Institute for the Wireless Internet of Things at Northeastern University

Colosseum Use Cases

Colosseum Team:
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Platforms for Advanced Wireless Research

MASSACHUSETTS TECHNOLOGY COLLABORATIVE

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WIoT Institute Mission

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

A Roadmap Toward 6G

Open,
Programmable,
Virtualized

Flexible Spectrum
Exploitation

Conquering the
Spectrum

AI-Native Processing
and Control

Connecting the
Metaverse

Institute for the Wireless Internet of Things

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

WIoT's Partners

Strategic Partners	Qualcomm, Dell, NVIDIA, Mavenir, TII Technology Innovation Institute, interdigital, T, MITRE, Keysight Technologies, AmpliTech Amplifying Global Communications
Industry Partners	Red Hat, Raytheon, VIAVI, intel, AT&T, Fujitsu, ETRI Electronics and Telecommunications Research Institute, MathWorks
Small Businesses	a5G Networks, Andro, AiRANACULUS, usignite, Nexcepta, zTouch, bionet, Qylur, EpiSci

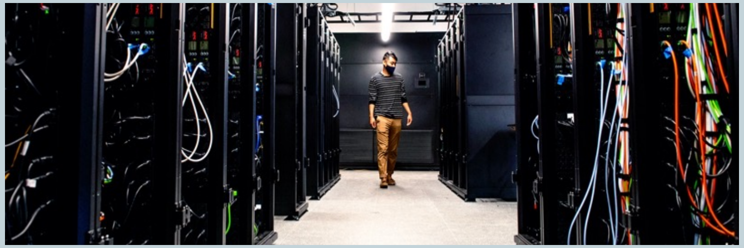
Testbeds and Platforms: Why?

Design

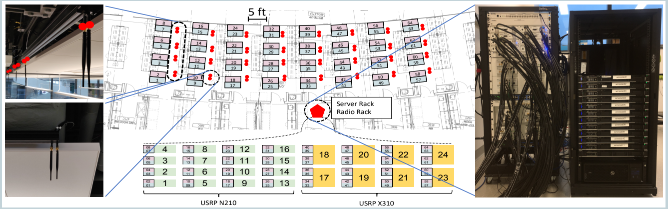
Data

Evaluation and validation

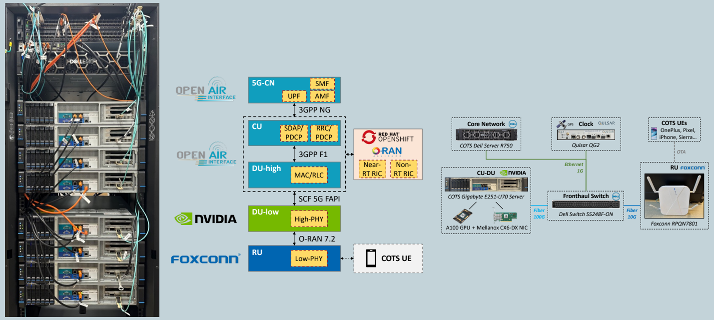
Colosseum



Arena + PAWR

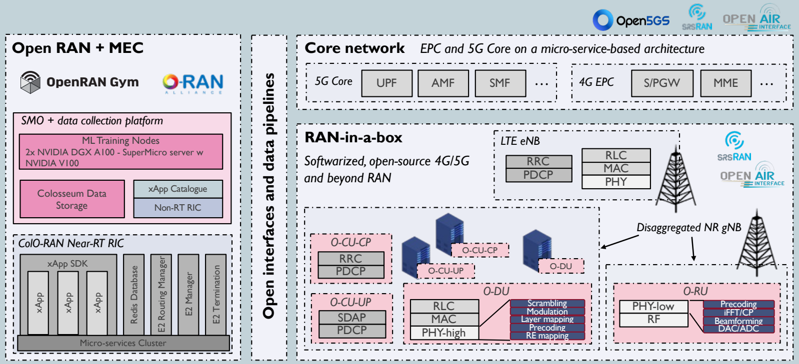


X5G



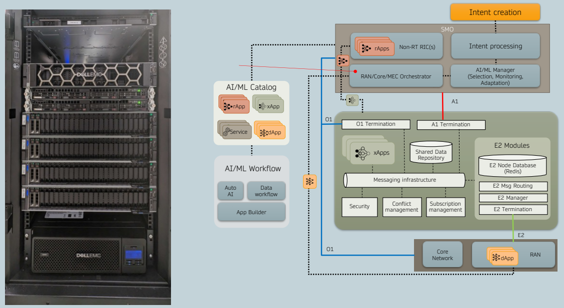
OpenRAN Gym

End-to-end programmable cellular



FCC Innovation Zones

Production 5G+AI automation



Colosseum: A New National Resource for Wireless Systems Research

- Massive $20M+ wireless systems testbed developed by DARPA for Spectrum Collaboration Challenge
- Transferred to Northeastern University in November 2019
- Transfer to Northeastern and opening to community supported by NSF CCRI grant #1925601
- Joins NSF PAWR Ecosystem of wireless testing platforms
- Supports remote shared access
  - 5G+ (softwarization, slicing, security, Open RAN)
  - Spectrum Sharing
  - AI + Wireless
  - IoT

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Platforms for Advanced Wireless Research

colosseum.net

Colosseum: World's Largest Emulator of Open RAN Systems

Large-scale experimentation of Open RAN systems with **hardware-in-the-loop**

- 171 high-performance servers w/ CPUs / GPUs
- **256 USRP X310s**
- **65,536 80 MHz** emulated RF channels
- Full-mesh networking capability
- **Diversified scenarios** for better generalization of **ML / AI models**
- Fosters **large-scale data collection** and **experimentation** in **Open RAN**

L. Bonati, P. Johari, M. Polese, S. D'Oro, S. Mohanti, M. Tehrani-Moayyed, D. Villa, S. Shrivastava, C. Tassie, K. Yoder, A. Bagga, P. Patel, V. Petkov, M. Seltser, F. Restuccia, A. Gosain, K. R. Chowdhury, S. Basagni, and T. Melodia, "Colosseum: Large-Scale Wireless Experimentation Through Hardware-in-the-Loop Network Emulation," Proceedings of IEEE DySPAN, December 2021

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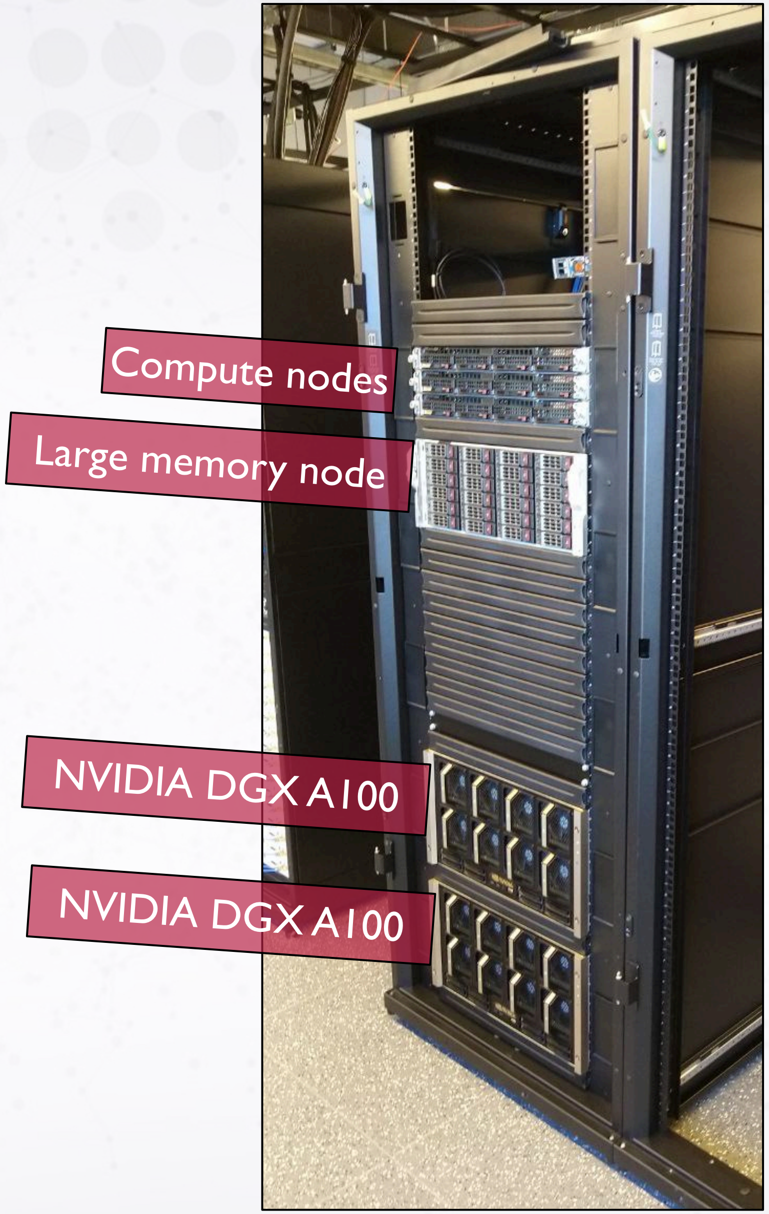
Colosseum as Enabler for AI/ML

Build **GPU-accelerated** software-defined, cloud-native applications for the **5G+ vRAN** on Colosseum.

- 2x NVIDIA DGX A100: 8 GPUs each, 10 petaFLOPS compute power
- 1x large memory node (Supermicro Superserver 8049U-E1CR4T): 6 GPUs, 3TB of RAM
- 3x compute nodes
- 1x Mellanox Infiniband switch: Tbps dedicated

8 NVIDIA A100 GPU 40 GB

Mellanox Infiniband switch



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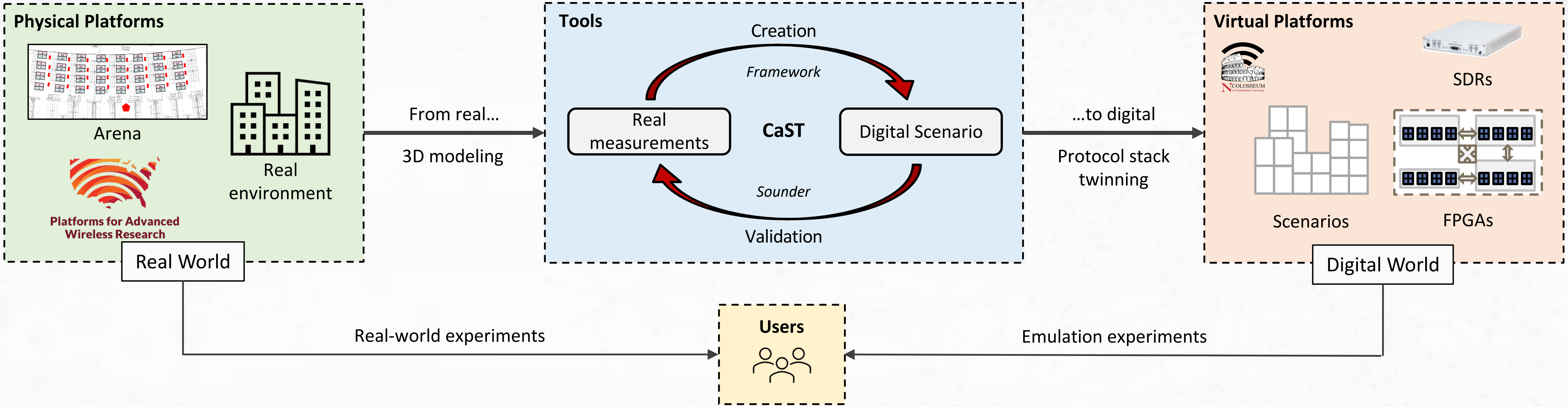
Colosseum: Much More Than a Supercomputer

- Colosseum has **RF hardware in the loop**
- Not only a simulation environment: **real-time emulation with real radio signals, stacks and emulated channels**
- Combines in a SINGLE instrument
  - Fidelity of hardware channel emulators
  - Flexibility of a virtualized data center
  - Scalability of a network simulator
- Fully programmable
- Investment by DARPA, NSF, Northeastern, State of Massachusetts

Colosseum as a Digital Twin

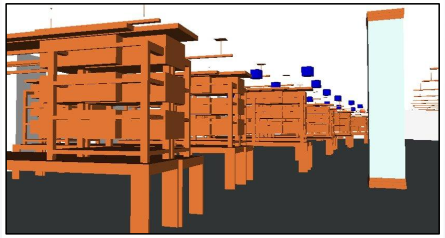
Capability: Create digital twin scenarios, run experiments close to reality, evaluate performance



Indoor Environment

Real World

CaST

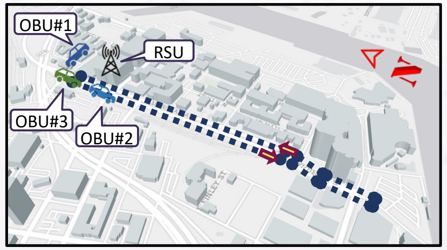


Digital World

Outdoor Environment

Real World

CaST



Digital World

D. Villa, M. Tehrani-Moayyed, C. Robinson, L. Bonati, P. Johari, M. Polese, S. Basagni, T. Melodia, *"Colosseum as a Digital Twin: Bridging Real-World Experimentation and Wireless Network Emulation,"* pp 1-15, IEEE Transactions on Mobile Computing, in press, 2024.

Colosseum Use Cases

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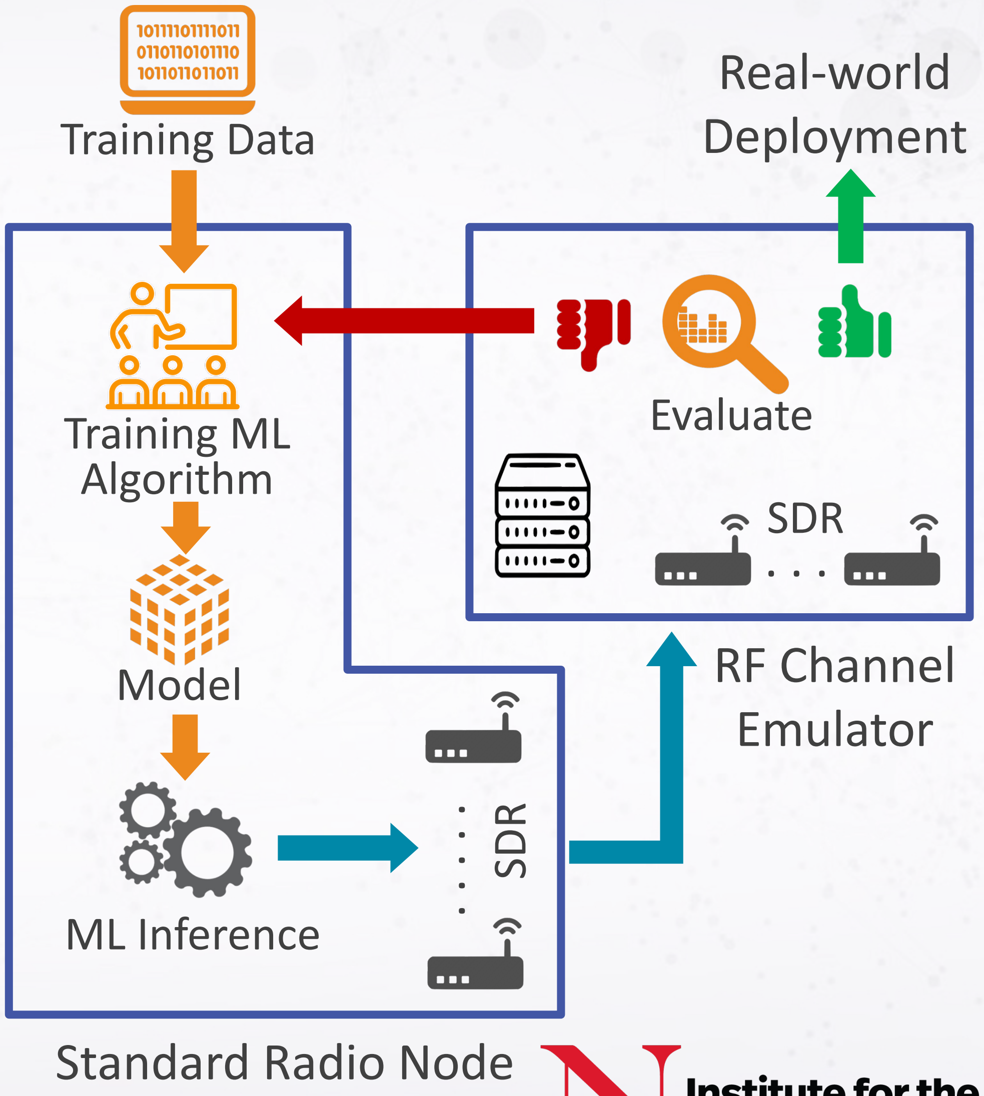
Artificial Intelligence and Wireless

- **Trend:** IoT applications are getting **smarter** by incorporating Artificial Intelligence
- **Challenge: Large-scale in-field deployment** of IoT devices to train and test with AI algorithms is challenging, time consuming and often expensive
- **Opportunity:** Colosseum provides a unique platform where the power of **AI meets the real-time wireless IoT** emulations whether it be Wi-Fi, Cellular or LPWAN
  - X310 Software Defined Radio
  - Powerful computation nodes equipped with GPUs
  - FPGAs for embedded AI-IoT testing



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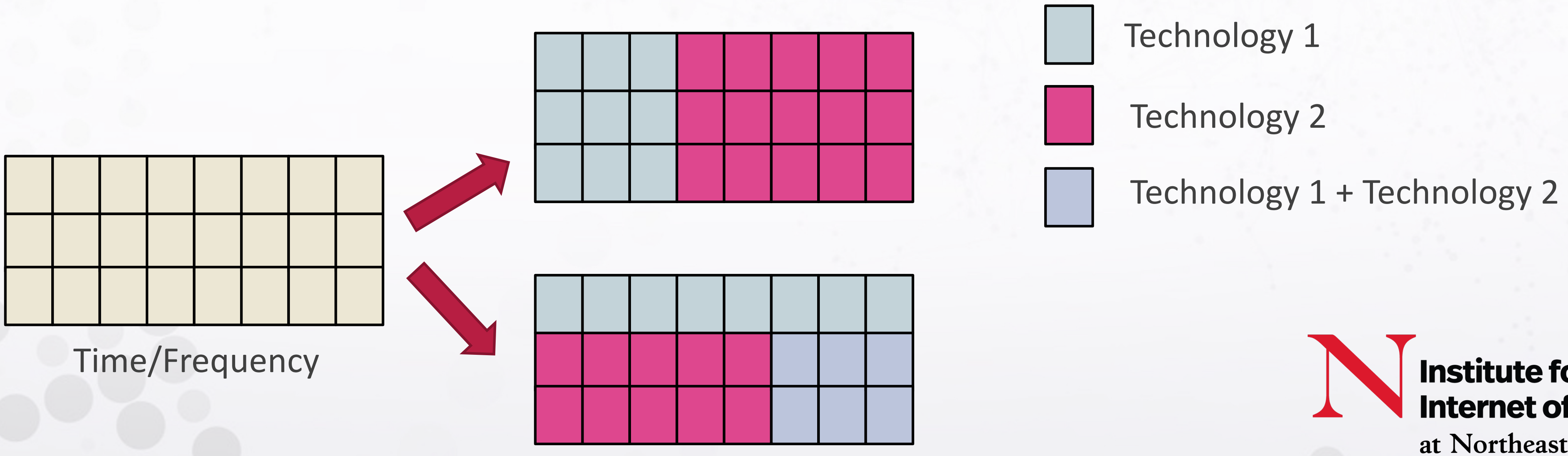
Spectrum Sharing

- **Trend:** With the **ever-increasing number of connected devices** and new technologies, **coexistence** is essential to overcome spectrum scarcity
- **Challenge:** Can several transmissions **coexist** on the same spectrum band **reliably**?
- **Opportunity:** With Colosseum AI capabilities, **adaptive solutions** can be designed and tested on **heterogeneous RF/traffic scenarios**
- **Preliminary results:** +95% accuracy in detecting Wi-Fi transmissions by using ML algorithms in LTE networks in Colosseum emulated coexistence scenarios



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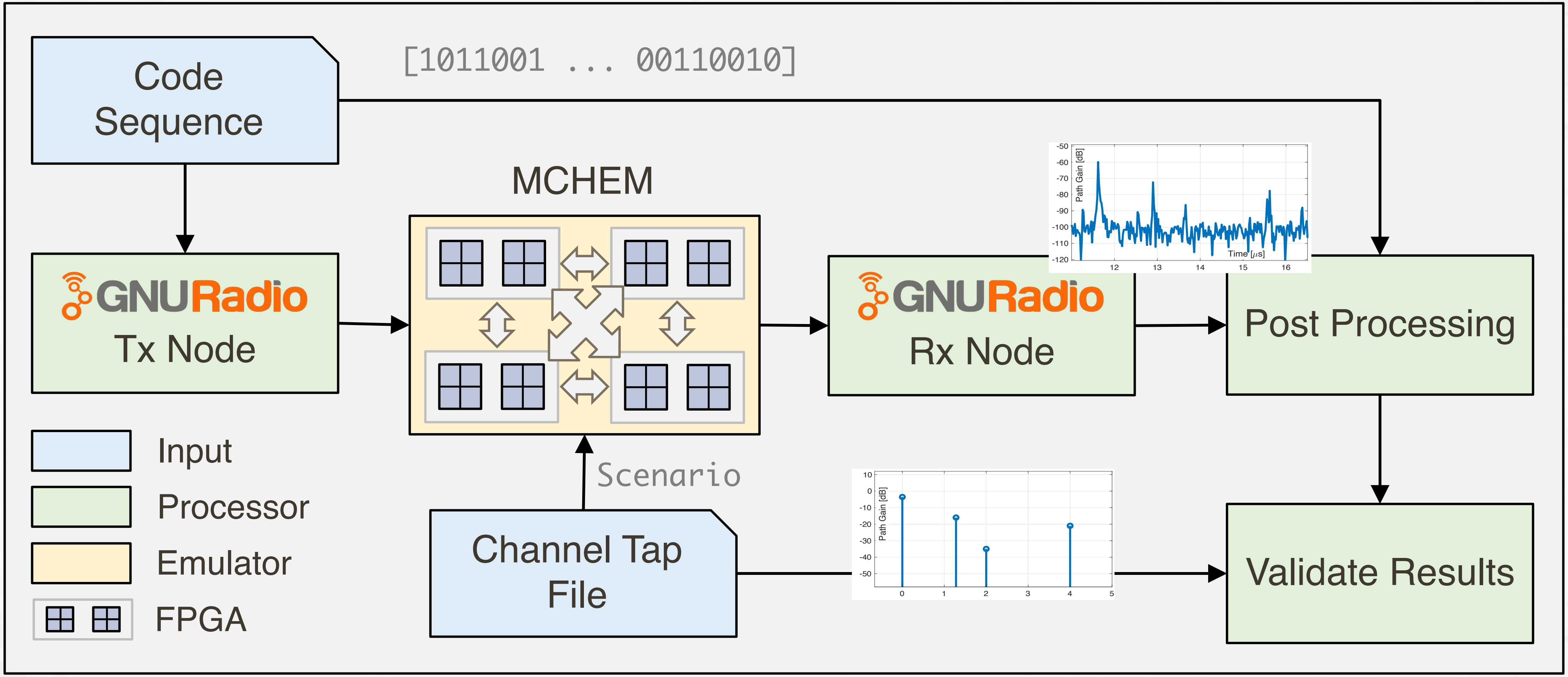
Channel Sounding



D. Villa, M. Tehrani-Moayyed, P. Johari, S. Basagni, T. Melodia, "*CaST: A Toolchain for Creating and Characterizing Realistic Wireless Network Emulation Scenarios*", Proceedings of ACM WiNTECH 2022, Sydney, Australia, October 2022

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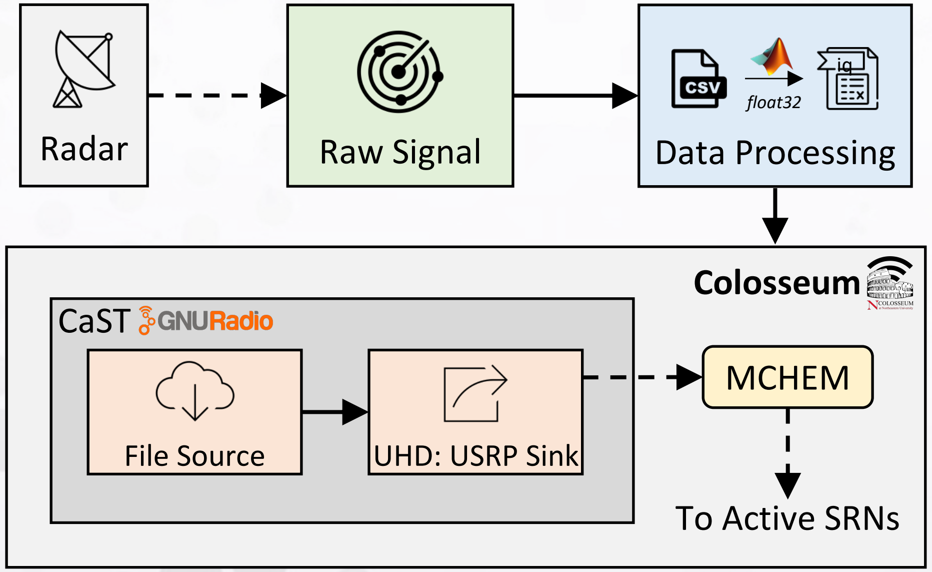
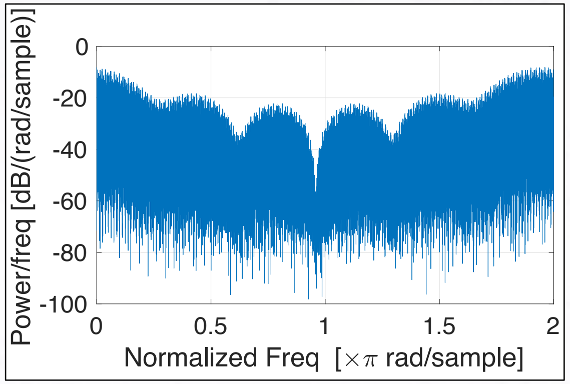
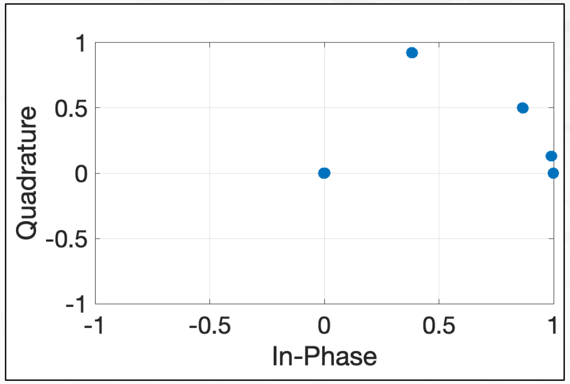
Radar Characterization

- **Weather Radar** synthetically generated:
  - S-Band [3.0-3.8] GHz
  - 6 MS/s for 17.8 ms
  - Re-Im values (IQ first quad)

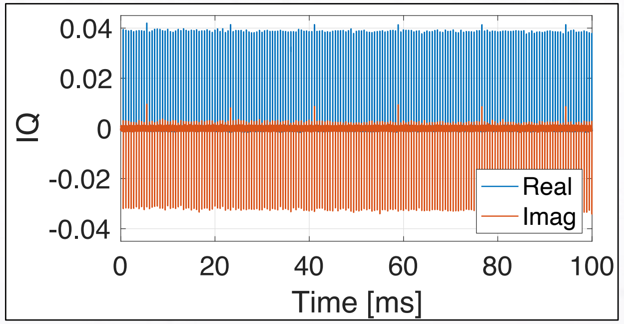




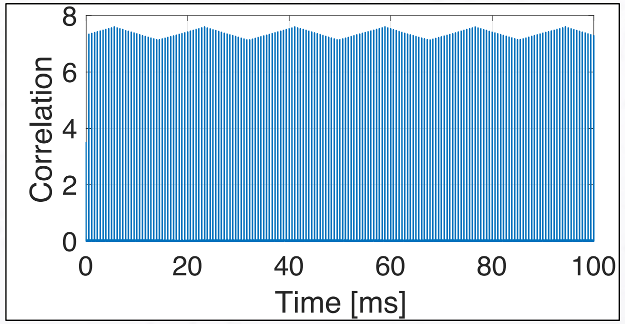
Radar PSD



Radar constellation



Received radar waveform



Radar correlation

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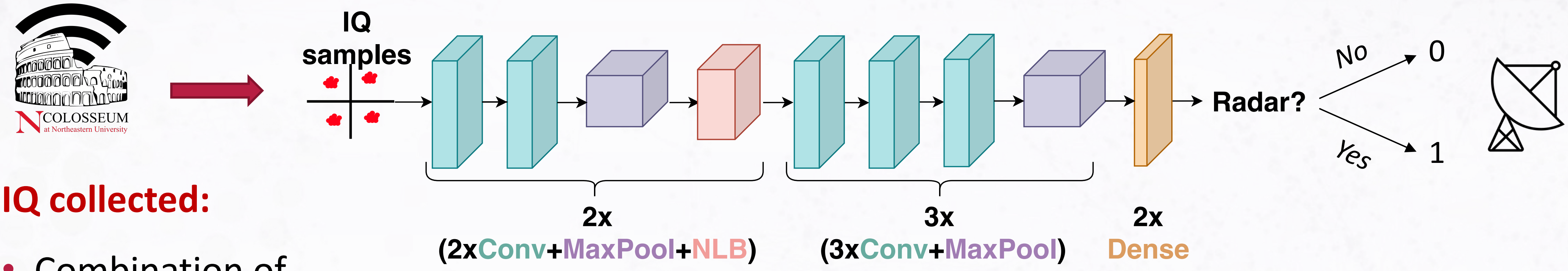
D. Villa, D. Uvaydov, L. Bonati, P. Johari, J. M. Jornet, and T. Melodia, "Twinning Commercial Radio Waveforms in the Colosseum Wireless Network Emulator," Proceedings of ACM WiNTECH, Madrid, Spain, October 2023

Intelligent Radar Detector

Data Collection through Colosseum → Train of an altered and smaller version of VGG16 → Radar Detection

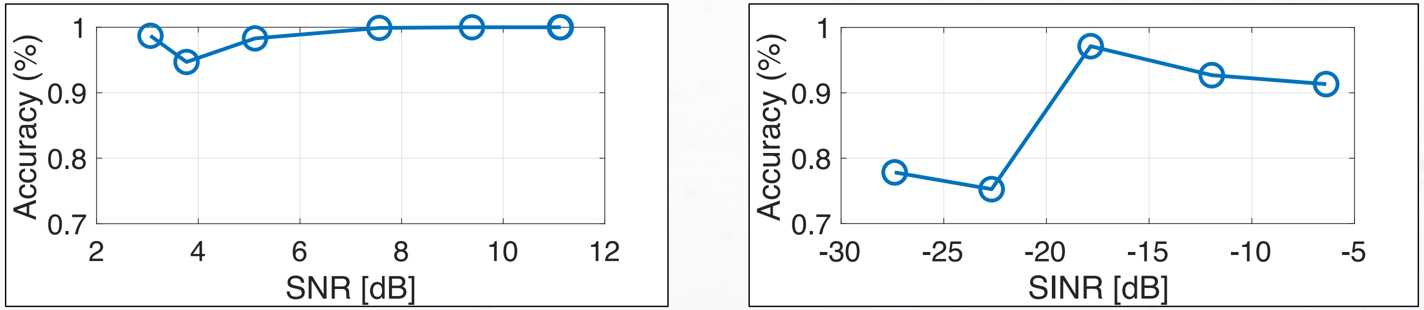


IQ collected:

- Combination of Radar and Data
- Varying node gains and positions

Data Input:

- [Batch-size, 1024, 2]



CNN radar detection accuracy results (S=Radar - I=Cellular)

Average accuracy: **88%**

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D. Villa, D. Uvaydov, L. Bonati, P. Johari, J. M. Jornet, and T. Melodia, "Twinning Commercial Radio Waveforms in the Colosseum Wireless Network Emulator," Proceedings of ACM WiNTECH, Madrid, Spain, October 2023

Open RAN on Colosseum

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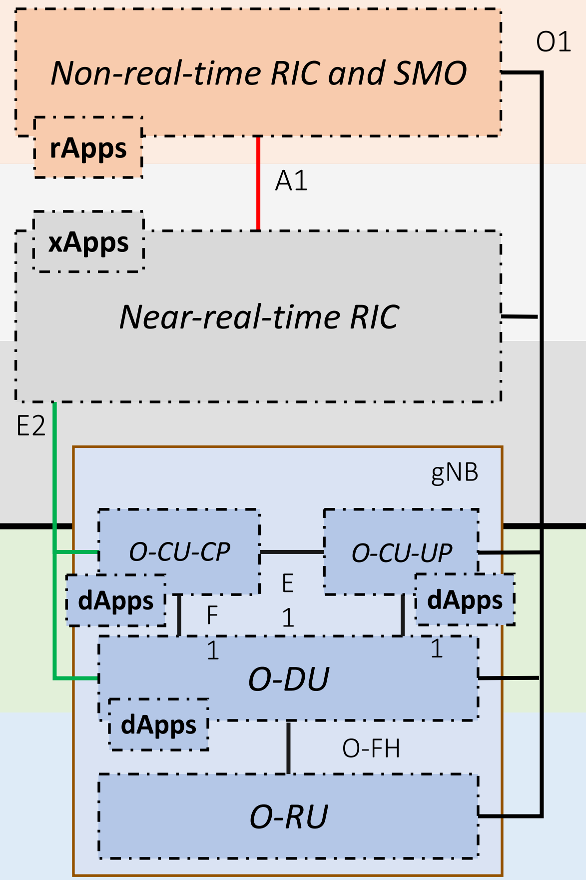
Intelligent Control Loops in O-RAN

Control and learning objective	Input data	Timescale	Challenges and limitations	
Policies, models, slicing	Infrastructure KPMs	Non-real-time > 1 s	• No real-time interactions with the RAN protocol stack (limits control use cases) • No access to the user plane of the RAN (security, privacy, data rates)	**Supported by O-RAN**
User Session Management e.g., load balancing, handover	CU KPMs e.g., number of sessions, PDCP traffic	Near-real-time 10-1000 ms		
Medium Access Management e.g., scheduling policy, RAN slicing	MAC KPMs e.g., PRB utilization, buffering	Near-real-time 10-1000 ms		
Radio Management e.g., scheduling, beamforming	MAC/PHY KPMs e.g., PRB utilization, channel estimation	Real-time < 10 ms	• dApp architecture and integration with stack (this paper) • Efficient and fast AI/ML models for closed-loop inference	**dApp Extension**
Device DL/UL Management e.g., modulation	I/Q samples	Real-time < 1 ms		

Architecture



Twinning O-RAN Systems in Colosseum

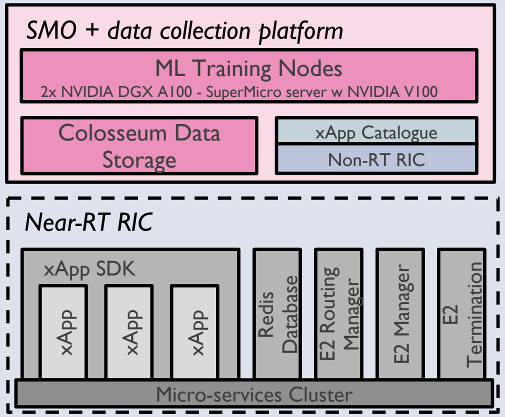
O-RAN ALLIANCE

O-DT: O-RAN Digital Twin to Automate O-RAN End-to-End AI/ML Development and Testing on Colosseum

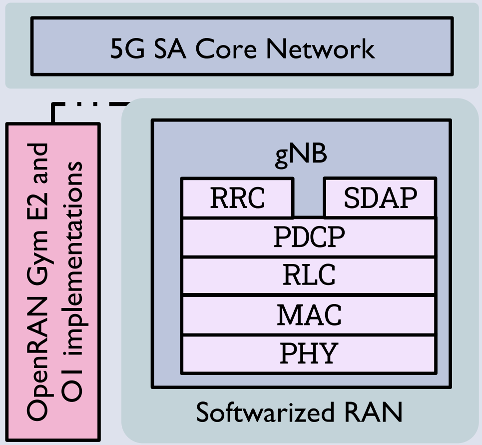
Automated end-to-end digital twin for AI/ML in O-RAN

OpenRAN Gym

RICs and AI/ML for O-RAN



OPEN AIR INTERFACE



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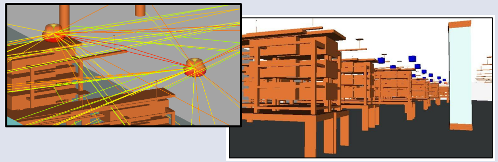
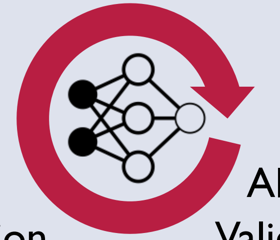
RF Digital Twin

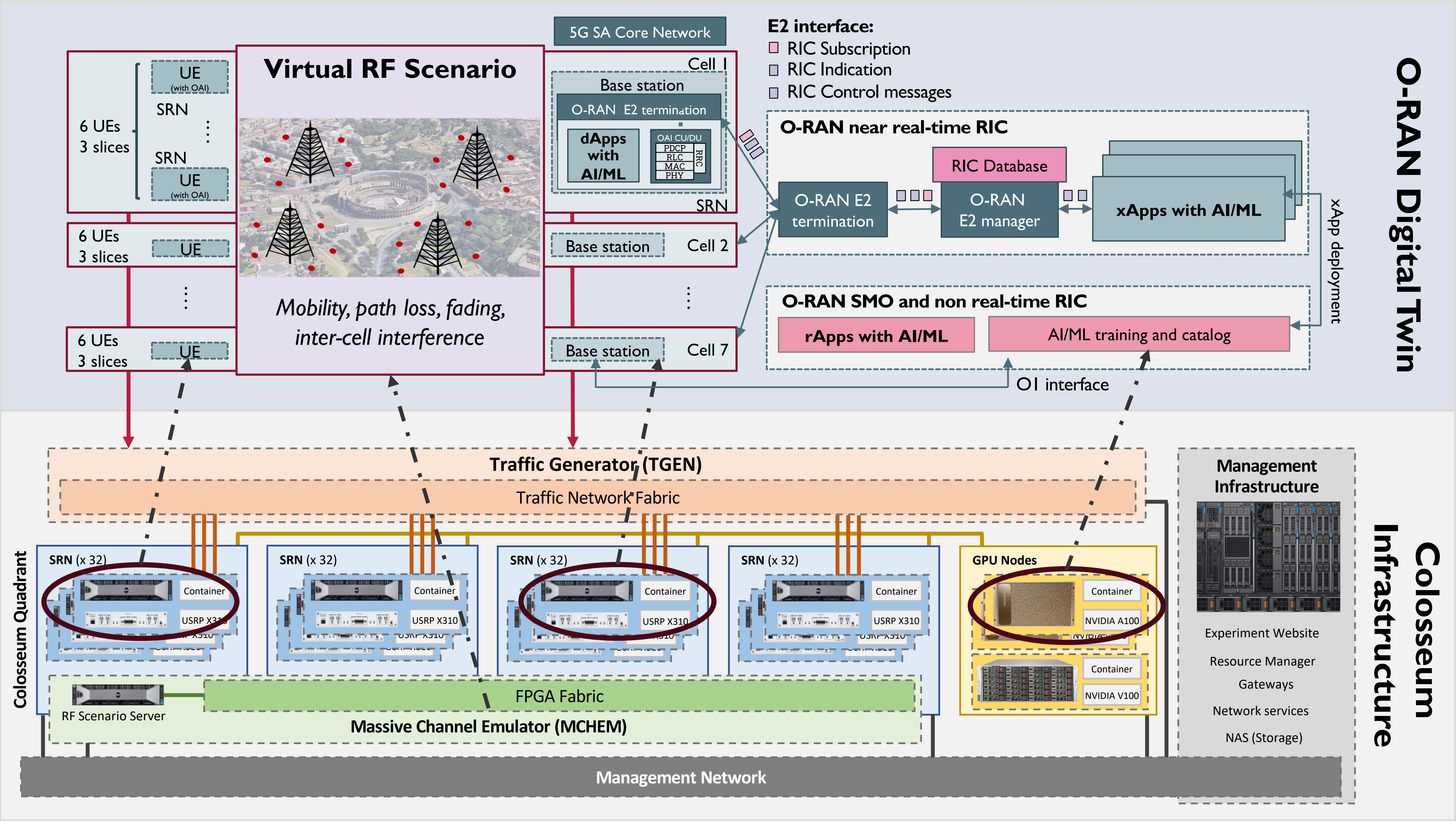


CI/CD/CT

Large-scale Experiment Orchestration

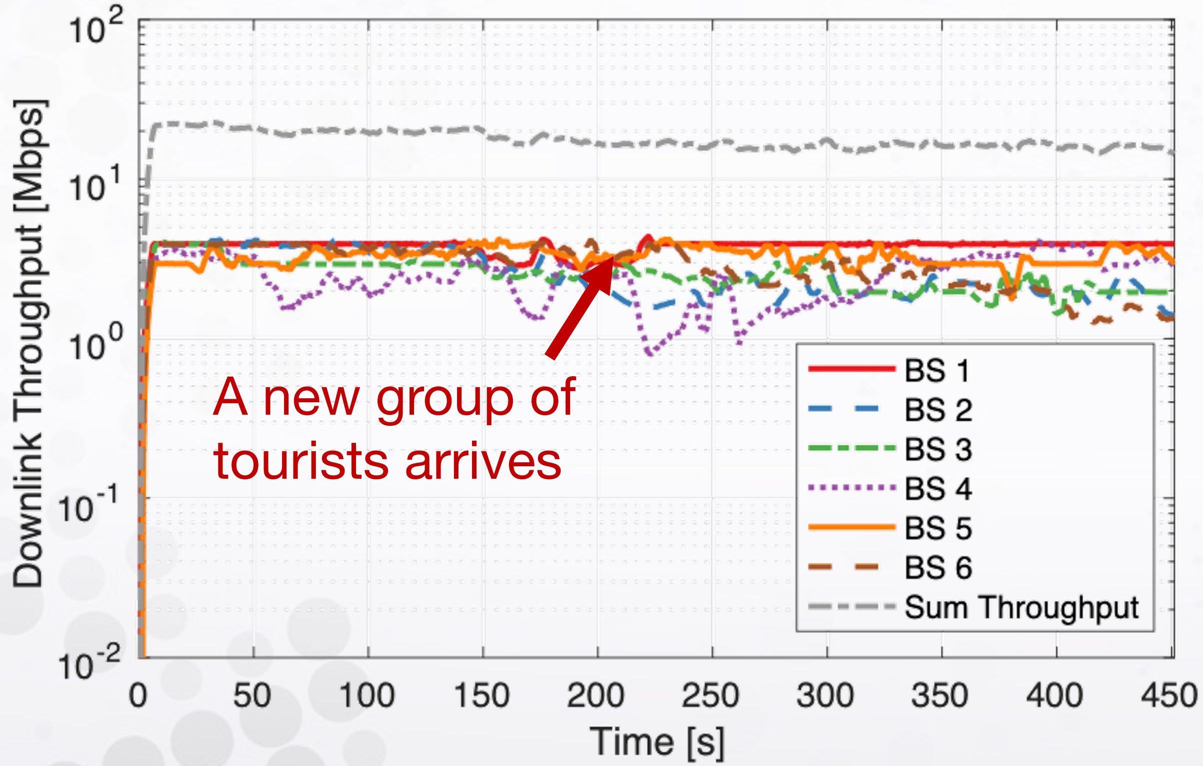


Colosseum: The Open RAN Digital Twin

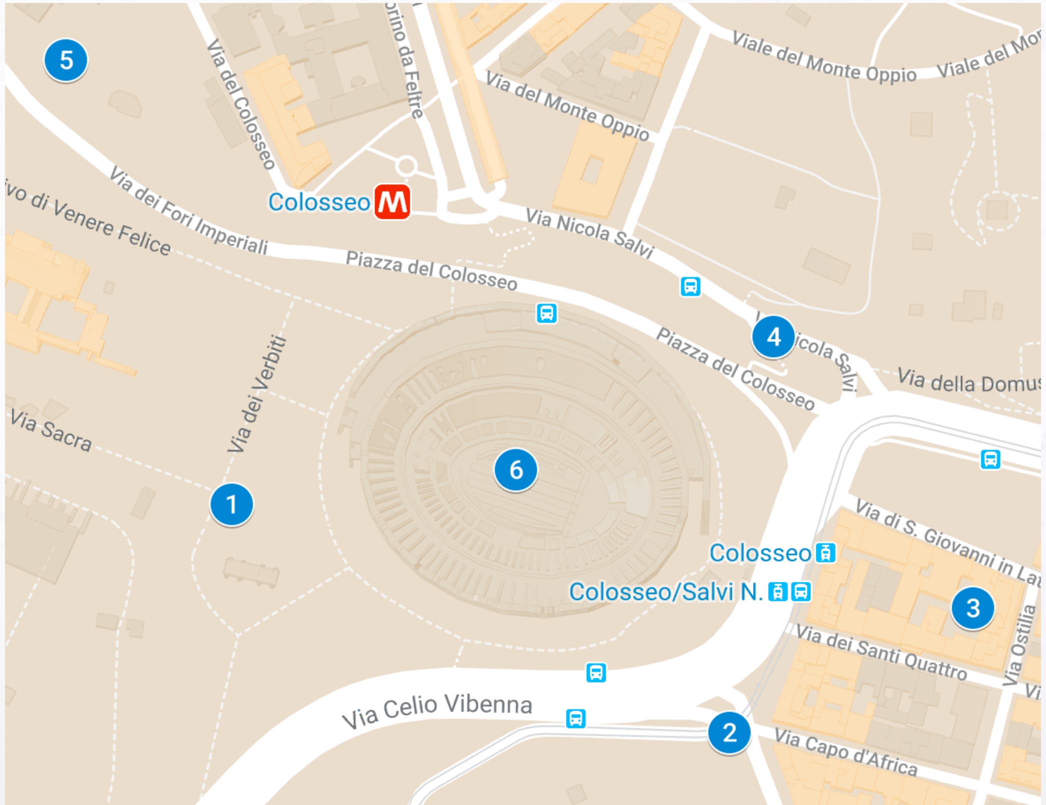


Colosseum 5G Capabilities

- Available containers with srsRAN, OpenAirInterface, O-RAN Near-real-time RIC
- Example:
  - Cellular network w/ srsRAN: 6 interfering base stations w/ mobile users
  - Downlink video streaming
  - Real-world scenario with base station locations in Rome, Italy (next to the actual Colosseum)



Downlink throughput



Base station locations

Prototype At-scale, Test in the Wild

- **Prototype** on Colosseum
- **Validate in real environment** on Arena
- **Test** large-scale capabilities **on city-scale platforms**

Test at-scale on emulated scenarios

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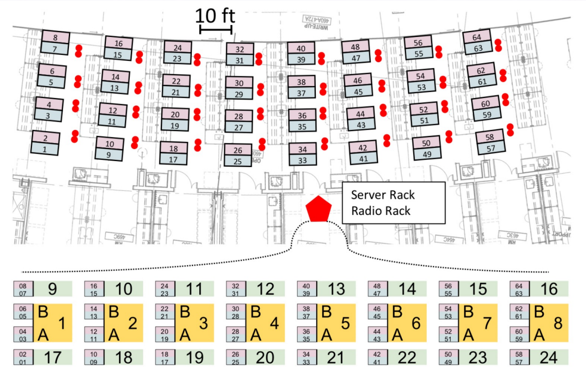
at Northeastern University

Validate in real wireless environment



Arena

Test large-scale capabilities

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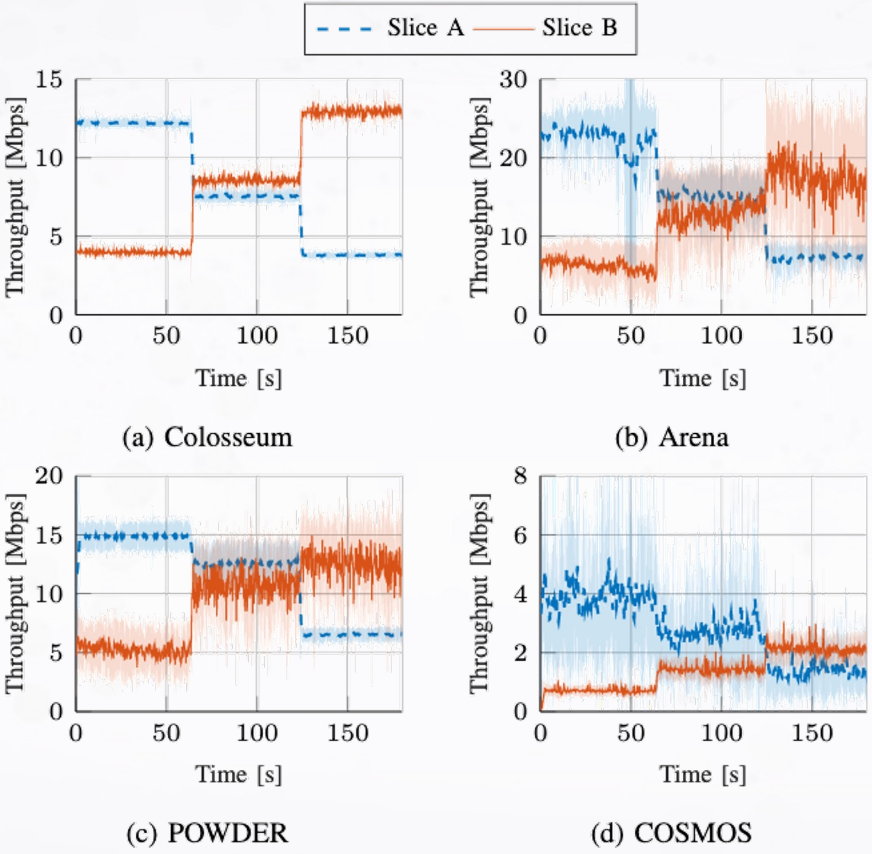
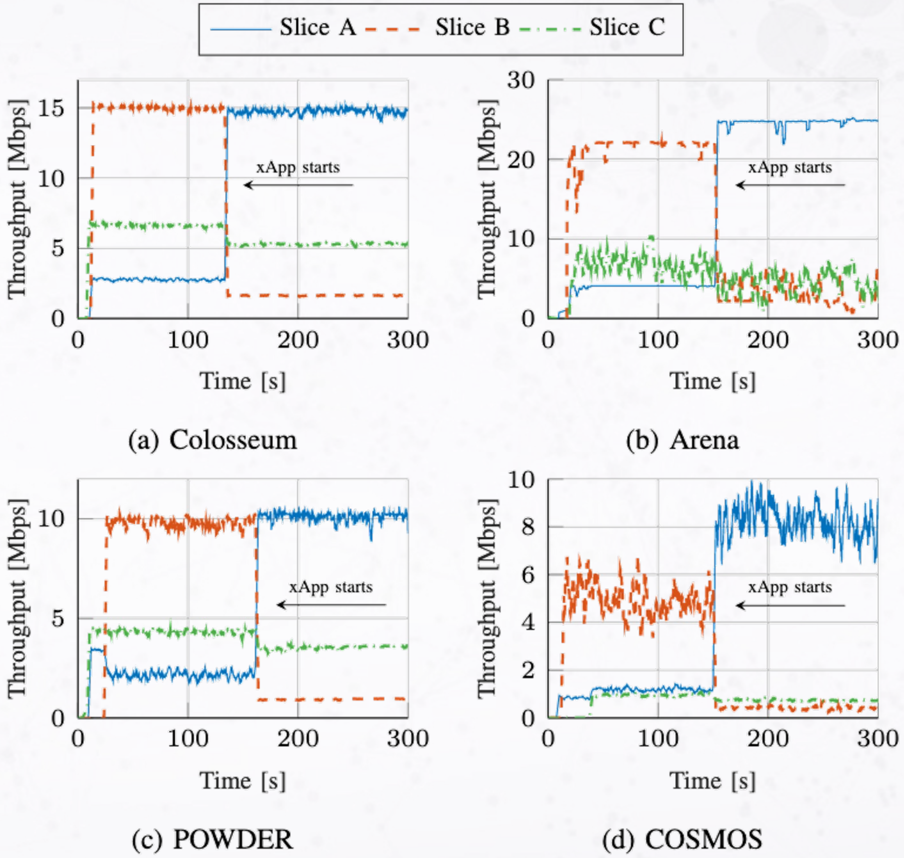
From Colosseum to PAWR

Periodic change of slicing resources



xApp closed-control loop



Results are consistent across ***very different platforms*** *with* ***heterogeneous environments***

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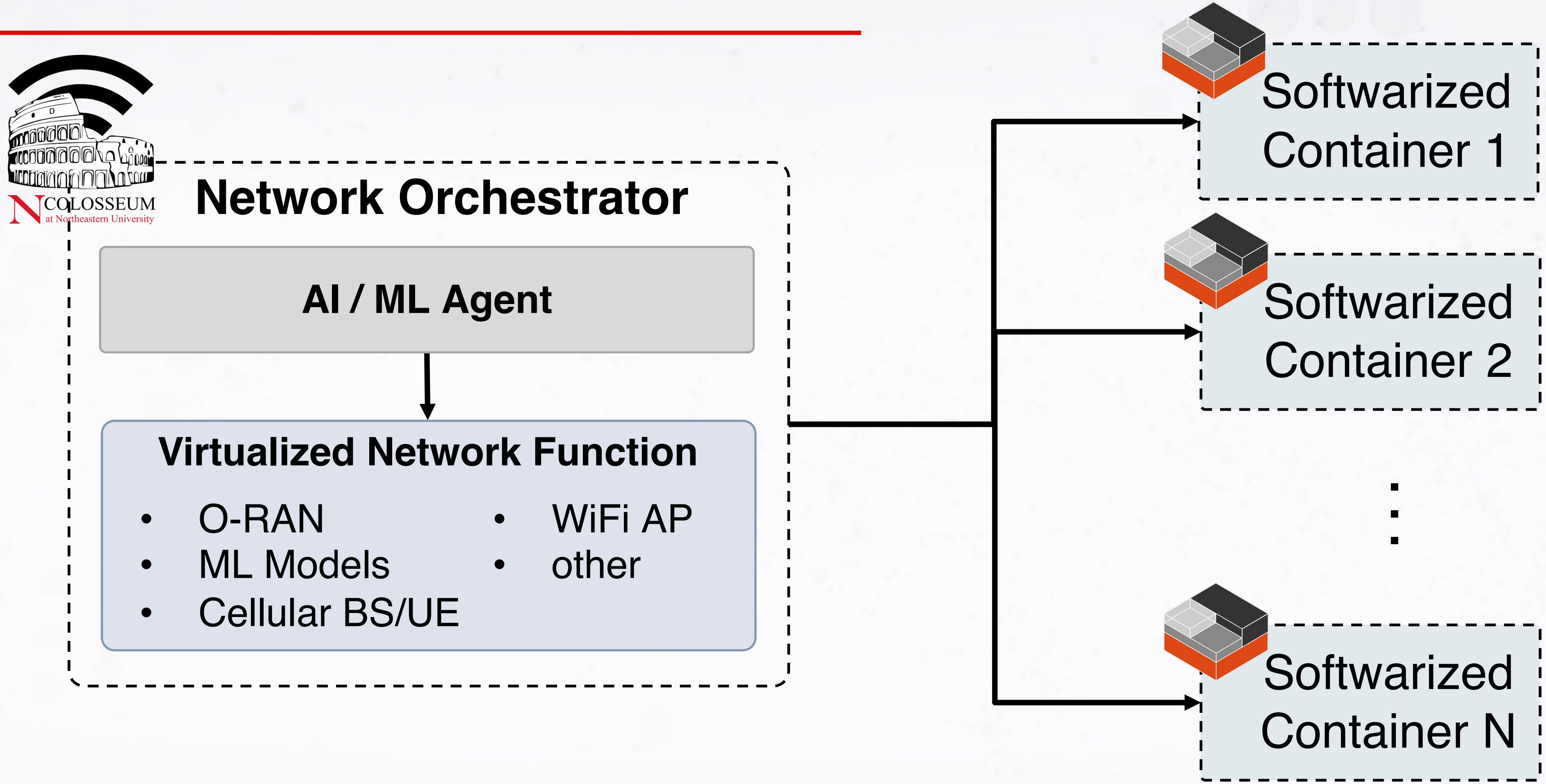
L. Bonati, M. Polese, S. D'Oro, S. Basagni, T. Melodia, "*OpenRAN Gym: AI/ML Development, Data Collection, and Testing for O-RAN on PAWR Platforms,*" Computer Networks, vol. 220, pp. 1-11, January 2023

Colosseum as Enabler for AI/ML



- Prototype AI/ML solutions at-a-scale on emulated RF and traffic scenarios
- Validate in real-world wireless environment

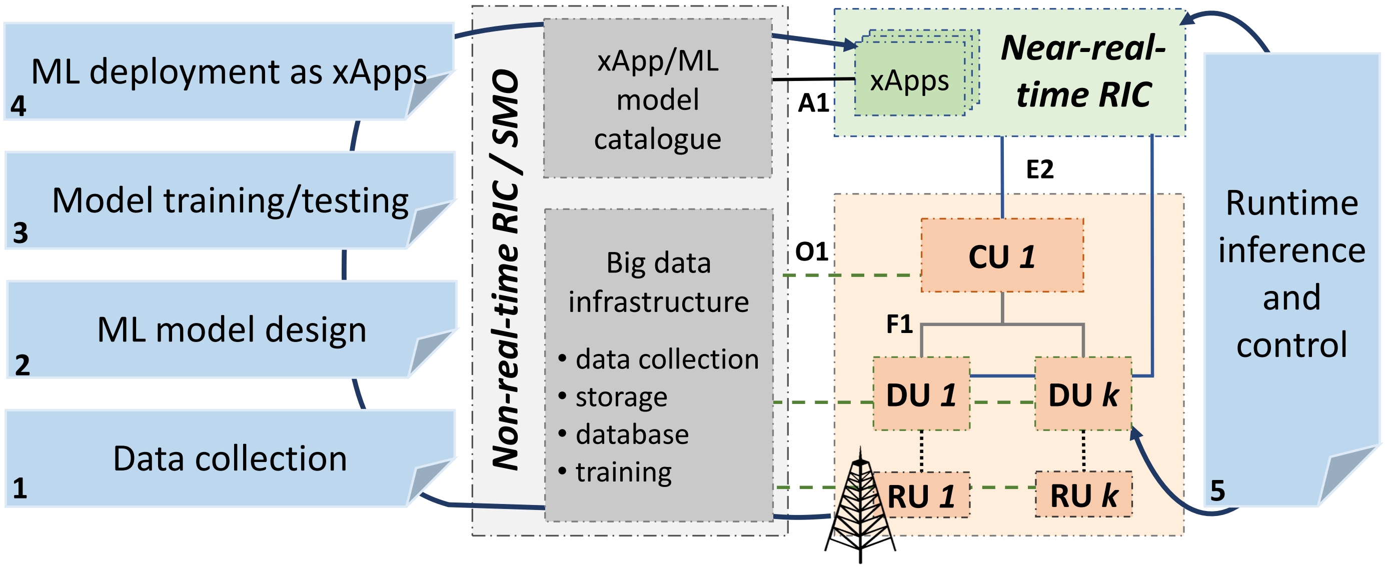
OpenRAN Gym

More info: L. Bonati, M. Polese, S. D'Oro, S. Basagni, T. Melodia, "*OpenRAN Gym: An Open Toolbox for Data Collection and Experimentation with AI in O-RAN,*" Proc. of IEEE WCNC Workshop on Open RAN Architecture for 5G Evolution and 6G, Austin, TX, USA, April 2022.

*An **open-source** toolbox for **xApp development** and Open RAN **experimentation***

Enables:

1. Data collection
2. AI/ML model design
3. Model training and testing
4. Model deployment on near-RT RIC as xApp
5. Runtime inference and control of a softwarized RAN



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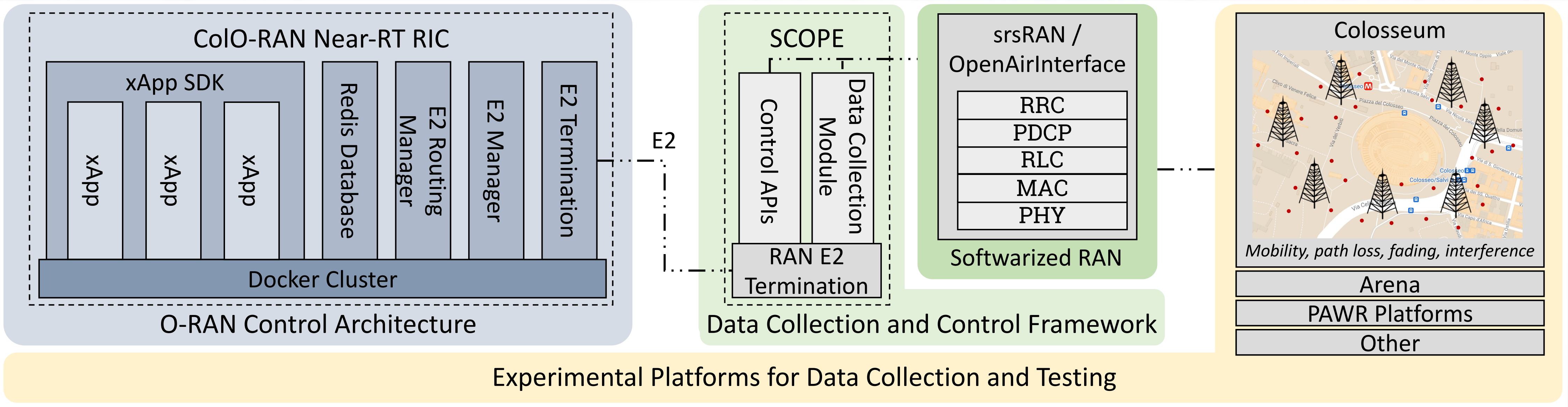
More info at openrangym.com

OpenRAN Gym Components

- O-RAN-compliant **near-real-time RIC** running on Colosseum (ColO-RAN)
- RAN framework for **data-collection and control** of the base stations (SCOPE)
- **Programmable** protocol stacks (based on srsRAN at this time)
- Publicly-accessible **experimental platforms** (e.g., Colosseum, Arena, PAWR platforms)



Developing Open, Programmable, and Intelligent Networks

Network slicing and scheduling

eMBB PRBs + scheduling policy

MTC PRBs + scheduling policy

URLLC PRBs + scheduling policy

RAN traffic steering

KPM xApp

State

Query

Agent xApp

Action

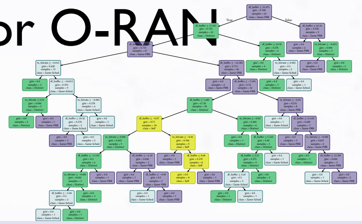
RC xApp

Telemetry

Control

RAN (E2 nodes)

Explainable AI for O-RAN



RAN

AI/ML for RAN Control

Understand AI choices

Automation and Energy Efficiency

Compute

Near RT-RIC

Scaling

dApps – closing the real-time loop in Open RAN

dApps

CU/DU

E2/O1

Near-RT and Non-RT RICs

xApps

rApps

- Programmable elements in DUs and CUs
- Spectrum sharing, beam management, inference on user plane
- Now considered in O-RAN ALLIANCE nGRG

The Missing Link – dApps: Control and Data Plane

Interactions with Control and User plane

Control plane

- O-RAN **closed-loop control** interacts with functionalities in the control **plane**
- **dApps extend it into real-time domain**
  - Beam management and optimization
  - Spectrum sharing
  - QoS enforcement
  - Interactions with the scheduler

User plane

- IQ, bits, bytes, packets
- Can't be moved to the RICs because of data-rate constraints security, privacy
- **dApps extend O-RAN into data-plane programmability**
  - Custom logic on data
  - Inference on I/Q samples
  - Packet tagging and flow inspection

Key to introduce new services to be monetized

dApps - Current Status

2022:

- Original dApp paper - propose the idea, discuss some use cases, present early architecture
  S. D'Oro, M. Polese, L. Bonati, H. Cheng, and T. Melodia, "dApps: Distributed Applications for Real-time Inference and Control in O-RAN," IEEE Communications Magazine, vo. 60, no. 11, Nov. 2022

2023

- Further research and development
- O-RAN nGRG: proposed and approved research item in RS-02 Architecture (RI06)

2024

- Architecture and prototype development
- O-RAN nGRG: first research report on dApp use cases

2025

- Released the first open-source dApp prototype
- Developed and published dApp use cases
- First paper on dApp architecture

- O-RAN nGRG: continuing work on a research report on dApp architecture

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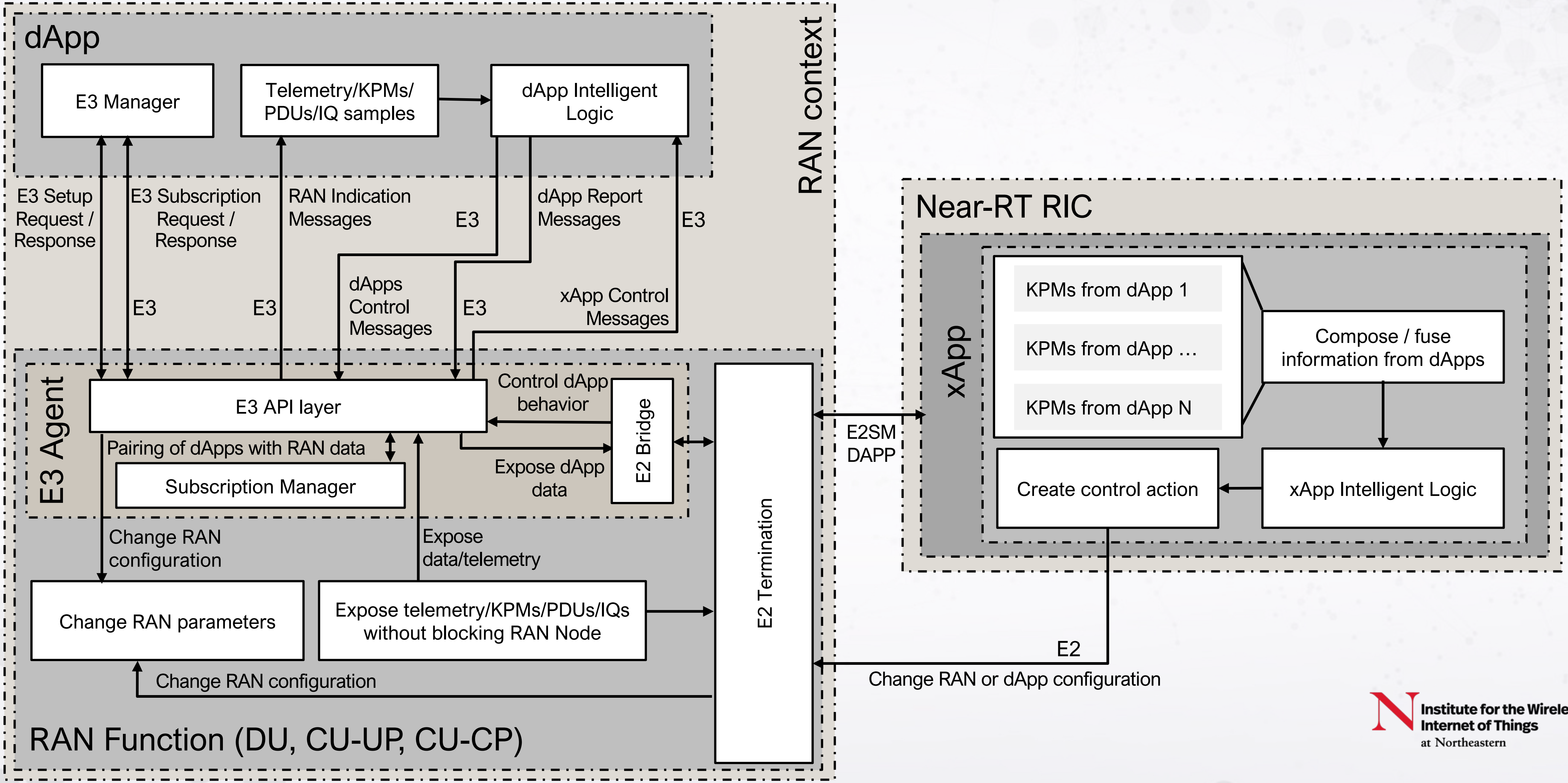
E3 interface for dApps and interactions with O-RAN



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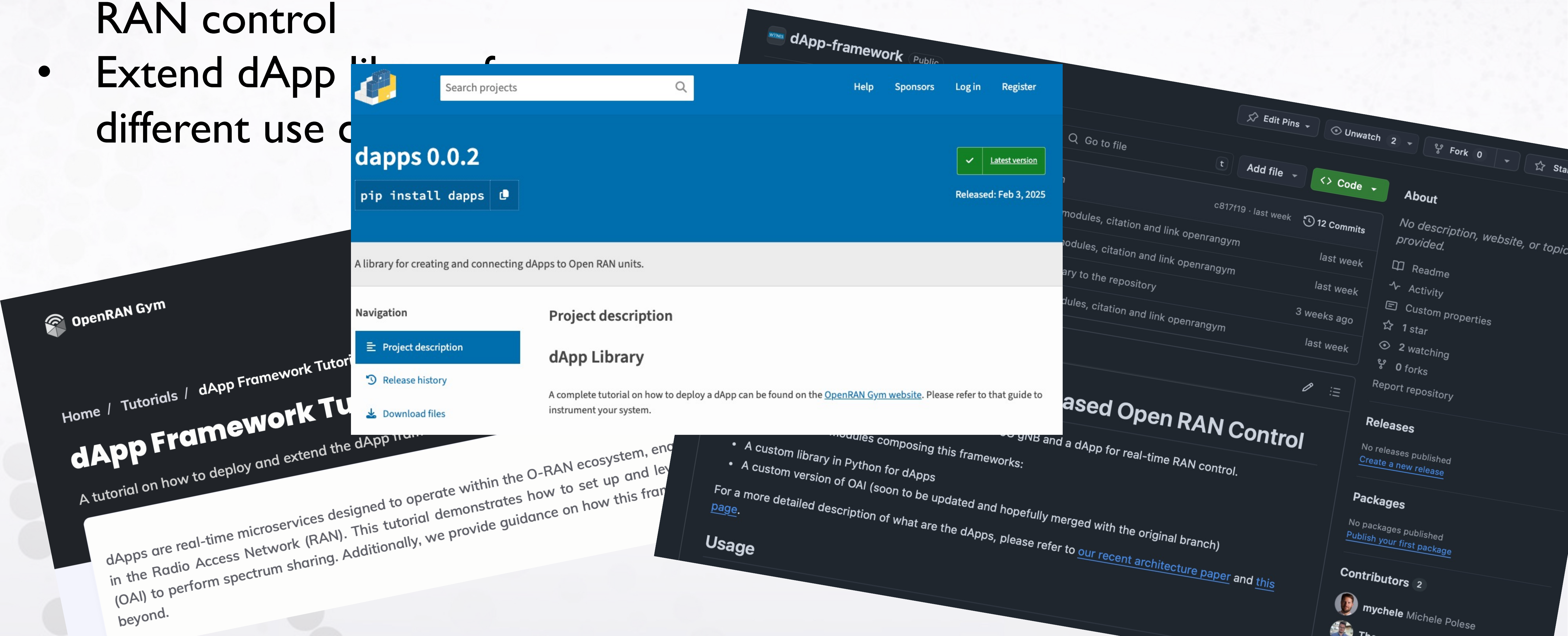
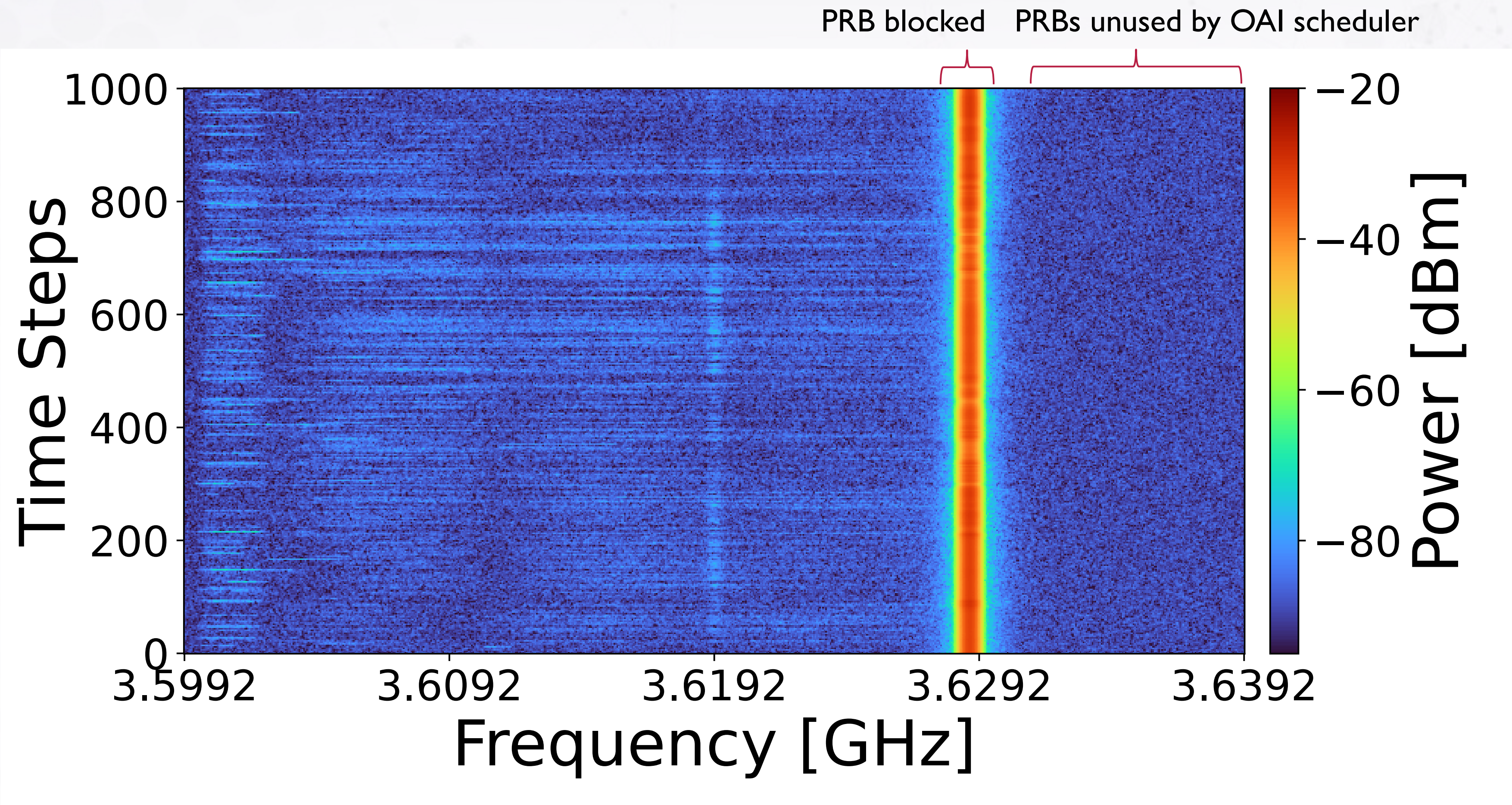
dApp Open-Source Framework

- Enable research on real-time RAN control
- Extend dApp li... f... different use c...

https://openrangym.com/tutorials/dapps-oai



Use case: dApp for Spectrum Sharing



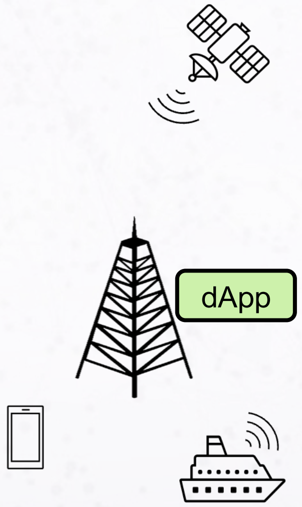
No incumbent

Incumbent in area (No dApp)

Incumbent in area (dApp on)

Shared Spectrum

No cooperation



The dApp **detects** the incumbent and **blocks** the scheduling of PRBs associated *in Real Time*

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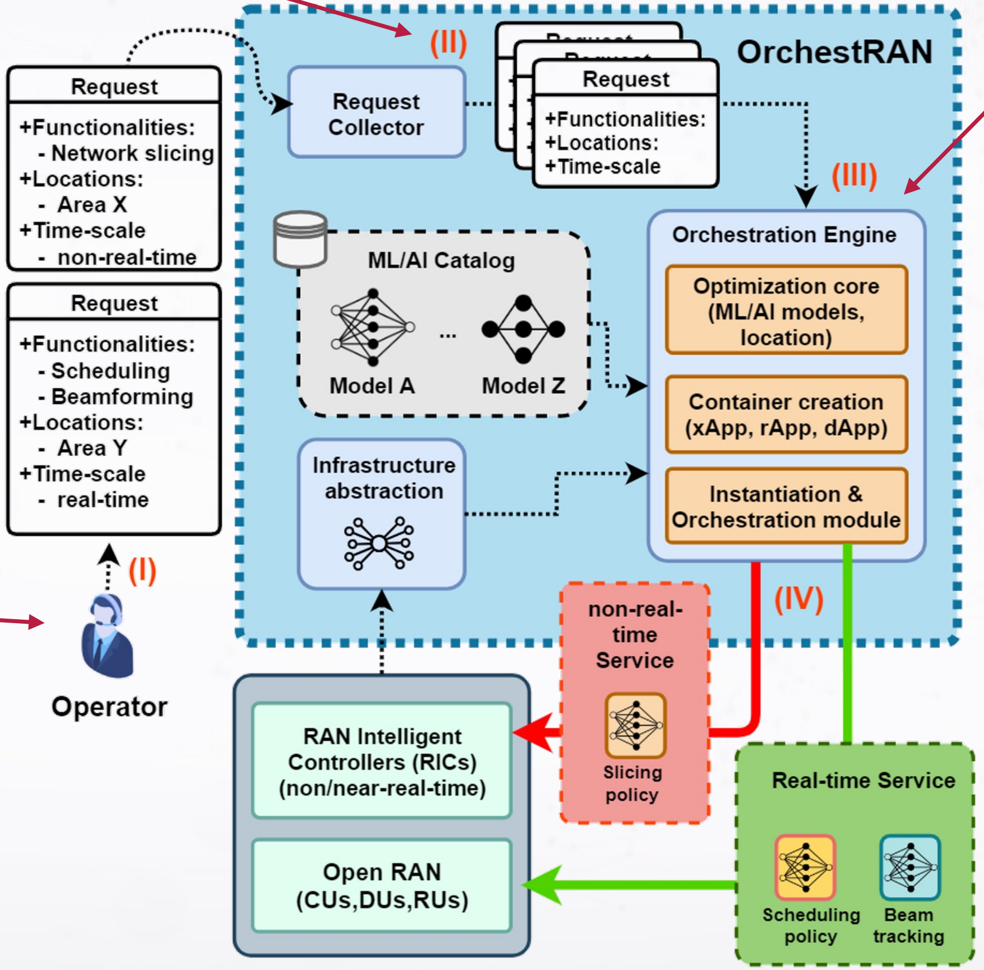
Intelligence Orchestration in Open RAN

(II) Collect requests

(III) Compute orchestration policy

- Which model
- Where and when



(I) Submit request:

- Functionalities
- Locations
- Time-scale

(IV) Deploy intelligence

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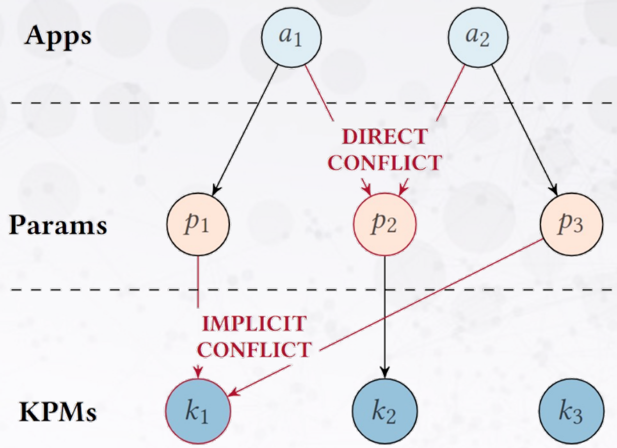
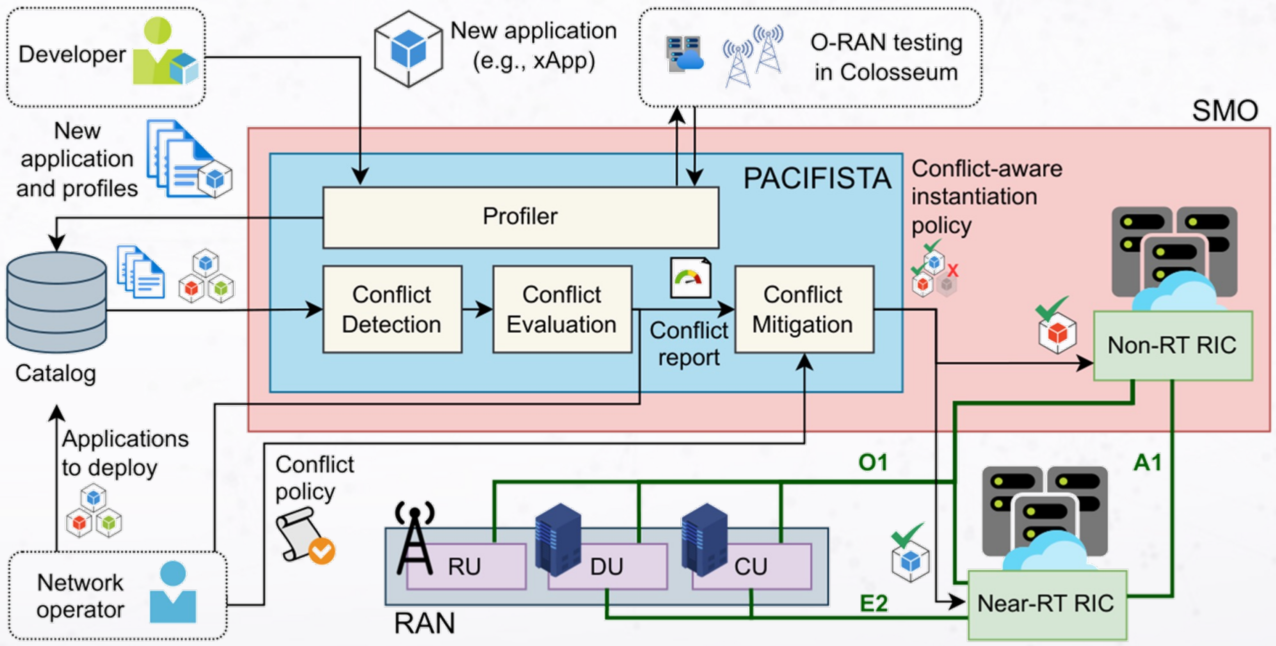
S. D'Oro, L. Bonati, M. Polese, T. Melodia, *"OrchestRAN: Network Automation through Orchestrated Intelligence in the Open RAN,"* Proceedings of IEEE INFOCOM, May 2022

Conflict Mitigation in O-RAN Applications



- Profile O-RAN applications (e.g., xApps, rApps) submitted by operators
- Identify and score potential conflicts with running applications
- Deploy conflicting applications if score below threshold



P. Brach del Prever, S. D'Oro, L. Bonati, M. Polese, M. Tsampazi, H. Lehmann, and T. Melodia, "PACIFISTA: Conflict Evaluation and Management in Open RAN" arXiv:2405.04395 [cs.NI], pp. 1-12, May 2024

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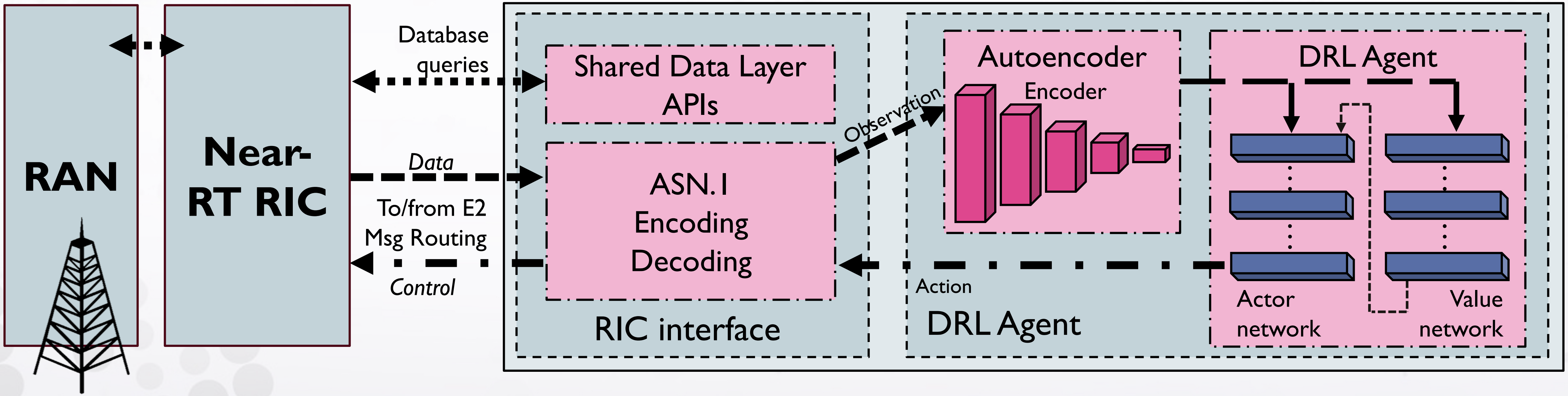
Design and Testing of DRL Control in Open RAN

Dataset available: openrangym.com

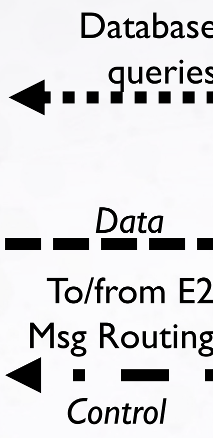
AI/ML that generalizes to different deployments and scenarios

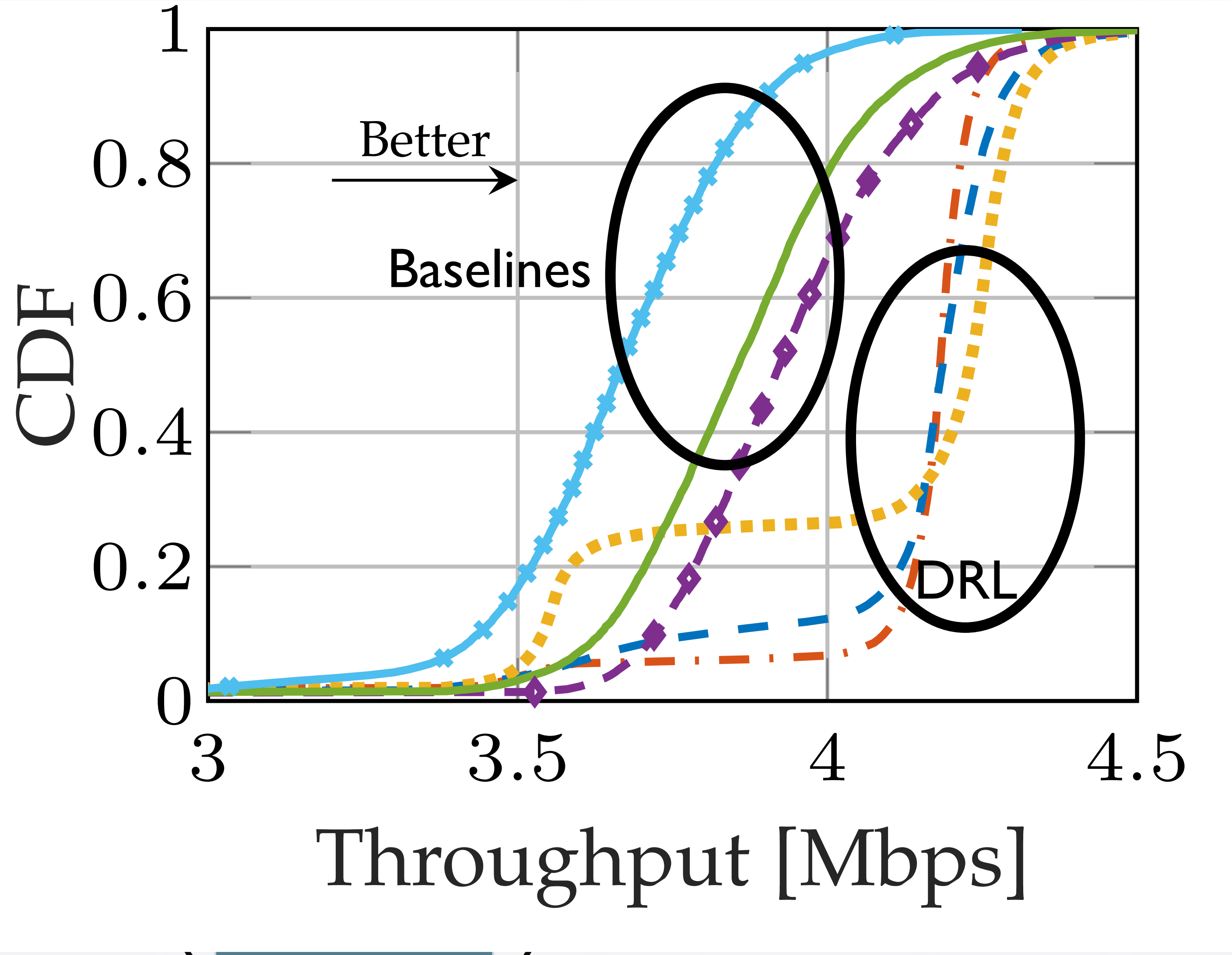
ColO-RAN xApp

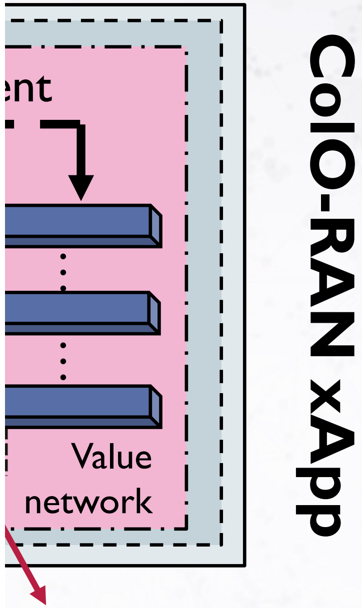


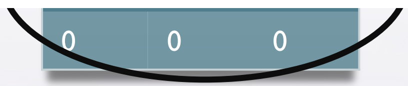
M. Polese, L. Bonati, S. D'Oro, S. Basagni, and T. Melodia, "ColO-RAN: Developing Machine Learning-based xApps for Open RAN Closed-loop Control on Programmable Experimental Platforms", IEEE TMC

Agent Design – Toward Deploying DRL on the RAN









- Generate a cc … d scheduling policies the RAN
- Deal with mis … late telemetry … satisfy goals of different

M. Polese, L. Bonati, S. D'Oro, S. Basagni, and T. Melodia, "ColO-RAN: Developing Machine Learning-based xApps for Open RAN Closed-loop Control on Programmable Experimental Platforms", IEEE TMC

Explainable AI – The EXPLORA Framework

Network slicing and scheduling

eMBB PRBs + scheduling policy	MTC PRBs + scheduling policy	URLLC PRBs + scheduling policy

- DRL is effective at controlling and optimizing O-RAN systems
- Inherently hard to explain and interpret
- Operator trust?
- Expected/anomalous behavior?

Explainable AI is still unexplored in mobile wireless networks

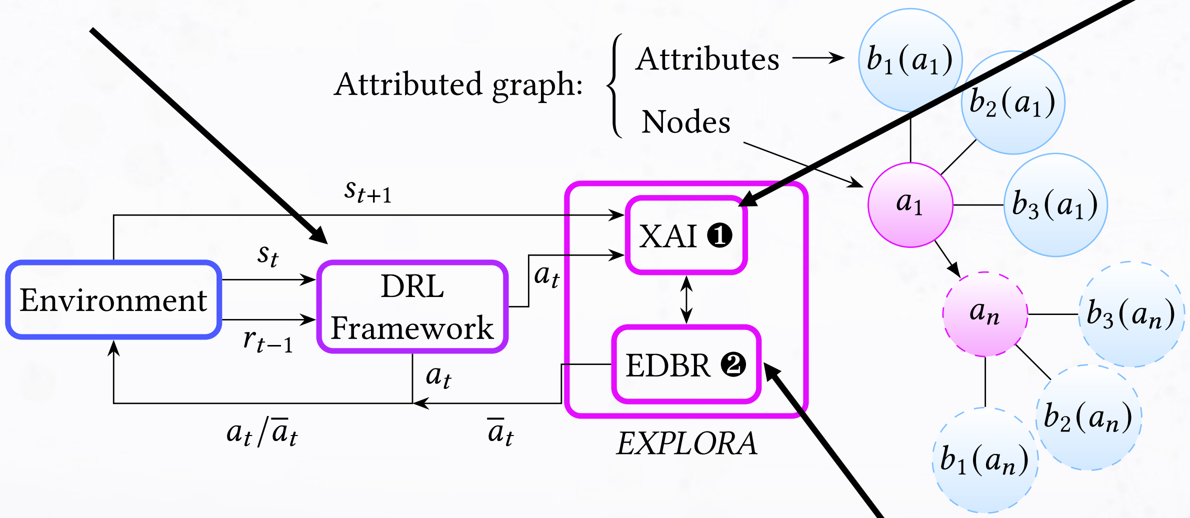
- Challenge: complex input/output relationship (problem for state-of-the-art methods, e.g., SHAP)
- Challenge: memory makes system non-linear
- Challenge: multi-modal control

Explainable AI – The EXPLORA Framework

EXPLORA: network-oriented explanations that link DRL action to network state

C. Fiandrino, L. Bonati, S. D'Oro, M. Polese, J. Widmer, T. Melodia, EXPLORA: AI/ML EXPLainability for the Open RAN, ACM CoNEXT'23

xApp(s) for network control



O-RAN deployment

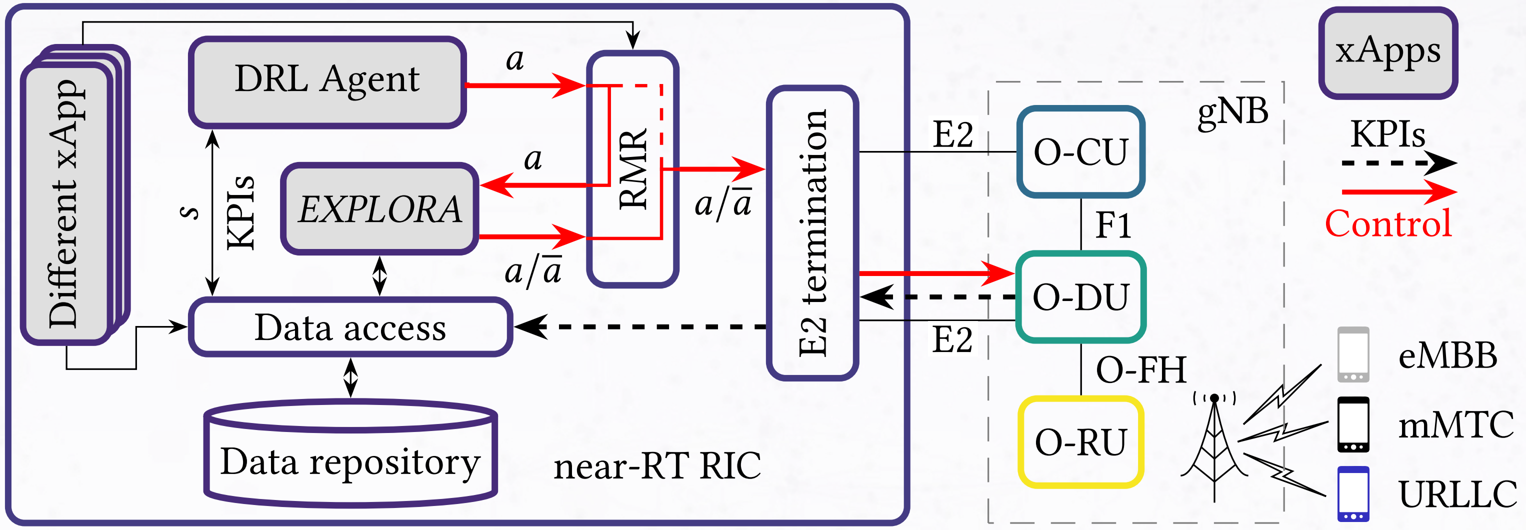
XAI:

- create attributed graph to connect **actions** (nodes) to effects on **RAN** (attributes)
- distill knowledge by analyzing **transitions** between actions (edges)

Explanation-Driven Behavior Refiner (EBDR):

- identify inefficiencies/anomalies
- adjust agent behavior with action steering

Prototyping EXPLORA



- Implemented as RIC component
- Tested on Colosseum with Open RAN environment
- 28 hours of experiments + 150 hours of offline data

C. Fiandrino, L. Bonati, S. D'Oro, M. Polese, J. Widmer, T. Melodia, EXPLORA: AI/ML EXPLainability for the Open RAN, ACM CoNEXT'23

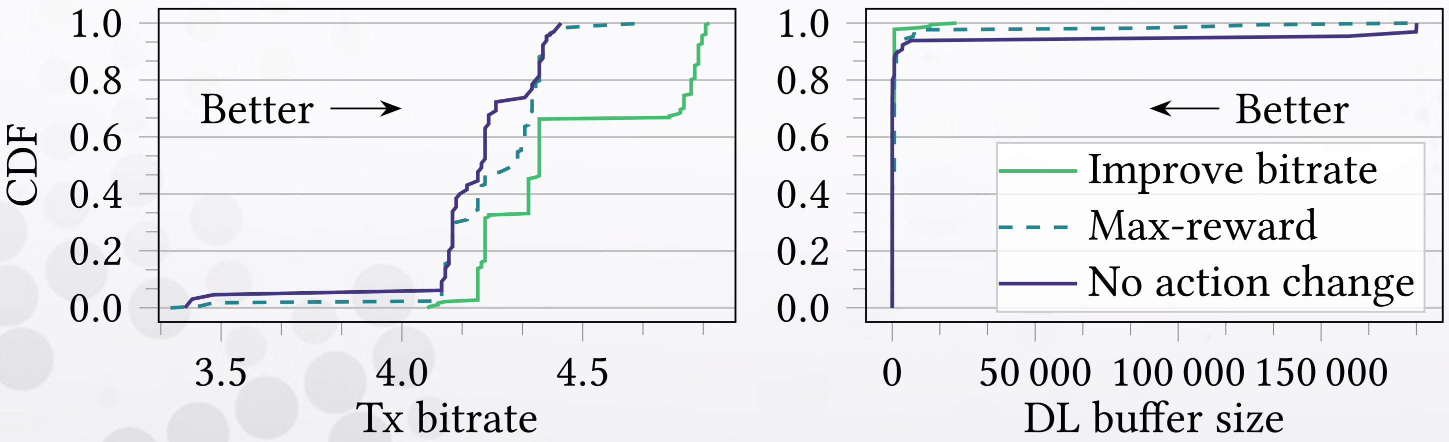
EXPLORA: Explanations and Action Steering

Different classes of transitions

Transition	Interpretation
Same-PRB	Produces minor changes in KPIs
Same-Sched.	Diminishes tx_bitrate, other KPIs augment/diminish according to the previous state
Distinct	Increases tx_bitrate, other KPIs augment/diminish according to the previous state
Self	No change in KPIs

Table 1. HT agent: summary of explanations

EXPLORA XAI module generates high-level explanations of the DRL agent behavior



EXPLORA EBDR steers the DRL agent behavior to improve specific KPIs

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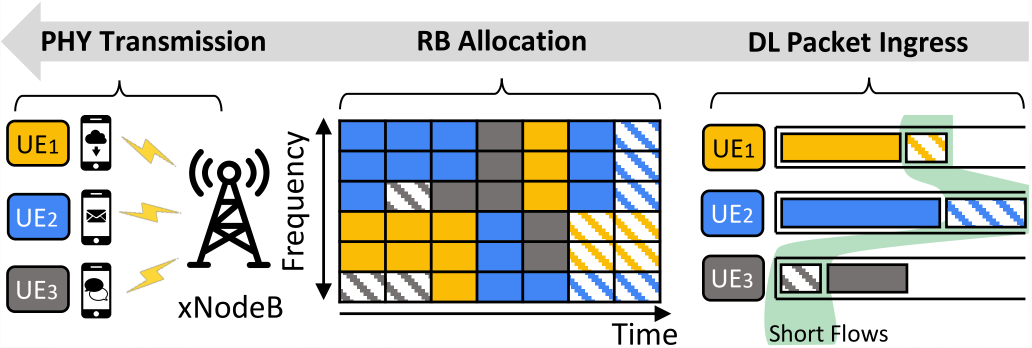
C. Fiandrino, L. Bonati, S. D'Oro, M. Polese, J. Widmer, T. Melodia, EXPLORA: AI/ML EXPLainability for the Open RAN, ACM CoNEXT'23

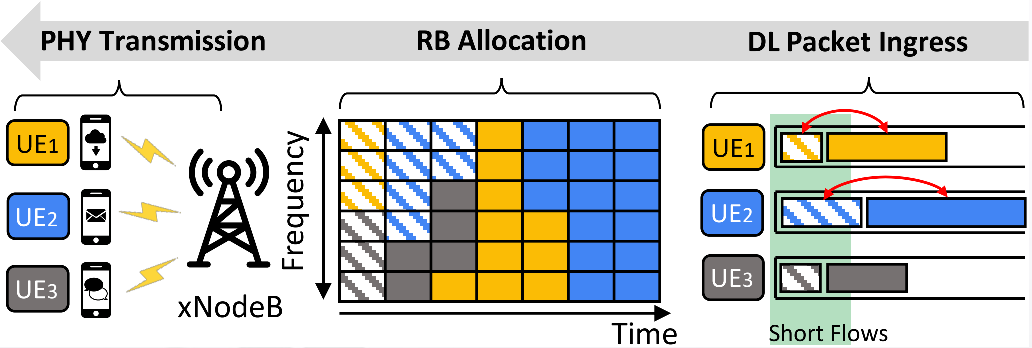
Colosseum Research Use Cases

OutRAN: scheduling optimization for low latency traffic flows

Jaehong Kim, Yunheon Lee, Hwijoon Lim, Youngmok Jung, Song Min Kim, Dongsu Han. 2022. OutRAN: Co-optimizing for Flow Completion Time in Radio Access Network, ACM CoNEXT'22



(a) Existing schedulers in operation, being flow-agnostic. Short flows (pattern-filled) suffer from queueing delay.



(b) OutRAN completes short flows first.

- Intelligent **scheduling** to minimize **flow completion time**
- Implemented as a combination of techniques at different layers of the stack
- Prototyped on srsRAN
- Tested on lab bench and Colosseum

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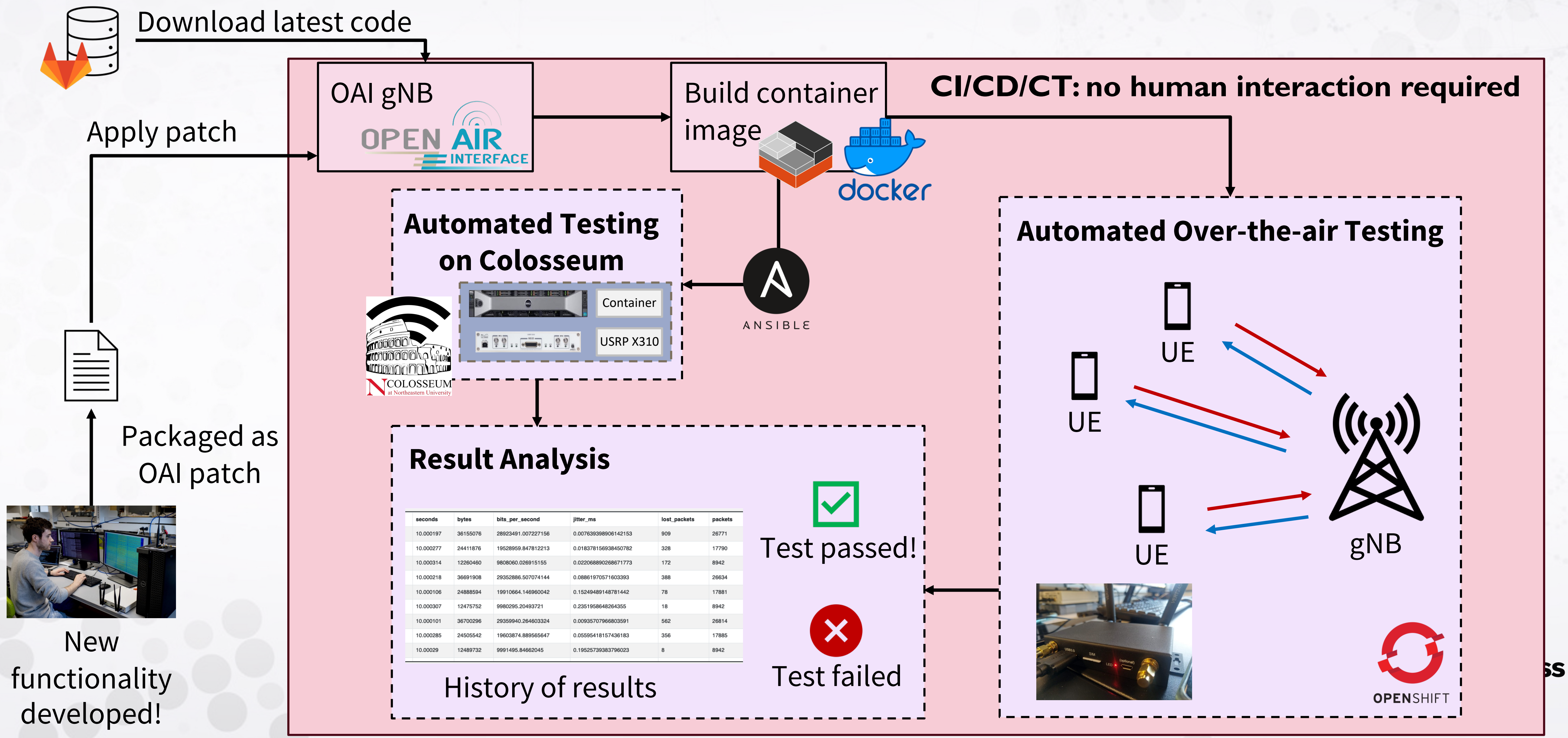
Automated Testing of New Functionality

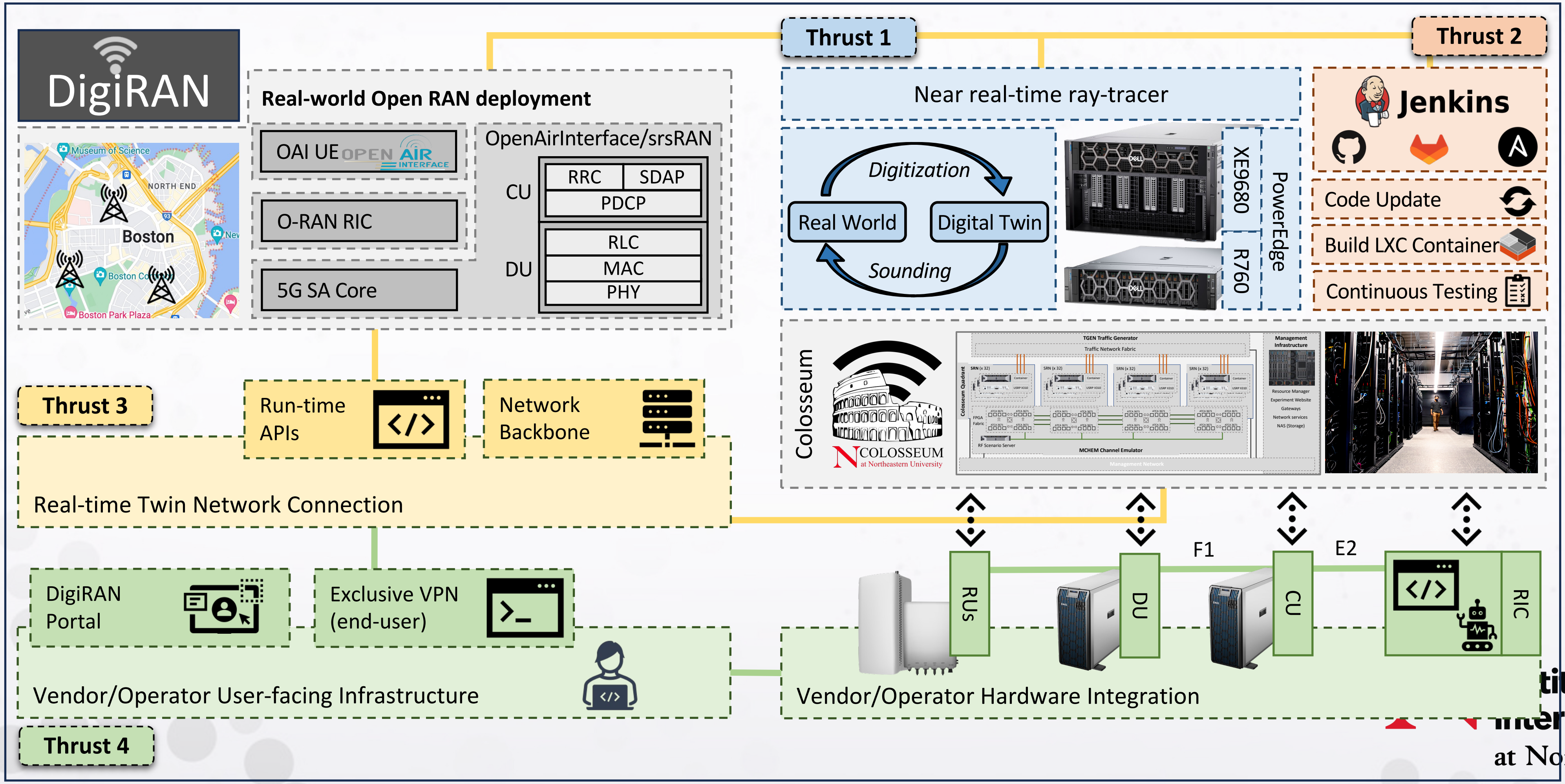


	seconds	bytes	bits_per_second	jitter_ms	lost_packets	packets
	10.000197	36155076	28923491.007227156	0.007639398906142153	909	26771
	10.000277	24411876	19528959.847812213	0.018378156938450782	328	17790
	10.000314	12260460	9808060.026915155	0.022068890268671773	172	8942
	10.000218	36691908	29352886.507074144	0.08861970571603393	388	26634
	10.000106	24888594	19910664.146960042	0.15249489148781442	78	17881
	10.000307	12475752	9980295.20493721	0.2351958648264355	18	8942
	10.000101	36700296	29359940.264603324	0.009357079668035 91	562	26814
	10.000285	24505542	19603874.889565647	0.05595418157436183	356	17885
	10.00029	12489732	9991495.84662045	0.19525739383796023	8	8942

L. Bonati, M. Polese, S. D'Oro, P. Brach del Prever, T. Melodia, "5G-CT: Automated Deployment and Over-the-Air Testing of End-to-End Open Radio Access Networks," IEEE Communications Magazine

DigiRAN – Digital Twin Framework for Open RAN Development, Testing & Integration

Goal: Extend Colosseum capabilities to model dynamic O-RAN scenarios and COTS devices



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Thank You! Q&A

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