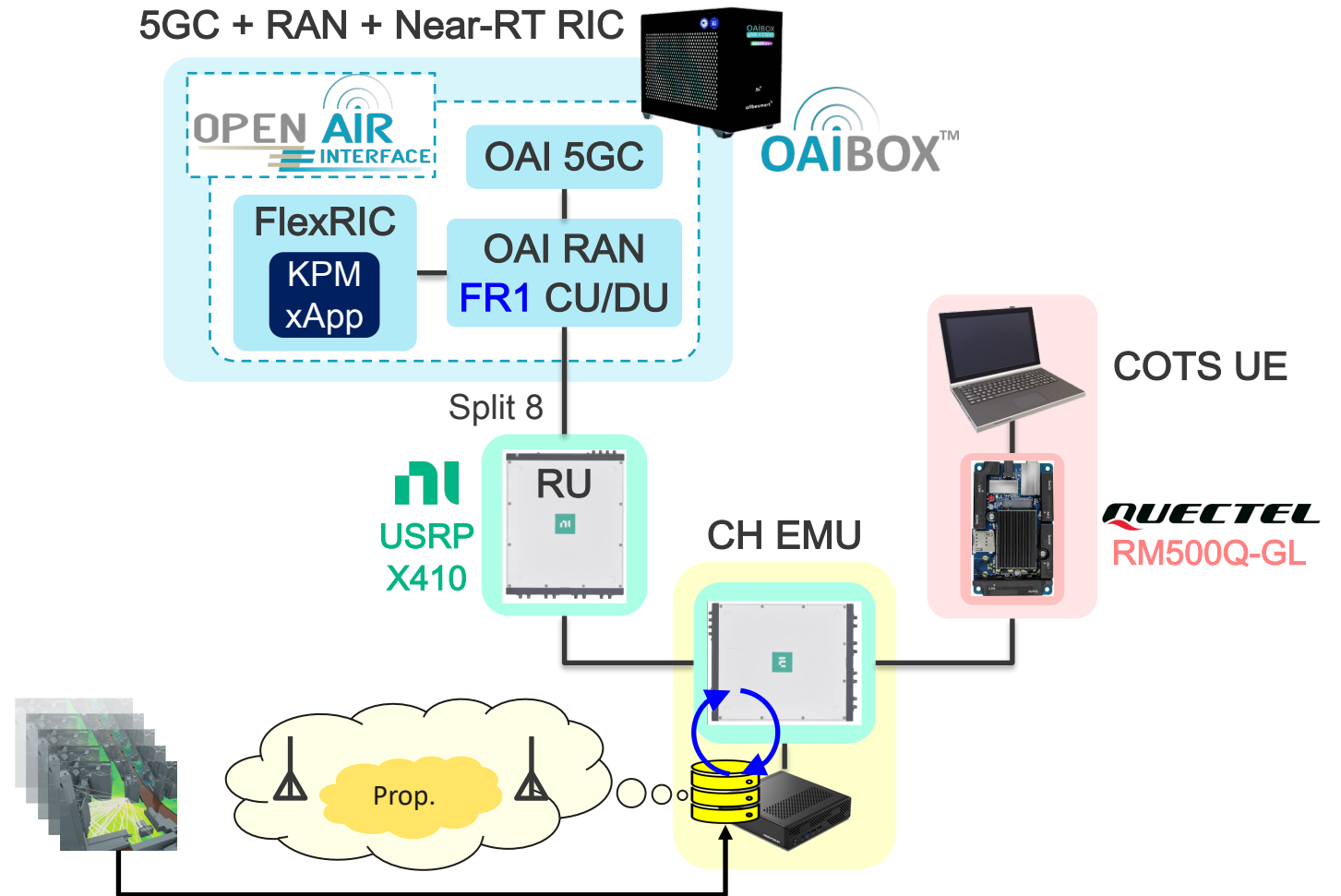
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– Radio Propagation

- Pre-compute dynamic radio prop. scenarios via ray tracing.
- Convolve baseband signal with channel impulse response (CIR) on FPGA (Channel Emulation).



● OAI-Based Wireless Digital Twin

– OAI Software Stack

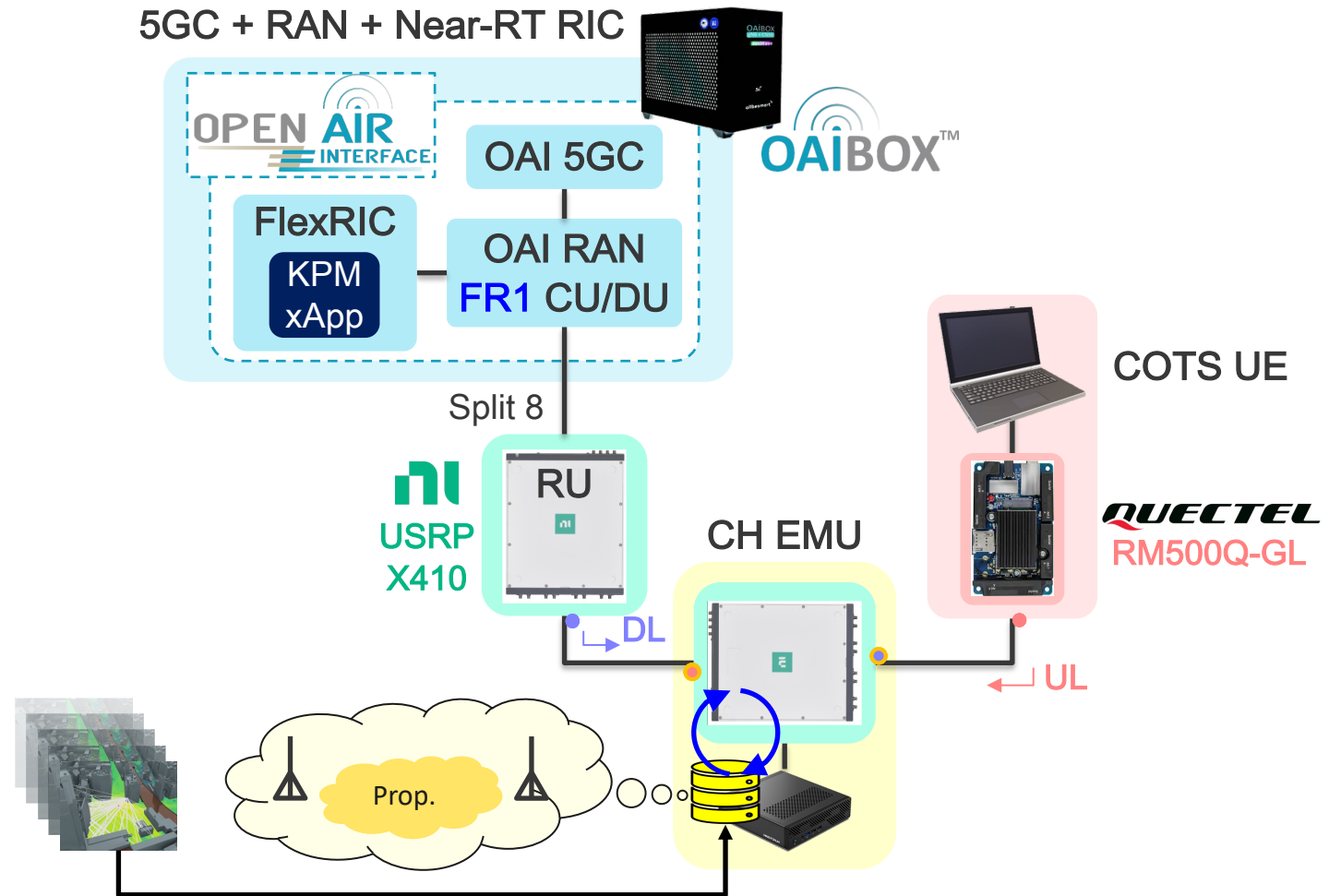
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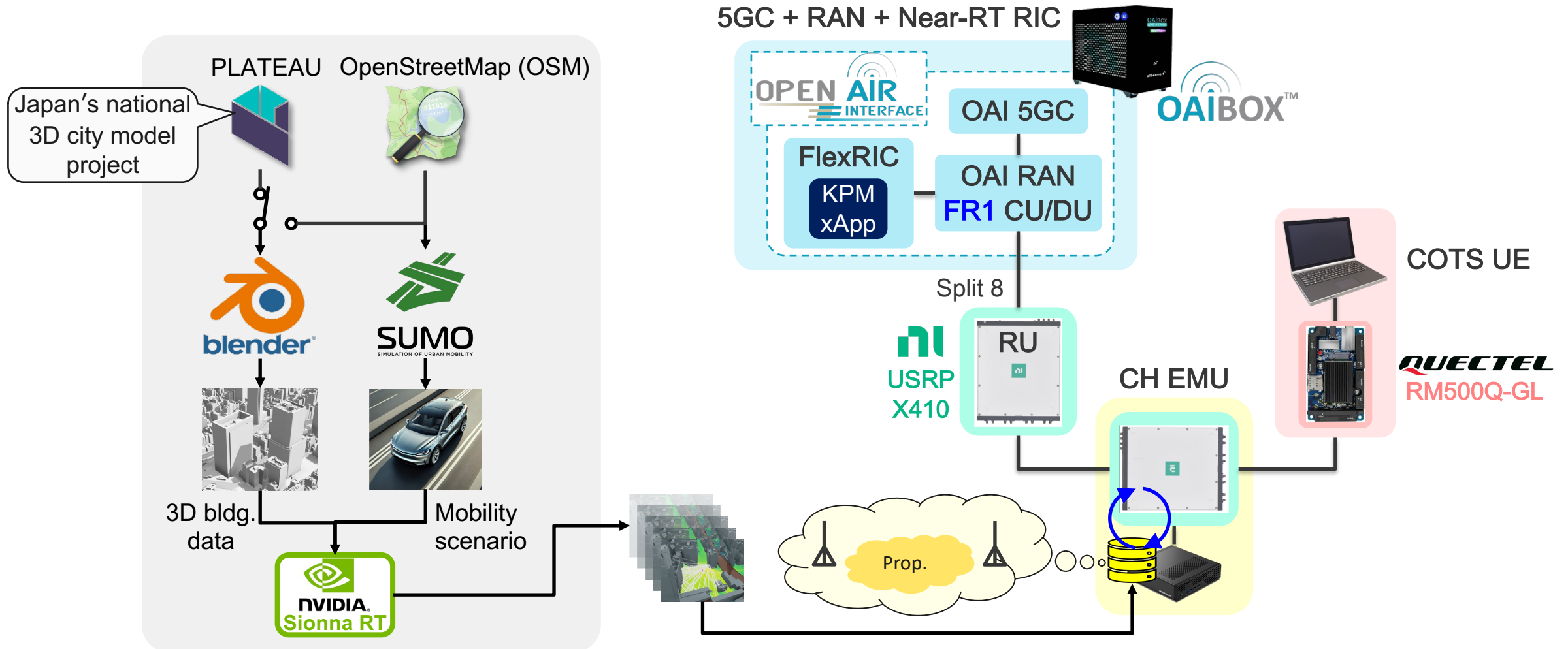
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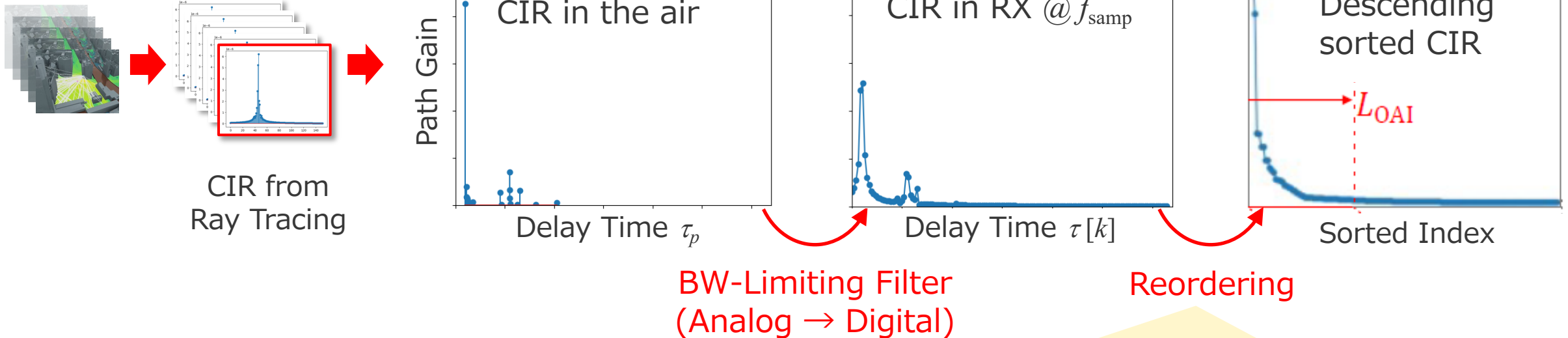
● CIR Pre-Computation Workflow



● CIR Pre-Computation

T. Iye et al., *IEEE Access*, vol. 13, pp. 175109-175122, 2025.

$$h(\tau) = \sum_{p=0}^{P-1} a_p \delta(\tau - \tau_p) \quad \bar{h}[k] = \sum_{p=0}^{P-1} a_p \text{sinc}(k - f_{\text{samp}} \tau_p)$$

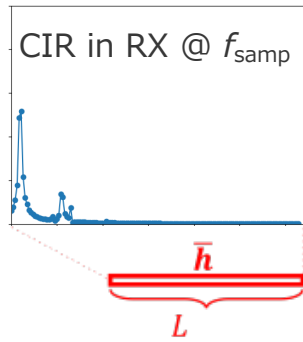


- Sort by amplitude in descending order to extract dominant components.
- Import up to L_{OAI} data points starting from the largest amplitude.
- Ignore contributions from $L_{\text{OAI}} + 1$ onwards to reduce computational load.

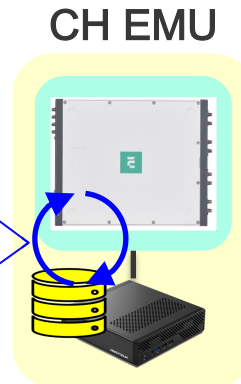
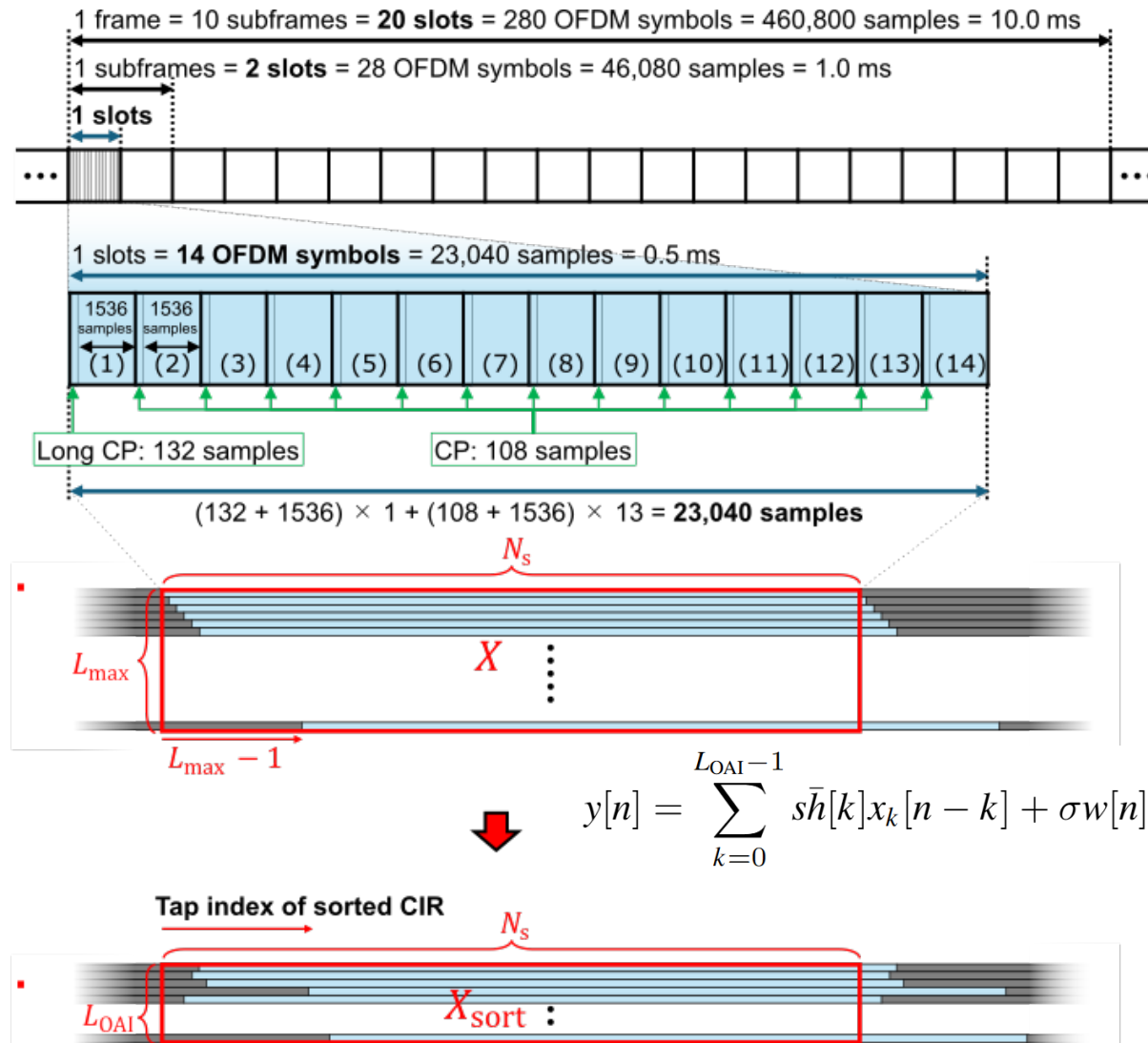
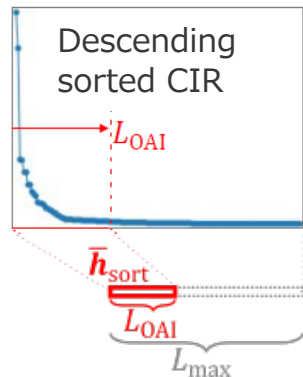
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High cost

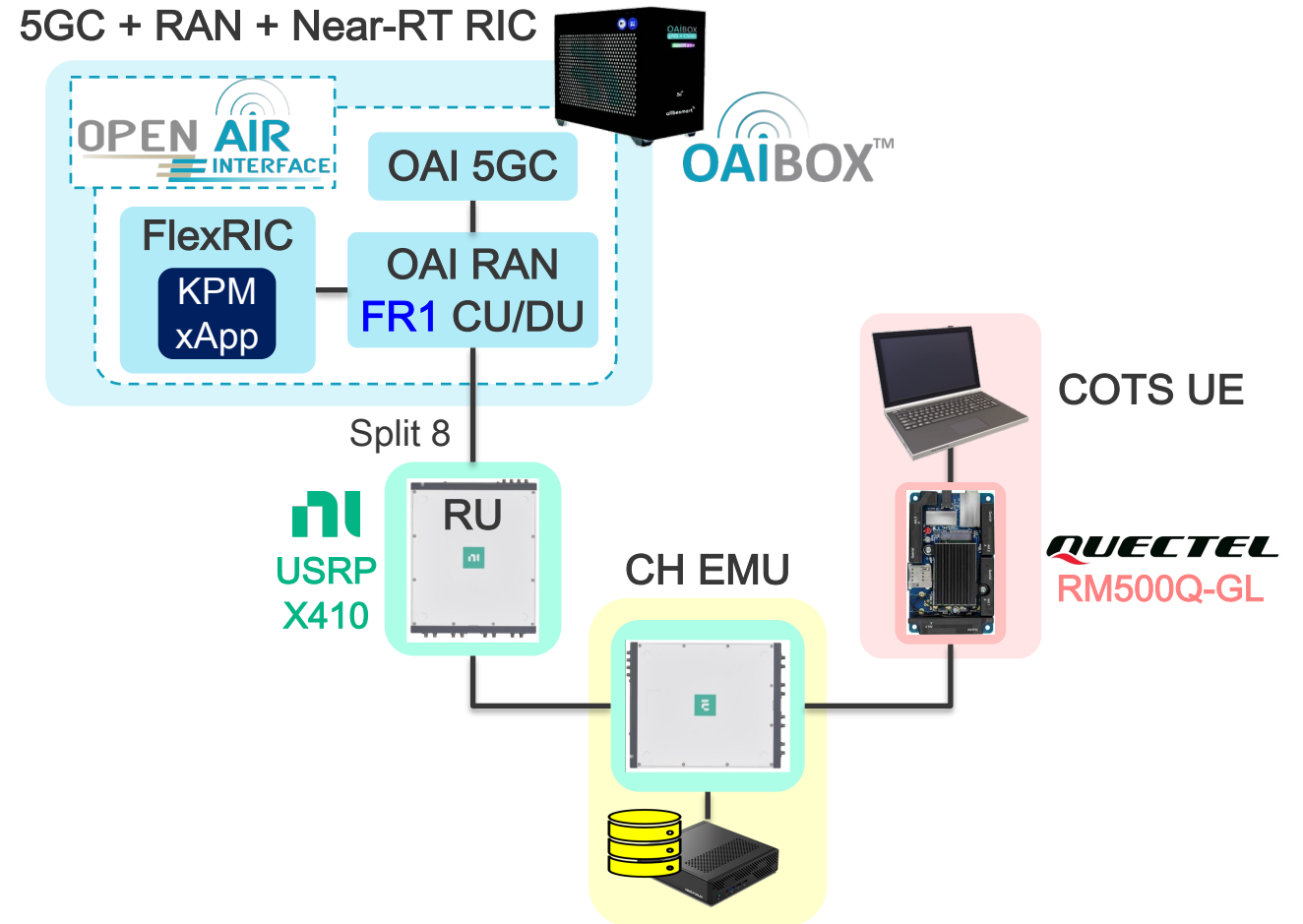


Low cost



Experimental Setup

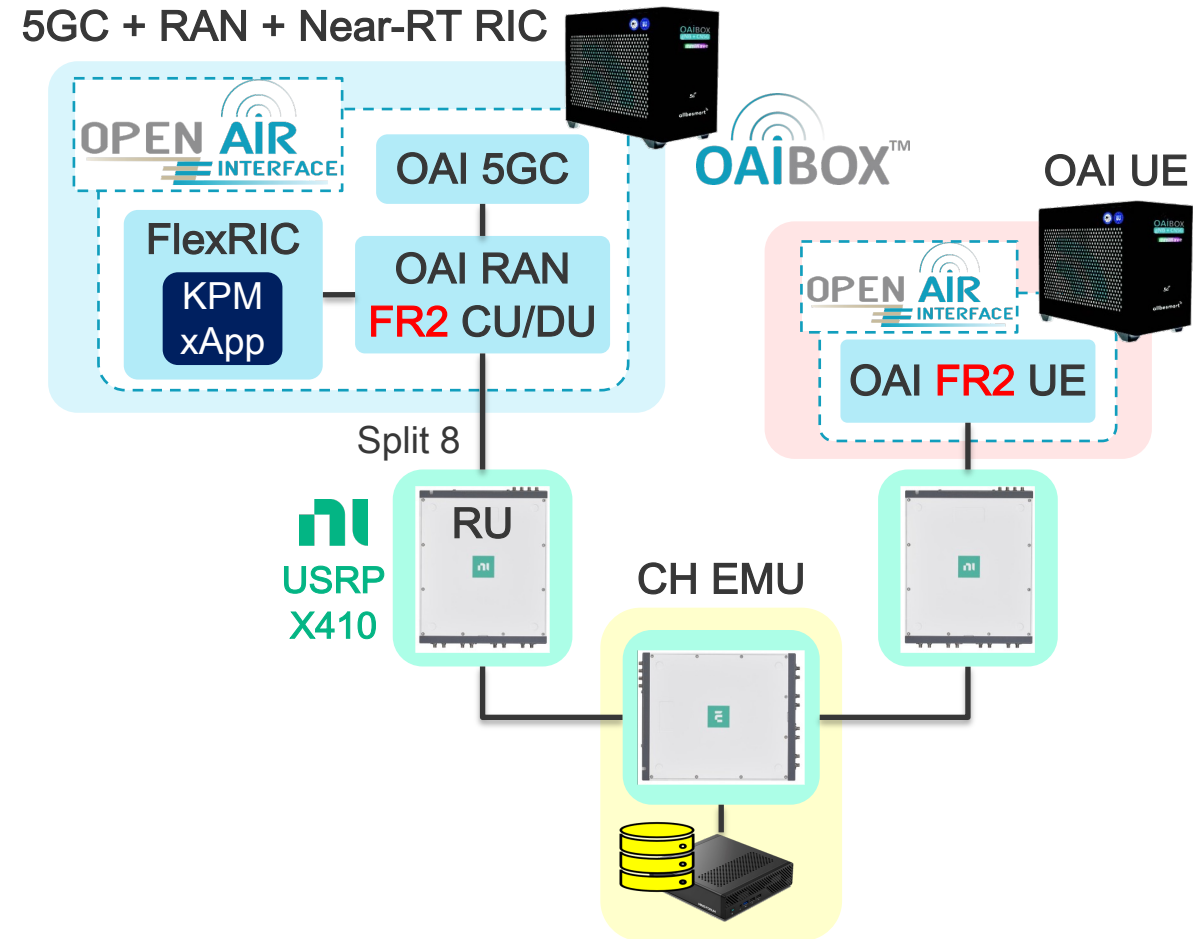
● For FR1



Experimental Setup

● For FR2

- Quectel FR2 module does not expose signal lines.
- Cable-connected testing requires **OAI UE** + **USRP**.



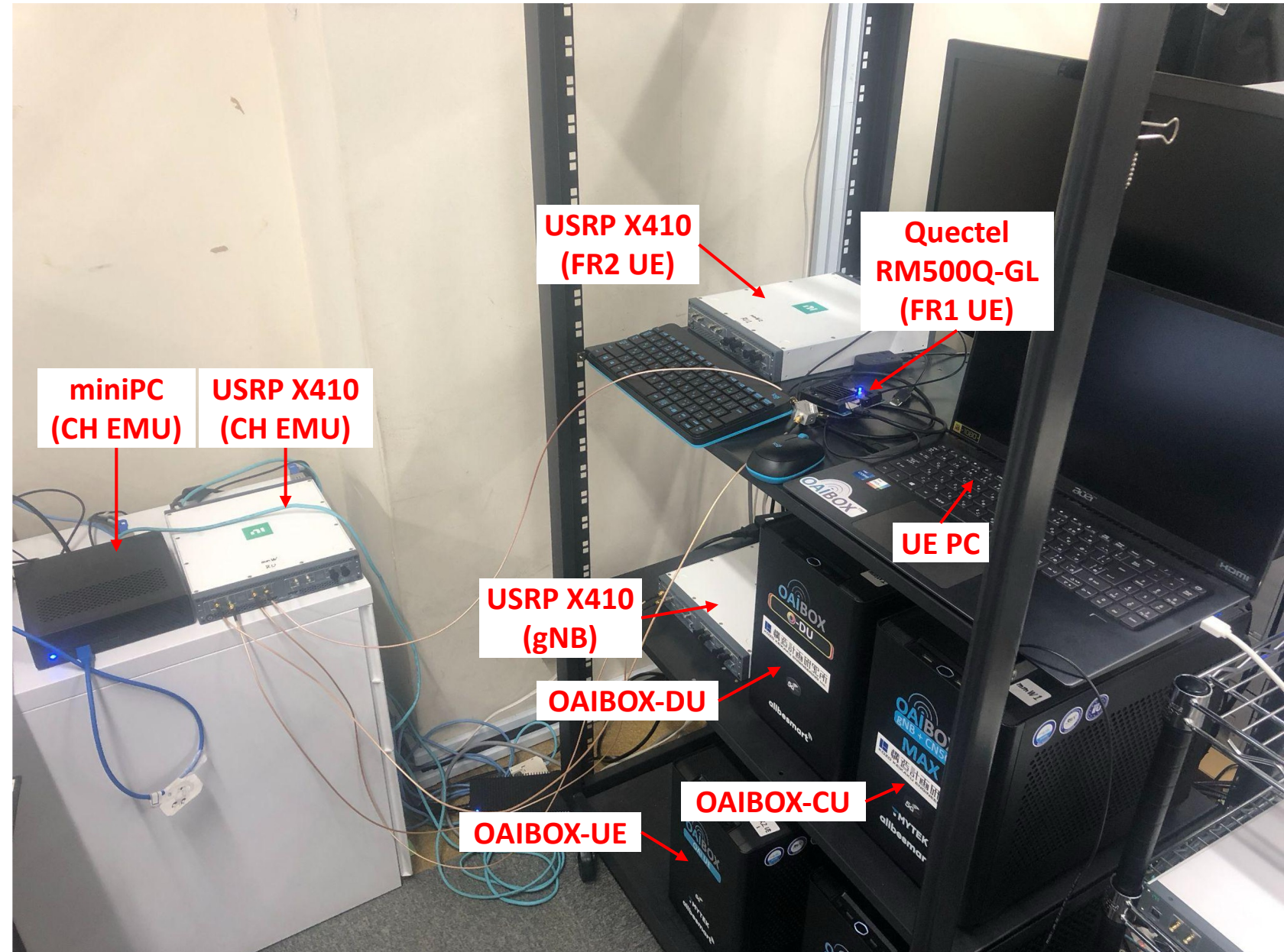
Experimental Setup

Hardware Configurations

Node	Device
gNB	OAIBOX-CU
	OAIBOX-DU
	USRP X410
FR1 UE	UE Control PC
	Quectel RM500Q-GL
FR2 UE	OAIBOX-UE
	USRP X410
CH EMU	MINISFORUM MS-A2
	USRP X410
GPU server	SYS-740GP-TNRT

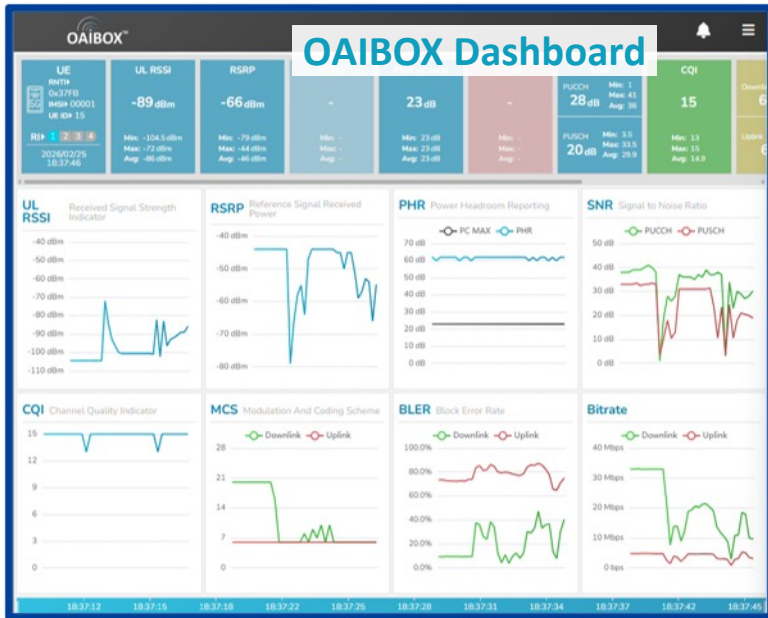


Note:
GPU server is installed
in a separate room.



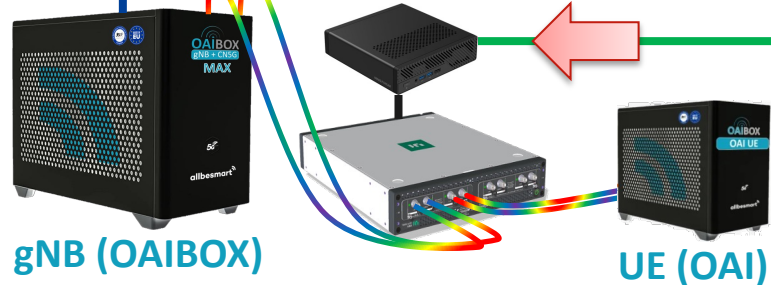
Experimental Setup

- Scenario-based CIR playback enables evaluation in time-varying channel.



Real-time Monitoring

Real-time-speed playback



The software interface is divided into several sections:

- Channel Configuration & Display CIR:** Includes controls for Channel Model (Scenario), Num. of Taps (24), Delay Spread (30 ns), and Coherence Time (1 m). It features buttons for "Start CSI trans.", "stop CSI trans.", "T: CIR, F: Pass Through", "stop USRP", and "STOP".
- Table of Delay Spread & Scenario Emulator:** Shows a graph of **Path Gain** vs **Elapsed time [ms]**. It includes fields for Max. Delay Index (192) and Num. of Scenario Steps (30000).
- Multipath Config. (Delay, Amplitude, Phase):** A table for configuring DL00 delay index and coefficients.
- Power Delay Profile (PDP):** A graph showing **Path gain [dB]** vs **Time [ns]**.
- Scenario Rendering:** A 3D visualization of a scenario with a heatmap of signal strength and a user figure.

Specs on X410-based Channel Emulator

- Supports **3GPP TDL** channel models
- Flexible **multipath configuration**

Table 7.7.3-2. Scenario specific scaling factors - for information only

Proposed Scaling Factor	DS _{desired} in [ns]	Frequency [GHz]						
		2	6	15	28	39	60	70
Indoor office	Short-delay profile	20	16	16	16	16	16	16
	Normal-delay profile	39	30	24	20	18	16	16
	Long-delay profile	59	53	47	43	41	38	37
UMi Street-canyon	Short-delay profile	65	45	37	32	30	27	26
	Normal-delay profile	129	93	76	66	61	55	53
	Long-delay profile	634	316	307	301	297	293	291
UMa	Short-delay profile	93	93	85	80	78	75	74
	Normal-delay profile	363	363	302	266	249	228	221
	Long-delay profile	1148	1148	955	841	786	720	698
RMa & RMa O2I	Short-delay profile	32	32	N/A	N/A	N/A	N/A	N/A
	Normal-delay profile	37	37	N/A	N/A	N/A	N/A	N/A
	Long-delay profile	153	153	N/A	N/A	N/A	N/A	N/A
UMi / UMa O2I	Normal-delay profile	240						
	Long-delay profile	616						

Table 7.7.2-1. TDL-A

Tap #	Normalized delay	Power in [dB]	Fading distribution
1	0.0000	-13.4	Rayleigh
2	0.3819	0	Rayleigh
3	0.4025	-2.2	Rayleigh
4	0.5868	-4	Rayleigh
5	0.4610	-6	Rayleigh
6	0.5375	-8.2	Rayleigh
7	0.6708	-9.9	Rayleigh
8	0.5750	-10.5	Rayleigh
9	0.7618	-7.5	Rayleigh
10	1.5375	-15.9	Rayleigh
11	1.8978	-6.6	Rayleigh
12	2.2242	-16.7	Rayleigh
13	2.1718	-12.4	Rayleigh
14	2.4942	-15.2	Rayleigh
15	2.5119	-10.8	Rayleigh
16	3.0582	-11.3	Rayleigh
17	4.0810	-12.7	Rayleigh
18	4.4579	-16.2	Rayleigh
19	4.5695	-18.3	Rayleigh
20	4.7966	-18.9	Rayleigh
21	5.0066	-16.6	Rayleigh
22	5.3043	-19.9	Rayleigh
23	9.6586	-29.7	Rayleigh

https://www.etsi.org/deliver/etsi_tr/138900_138999/138900/14.02.00_60/tr_138900v140200p.pdf



Item	Specifications / Performance
Num. of RX/TX Ports	4/4
Num. of Channels	8 (Downlink 2x2 / Uplink 2x2)
Sampling Rate	46.08 / 61.44 / 122.88 Msps
Max Signal Bandwidth	100 MHz
Max Num. of Taps	24
Max Tap Delay	1023 samples (e.g. 22 us at 46.08 Msps)
System Latency	2.5 us
Max Path Loss	60 dB
Channel Config. Features	<ul style="list-style-type: none"> • 3GPP TDL Models A/B/C/D/E • Manual channel coefficients • Delay spread: 22 us • PDP visualization
Scenario Playback Features	<ul style="list-style-type: none"> • SISO / 2x2 MIMO • Min. CIR update interval: 200 us (Max Doppler Shift: 1 kHz) • PDP visualization • Visualization of scenario-based path gain variations

● Scenario Settings

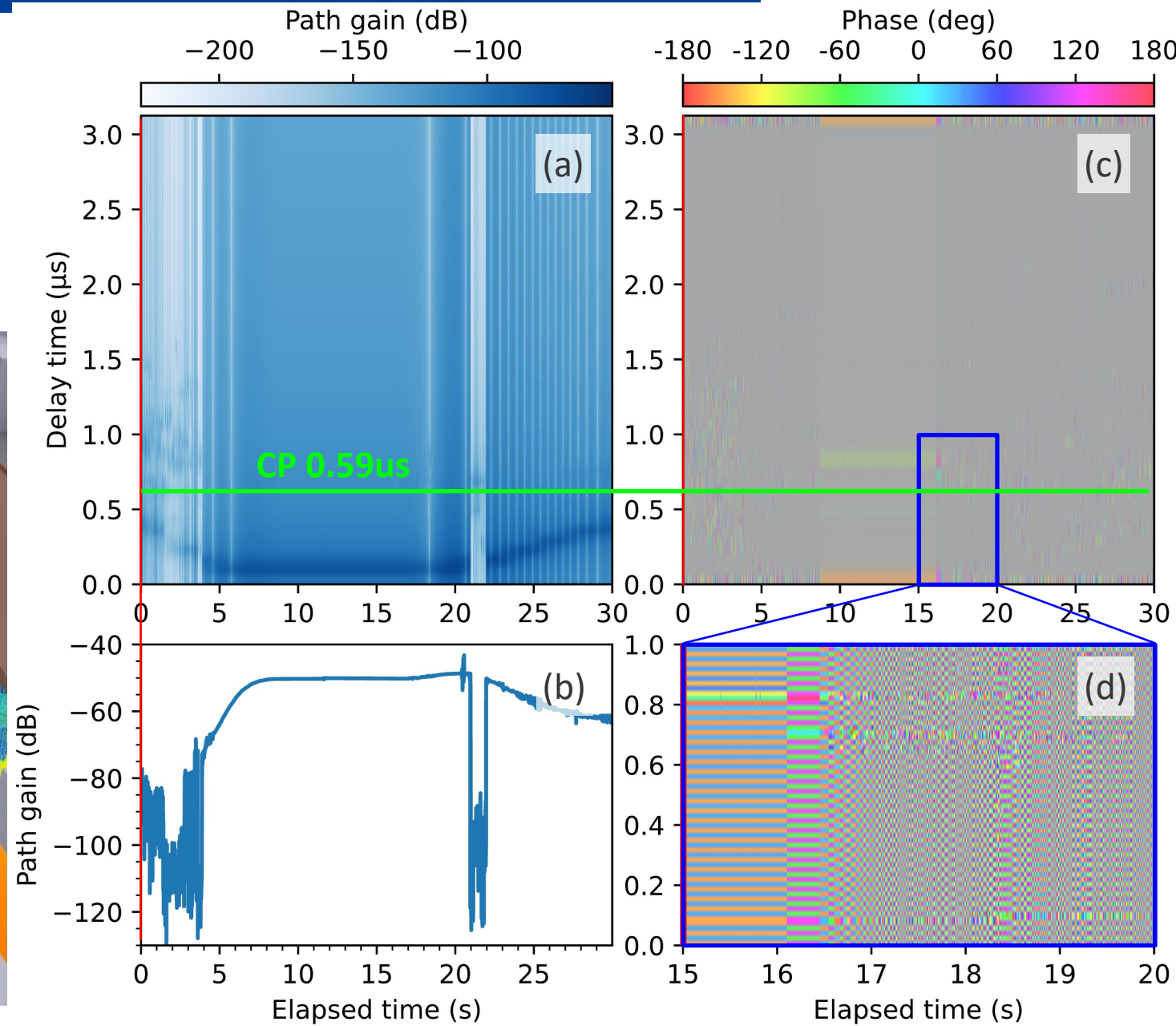
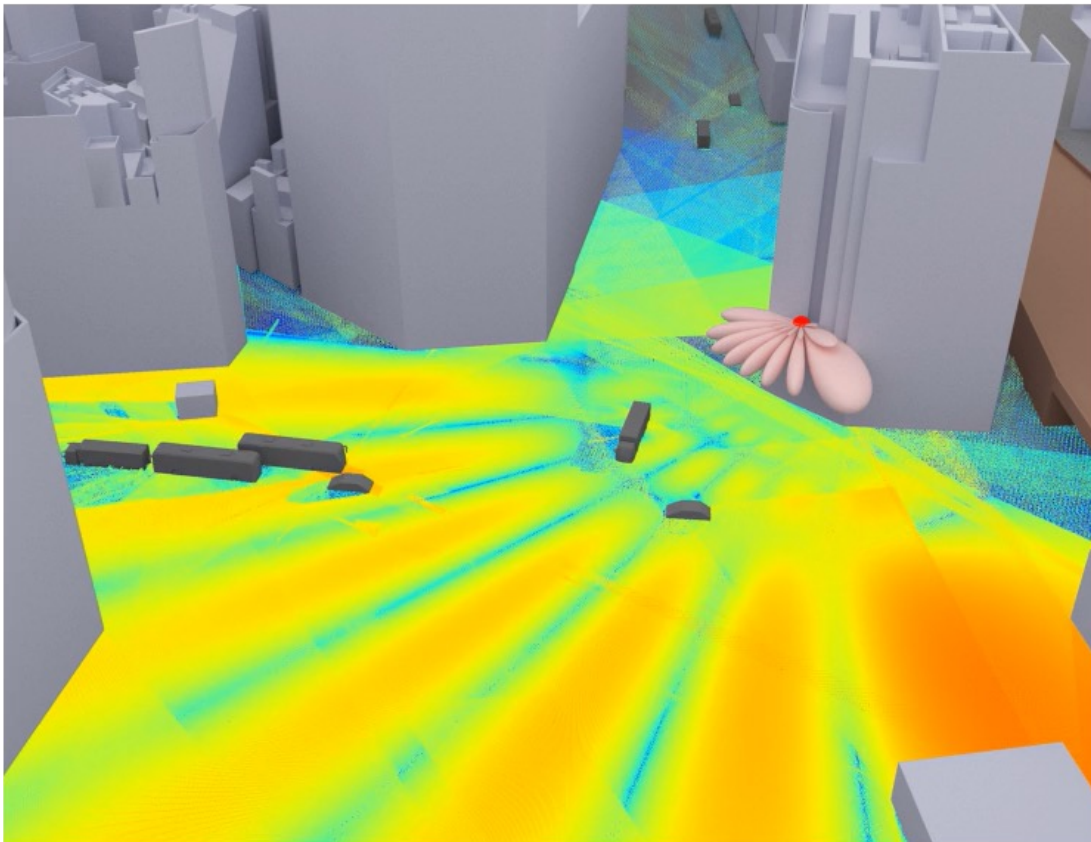
- **30-second multi-vehicle mobility scenario** around **Shibuya Crossing** executed in a loop.
- **One-to-one 5G Comm.** between gNB & UE
- Wide roadways, reflections from glass-facade building walls and metallic vehicles
- **LoS blockage** occurs when passing a bus.
- CIR calculated every **200 us** (150,000 points).
- **24-tap** convolution
- Real-time monitoring of KPIs (RSRP, SNR, MCS, Bitrate, etc.)

Simulator	Parameters	Value (FR2)
Common	Frequency Band	n256
	Carrier Frequency	28.0 GHz
	TX Antennas	8×8
	RX Antennas	1
	Sampling Rate	61.44 Msps
Sionna RT	TX Antenna Pattern	TR 38.901
	RX Antenna Pattern	isotropic
	UE Height	1.5 m
	gNB Height	10.5 m
	Reflection/Diffraction/ Scattering/Transmission	T/T/F/F
	Max Interactions	5
	Launched Rays	10 ⁸
	Radio Map Resolution	0.1 m × 0.1 m
	Radio Map Height	0.5 m
OAI	CIR Frequency	200 us
	Scenario Duration	30 s
	Architecture	5G NR SA
	Bandwidth	50 MHz
	Subcarrier Spacing (SCS)	120 kHz
	FFT Size	512
	Transmission Mode	SISO
	Duplex	TDD
	TDD Slot Pattern	DDDSU
	S-Slot Config	6D+4G+4U

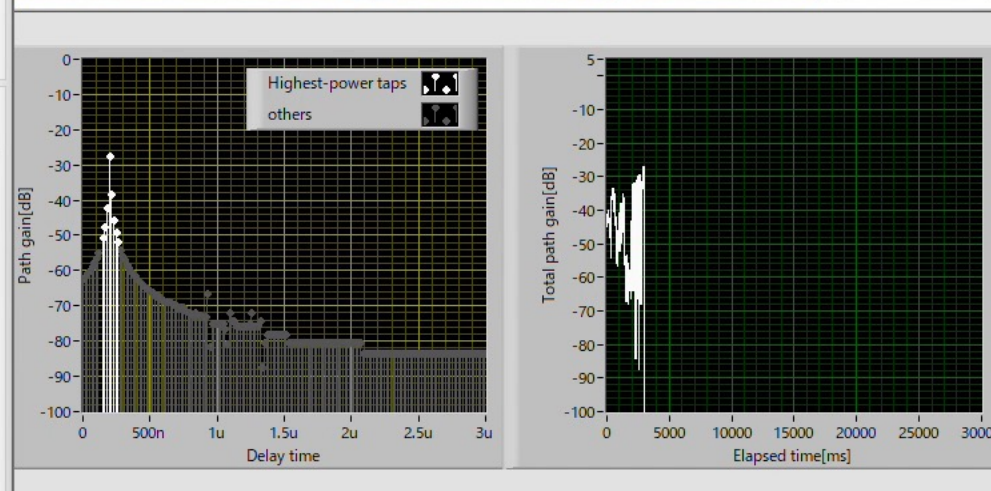
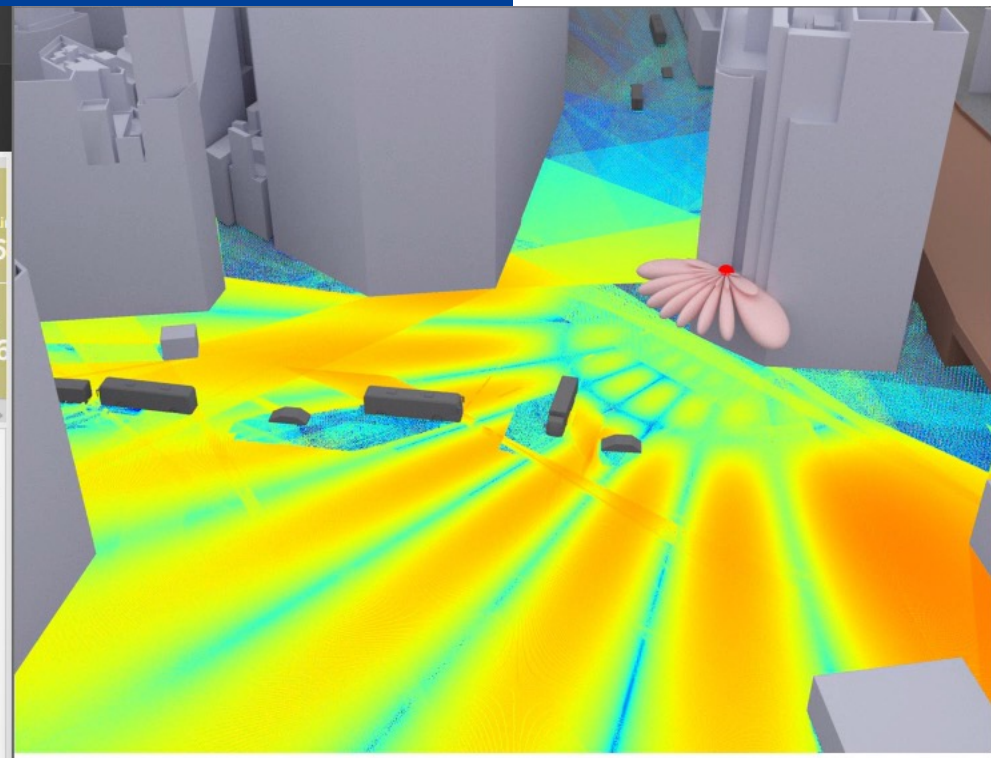
FR2 Mobility Tracking Scenario: CIR Results

FR2 Channel Emulation Scenario

- (a) Power Delay Profile (b) Path Gain
- (c)(d) Phase Delay Profile
- Path gain variation: approx. 60–80 dB
- Gain drop due to blockage: 50–70 dB



FR2 Mobility Tracking Scenario: Emulation



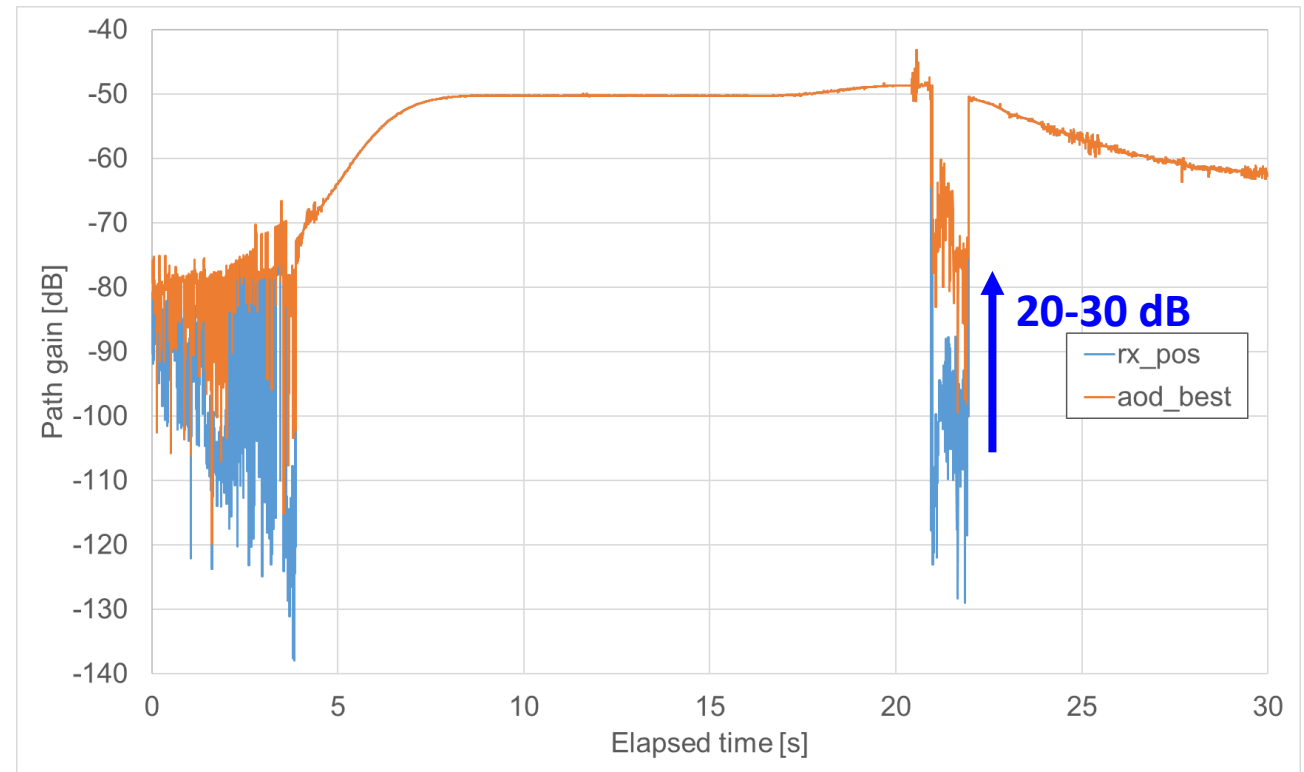
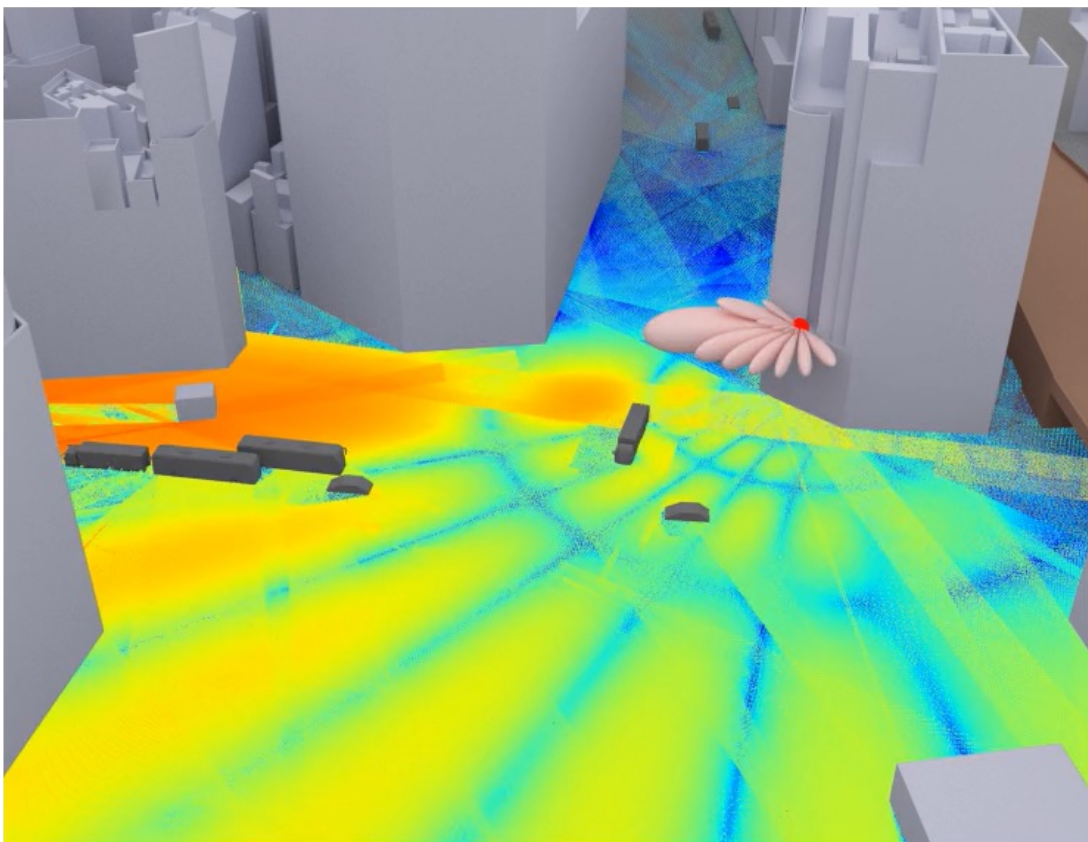
● KPI Measurement Results in OAI

- RSRP, MCS, BLER, and Throughput measured via FlexRIC xApp (E2SM KPM v03.00).
- High correlation between RSRP observed in OAI and path gain calculated by Sionna RT.
 - **Relative power variation: OK**
- No delay taps exceed the CP length among the 8 considered components
 - **No Inter-Symbol Interference**
- **UE frequently detaches from gNB temporarily** (re-attaches within a few seconds) when RSRP drops sharply due to bus blockage.

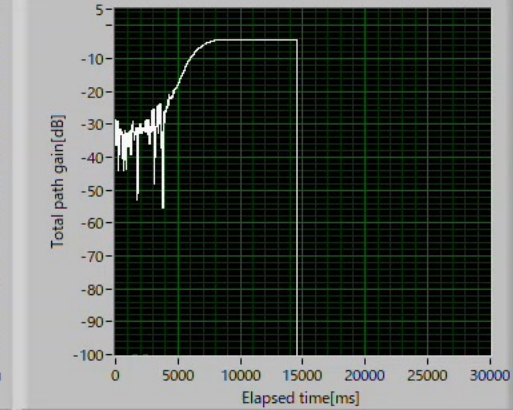
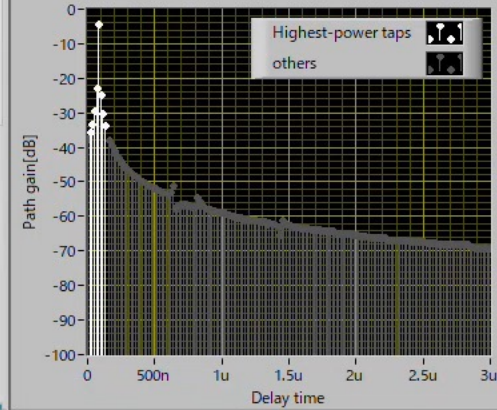
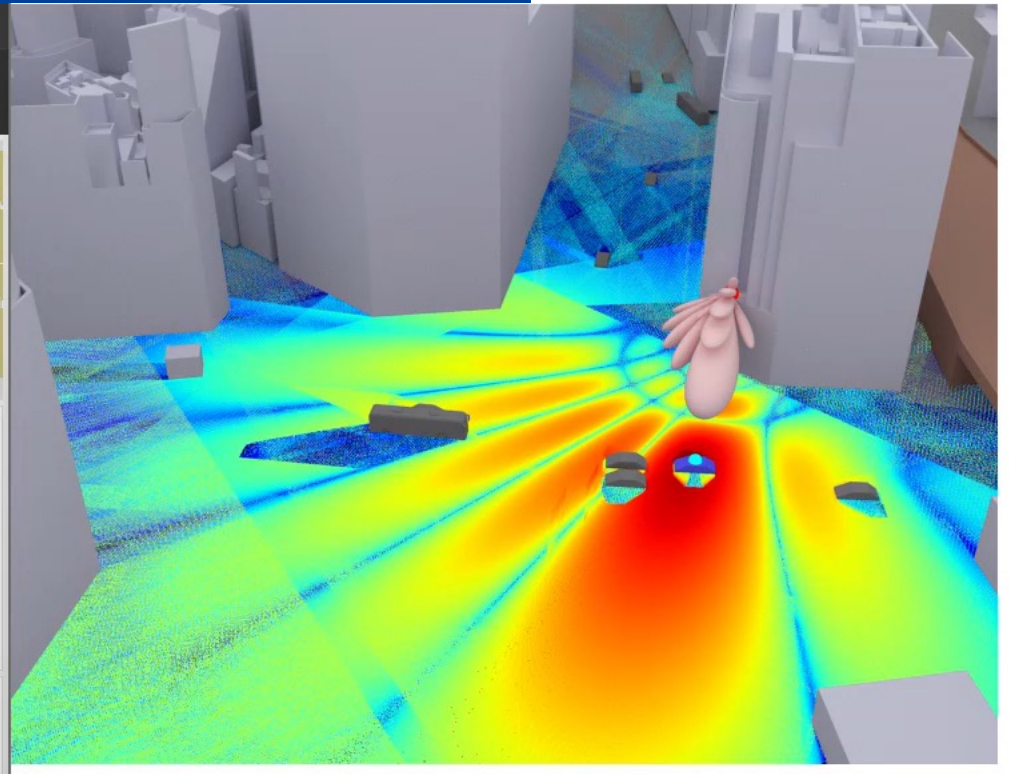
FR2 Best-Path Tracking Scenario: Results

FR2 Channel Emulation Scenario

- Beam is always steered toward **AoD of the best path**, assuming it is known.
- Path gain variation: approx. 40–60 dB (**~ 20 dB improvement**)
- Gain drop due to blockage: 30–40 dB (**20-30 dB improvement**)
- **Blockage effects are mitigated.**



FR2 Best-Path Tracking Scenario: Emulation



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Blockage-robust beam management or coverage by multiple RUs is required.

● Evaluation of Doppler Effect Impacts Considering Mobility Speed

- To account for dynamic radio environment, CIR calculation interval t_{int} must be shorter than the fading period T_f caused by the Doppler effect.

$$v_{\text{max}} = 40.0 \text{ [km/h]} (= 11.11 \text{ [m/s]})$$

- **FR2** Scenario:

$$T_f = \frac{c}{f v_{\text{max}}} = \frac{2.99792 \cdot 10^8}{28.0 \cdot 10^9 \times 11.11} = 0.964 \cdot 10^{-3} \text{ [s]}$$

Requires $t_{\text{int}} < T_f = 0.96 \text{ [ms]}$



Current $t_{\text{int}} = 0.2 \text{ [ms]}$ is sufficiently short.

- Developed SDR-based channel emulator
- Constructed OAI-based wireless digital twin using OSS and open data.
- Integrated high-fidelity ray tracing with real-time SDR emulation.
- Validated blockage impacts in dense urban environments.
- **Next Steps:**
 - Multi-gNB & multi-UE support.
 - 400 MHz bandwidth.
 - Millisecond-order propagation delay for NTN.
 - Toward a true digital “twin” validated/calibrated with measurement data.

Appendix

Evaluation using 5G NR NLoS model, TDL-C.

40 MHz bandwidth, 2×2 MIMO, TDD pattern: DDDFU, and adaptive modulation.

■ TDL-C, Delay spread=300ns

MCS Modulation And Coding Scheme



Bitrate



Avg. KPI: DL MCS = 19 (64QAM), DL Bitrate = 184 Mbps

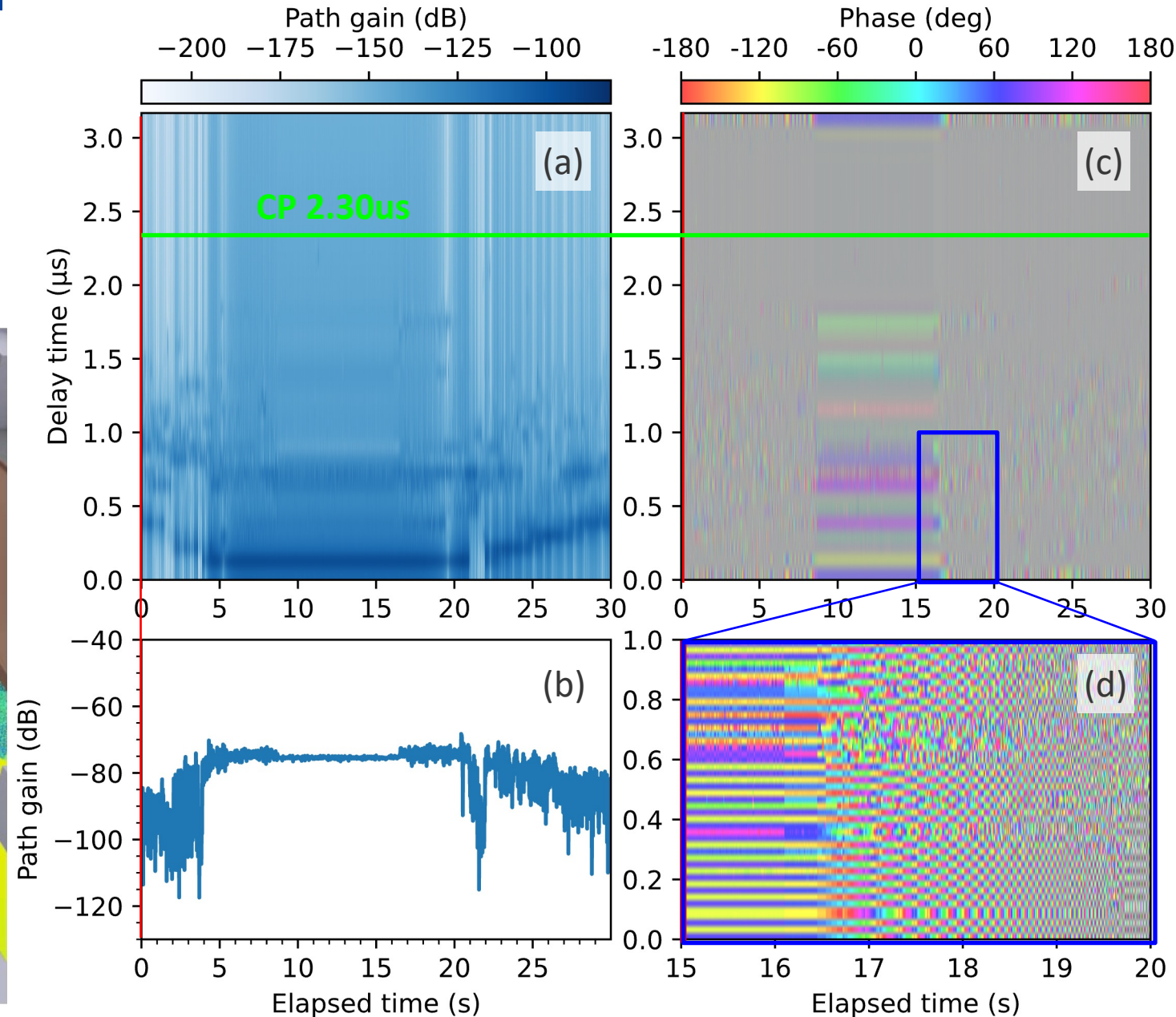
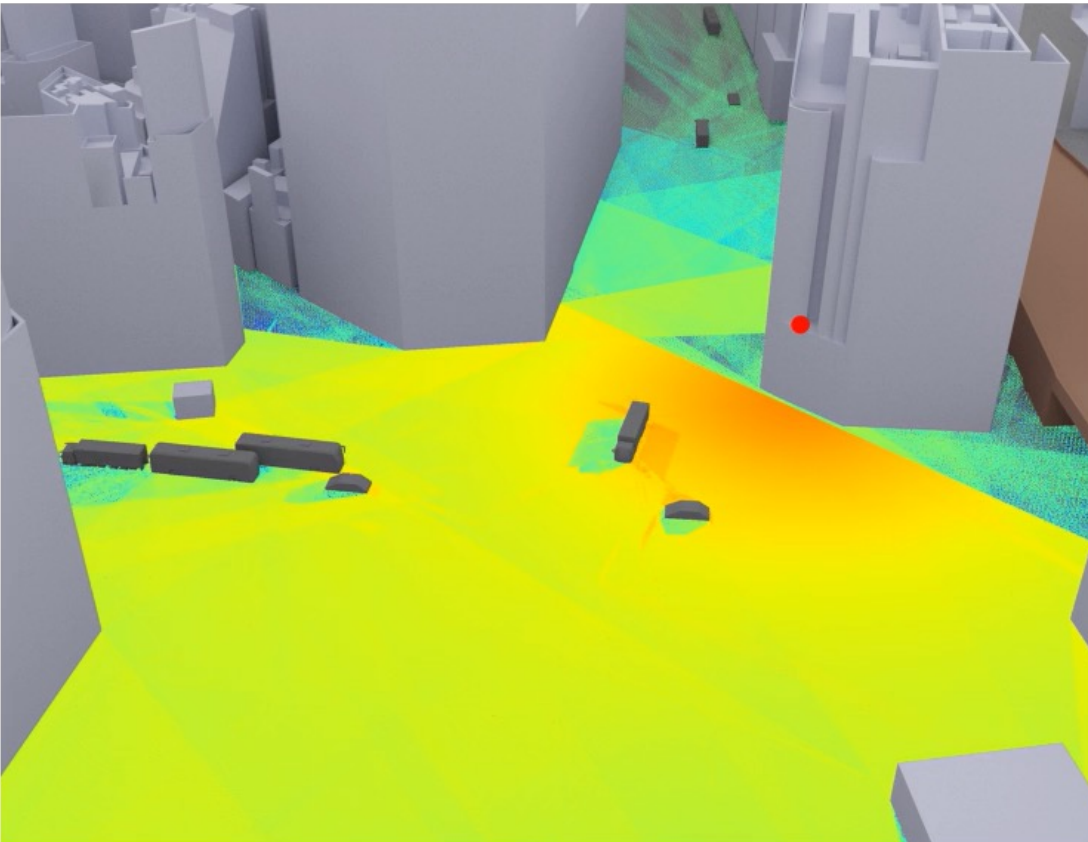
TDL-C has strong frequency selectivity due to multipath fading, causing deep fading notches.



FR1 Mobility Scenario: CIR Results

FR1 Channel Emulation Scenario

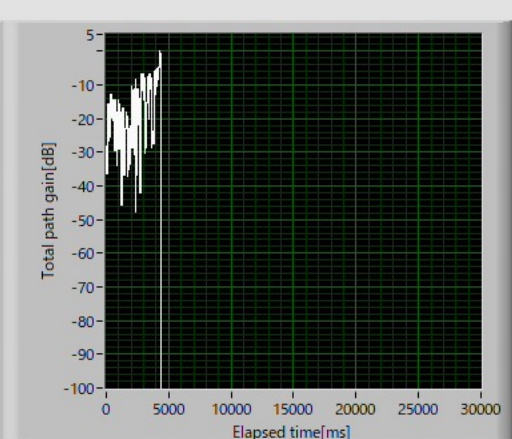
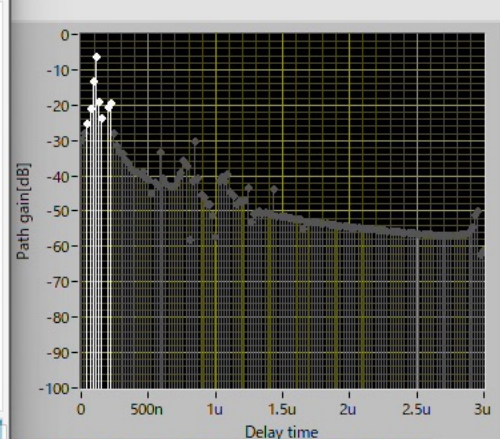
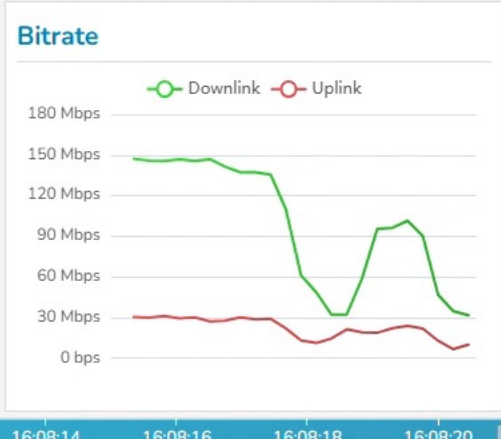
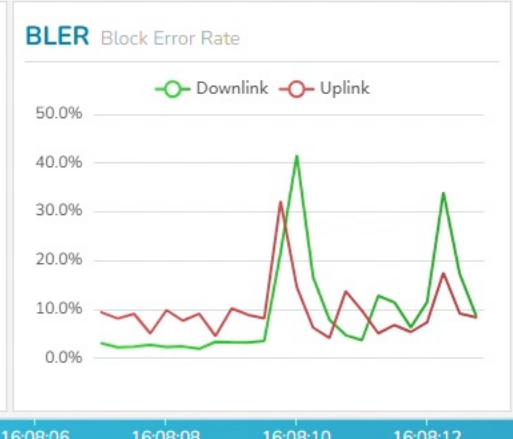
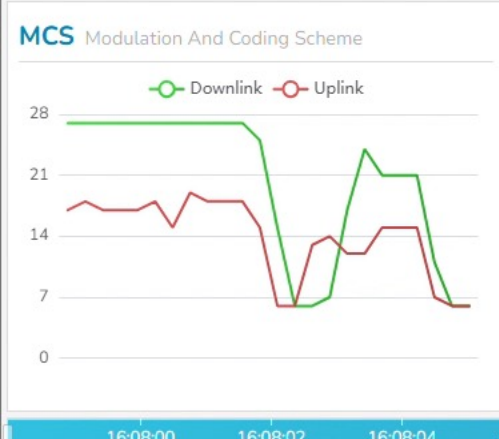
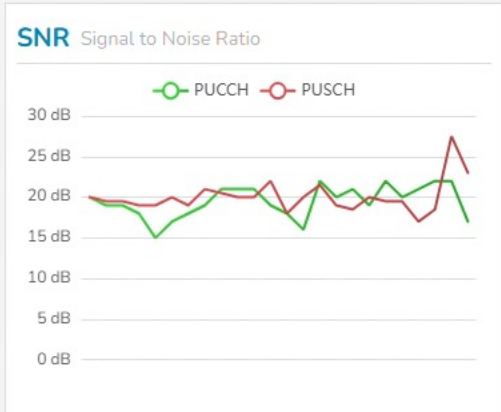
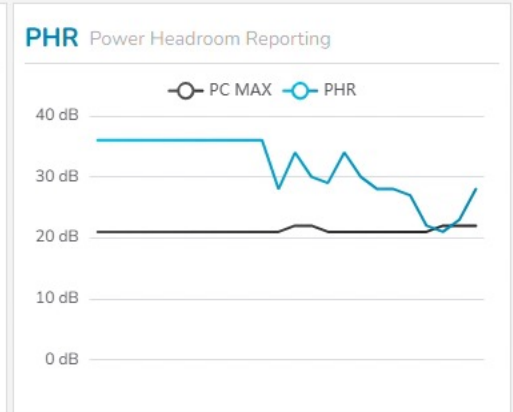
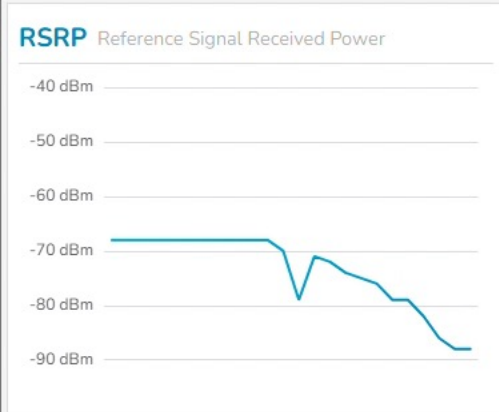
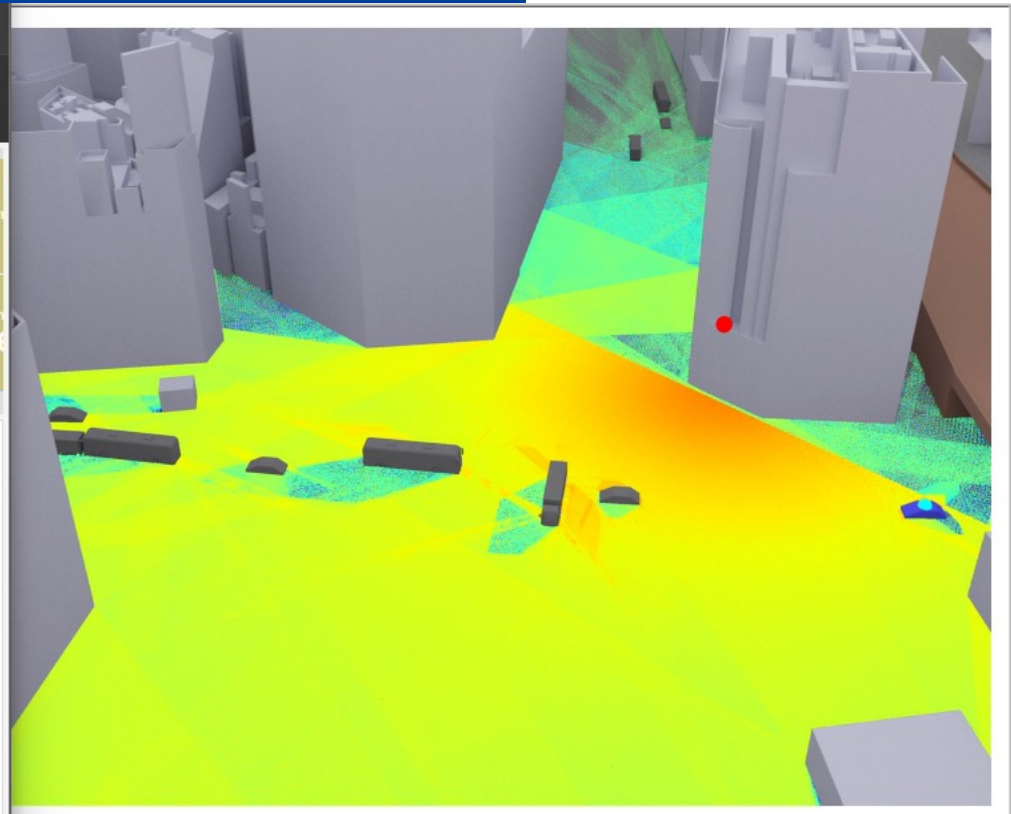
- (a) Power Delay Profile (b) Path Gain
- (c)(d) Phase Delay Profile
- Path gain variation: approx. 20–40 dB
- Gain drop due to blockage: 20–30 dB



FR1 Mobility Scenario: Emulation

OAIBOX™

UE RNTI▶ 0x8AFD IMSI▶ 00031 UE ID▶ 3 RI▶ 1 2 3 4 2026/02/24 16:08:21	UL RSSI -86 dBm Min: -86 dBm Max: -77.6 dBm Avg: -81.6 dBm	RSRP -88 dBm Min: -88 dBm Max: -68 dBm Avg: -70.3 dBm	RSRQ -11 dB Min: -11 dB Max: -10.5 dB Avg: -10.6 dB	PHR (PHR) 21 dB Min: 21 dB Max: 36 dB Avg: 33.9 dB	SINR 13.5 dB Min: 13.5 dB Max: 23.5 dB Avg: 22.9 dB	SNR PUCCH: 22 dB (Min: 15, Max: 22, Avg: 20) PUSCH: 27.5 dB (Min: 17, Max: 27.5, Avg: 20.6)	CQI 15 Min: 15 Max: 15 Avg: 15
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- High correlation between RSRP observed in OAI and path gain calculated by Sionna RT.
 - **Relative power variation: OK**
- No delay taps exceed the CP length among the 8 considered components
 - **No Inter-Symbol Interference**
- In **FR1**, we achieved 150 Mbps throughput at maximum, approaching the theoretical limit of 156 Mbps.