Institute for the Wireless Internet of Things
at Northeastern University

Colosseum Use Cases

Colosseum Team:
Tommaso Melodia, Stefano Basagni, Manu Gosain, Kaushik Chowdhury,
Pedram Johari, Leonardo Bonati, ***Michele Polese***, Davide Villa

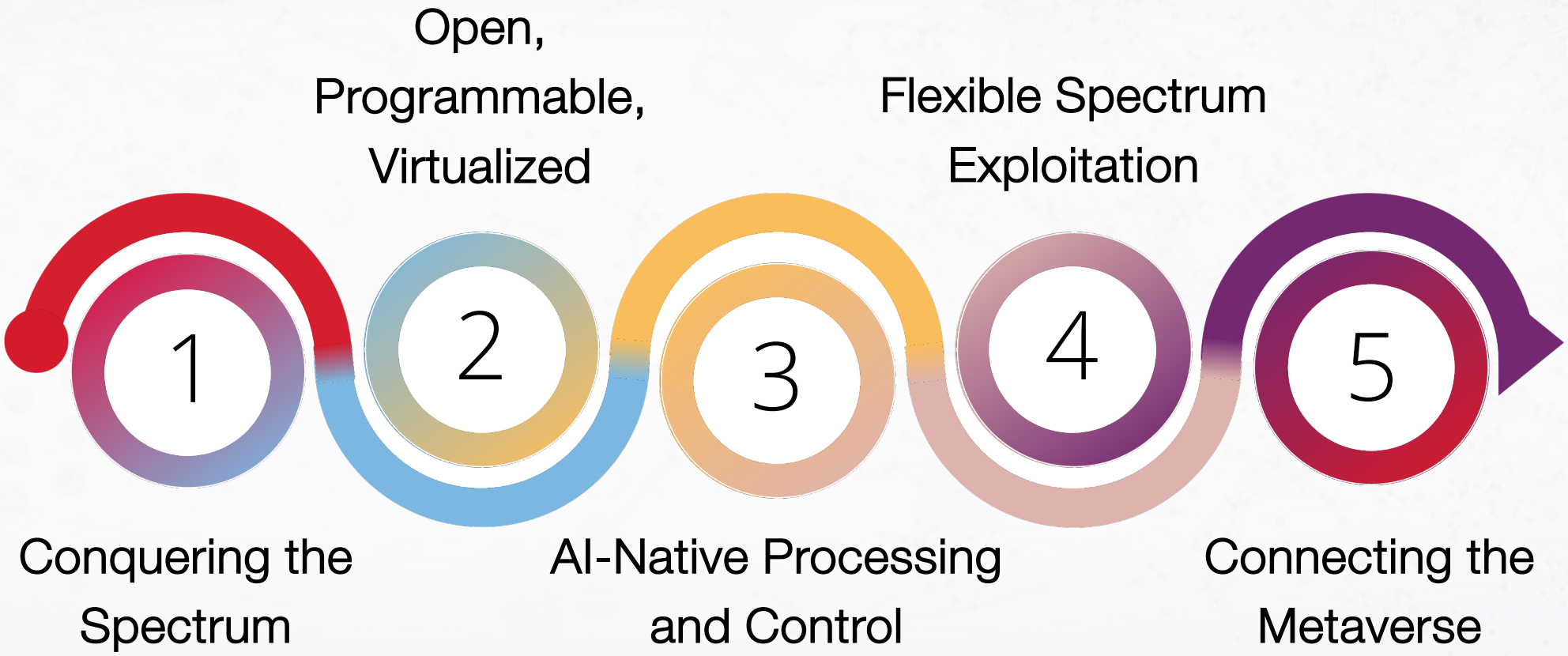
Platforms for Advanced Wireless Research

COLOSSEUM at Northeastern University

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



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-Mobile, 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

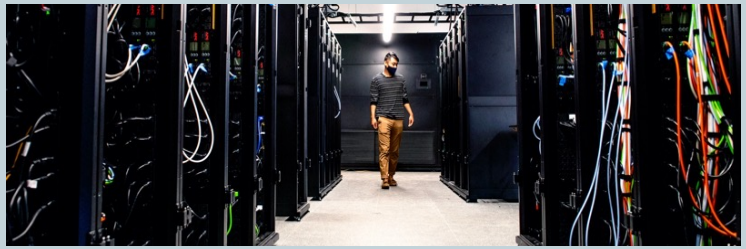
Testbeds and Platforms: Why?

Design

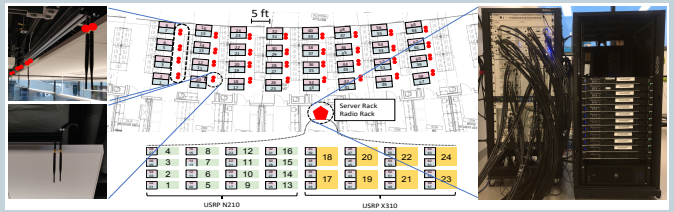
Data

Evaluation and validation

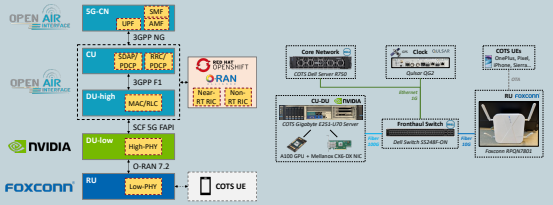
Colosseum



Arena + PAWR

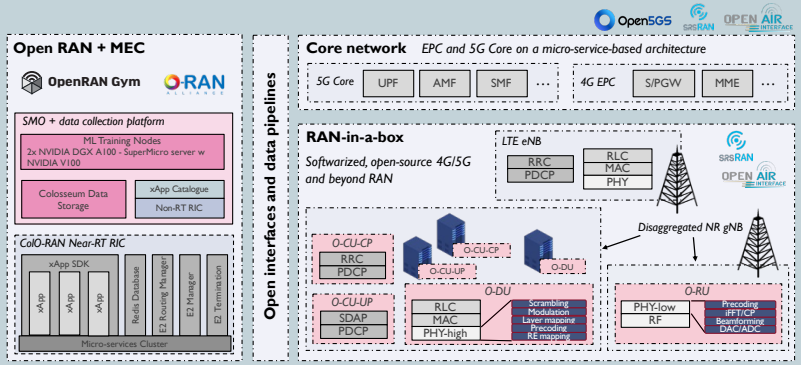


X5G



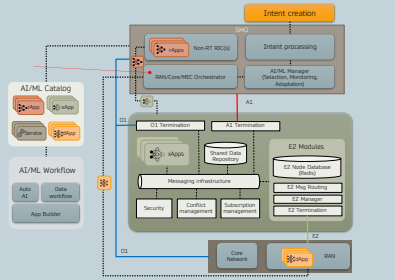
OpenRAN Gym

End-to-end programmable cellular



FCC Innovation Zones

Production 5G+AI automation



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Platforms for Advanced Wireless Research

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

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

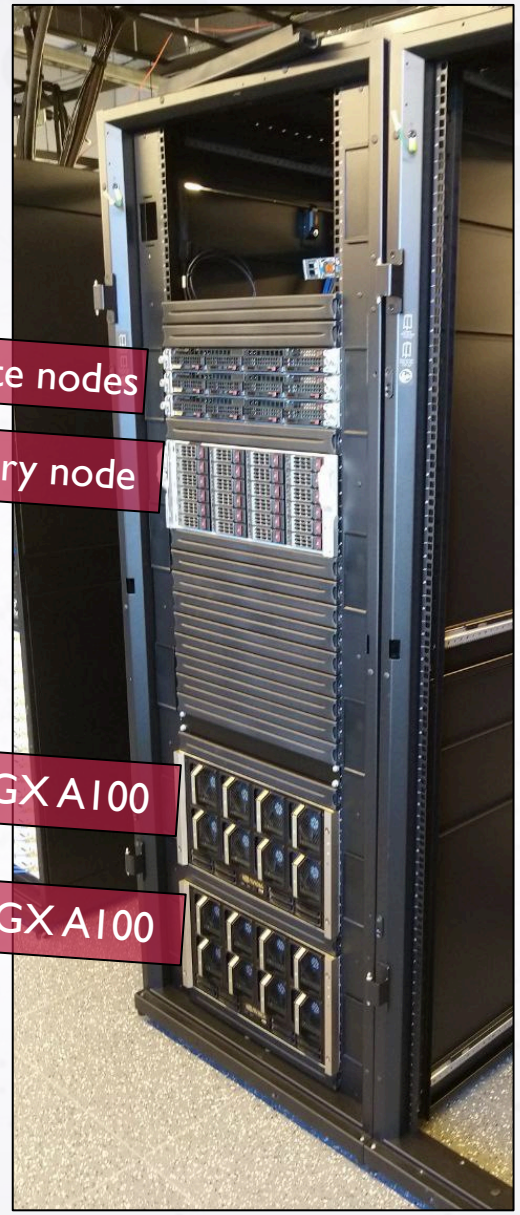
Colosseum as Enabler for AI/ML

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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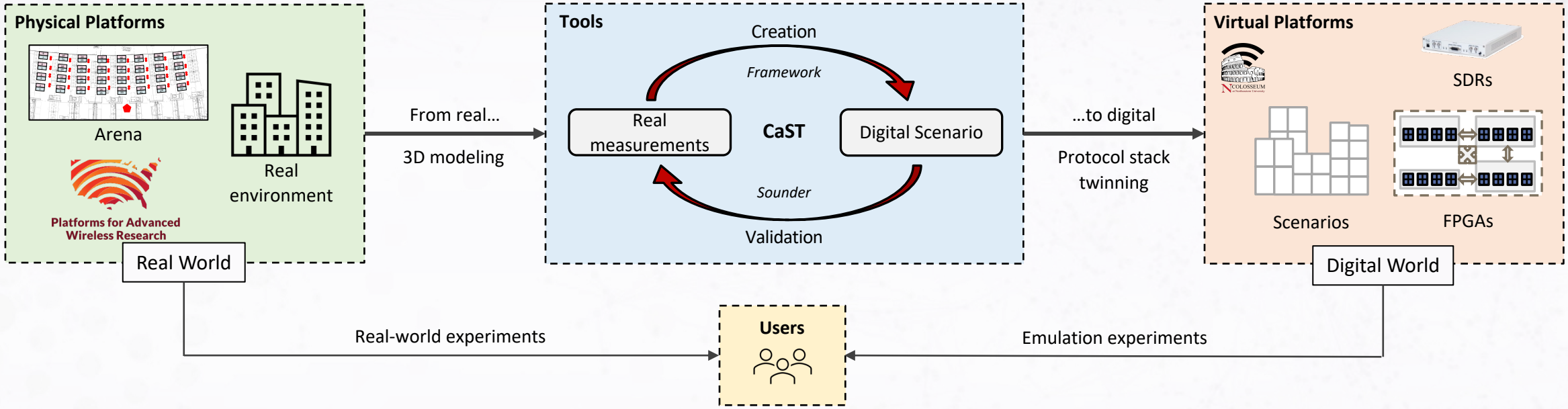
Colosseum: Much More Than a Supercomputer

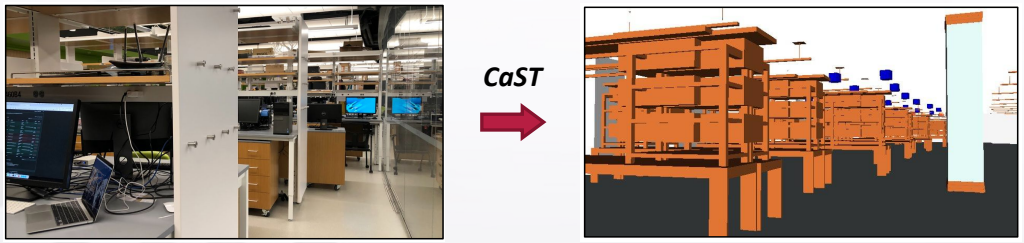
- Colosseum has **RF hardware in the loop**
- Not only a simulation environment: **real-time emulation with real radio signals, stacks and emulated channels**
- Combines in a SINGLE instrument
  - Fidelity of hardware channel emulators
  - Flexibility of a virtualized data center
  - Scalability of a 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

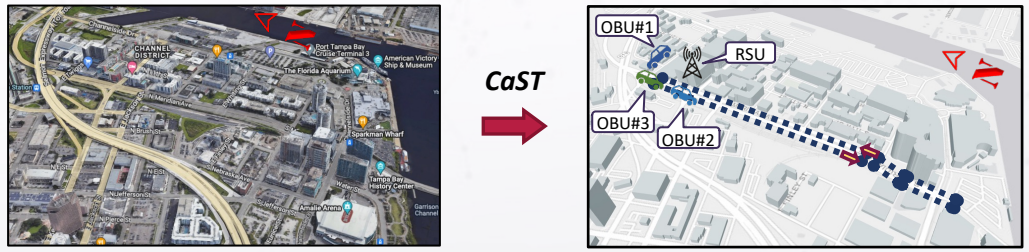


Indoor Environment



Real World *Digital World*

Outdoor Environment



Real World *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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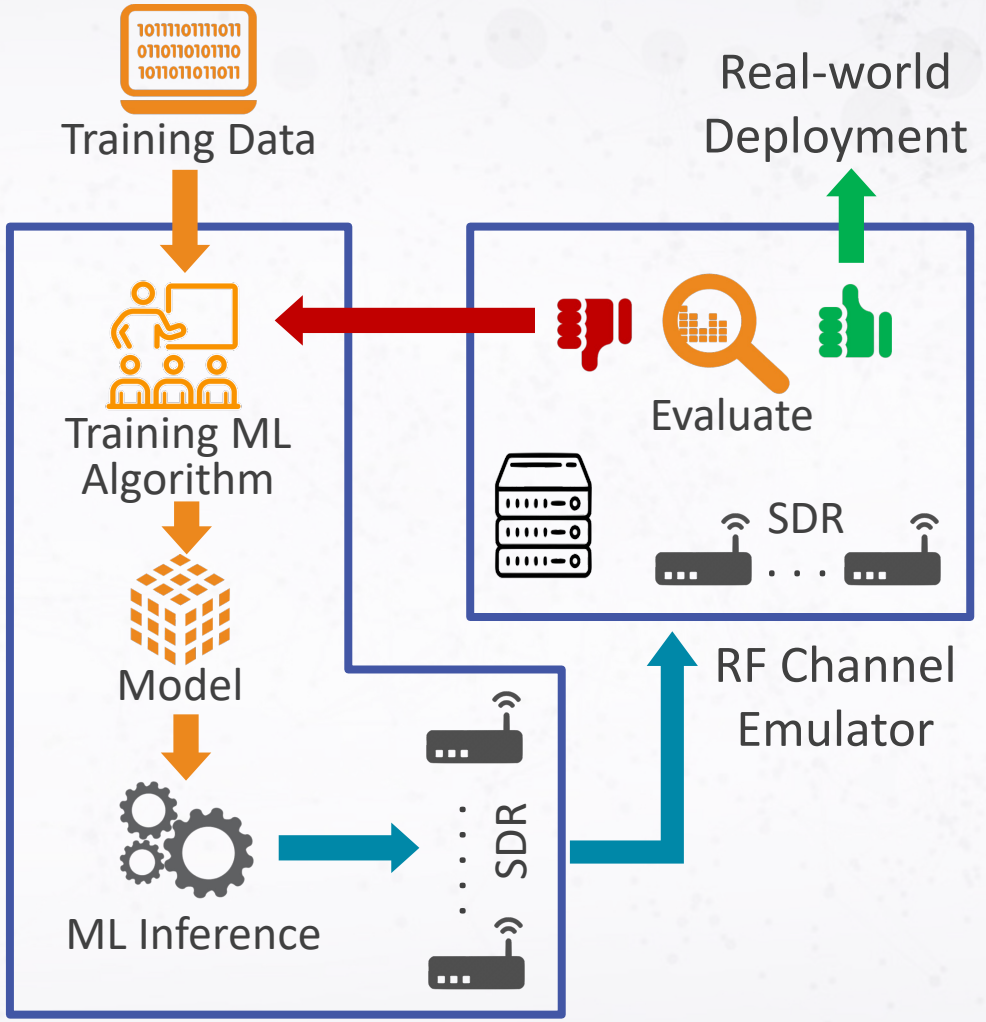
Artificial Intelligence and Wireless

- **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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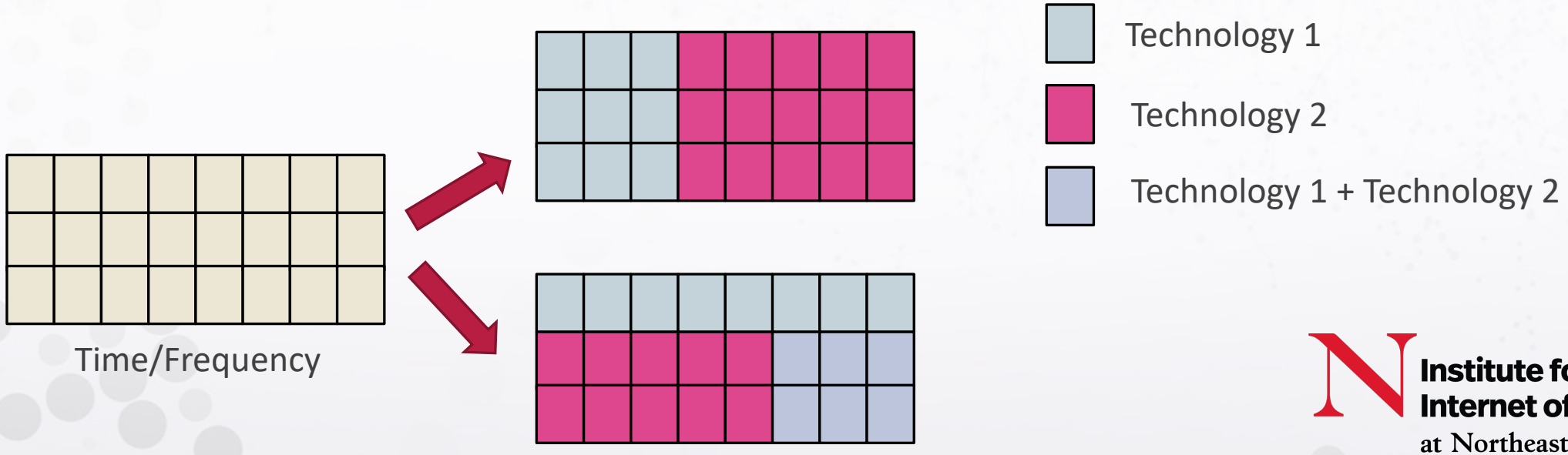
Spectrum Sharing

- **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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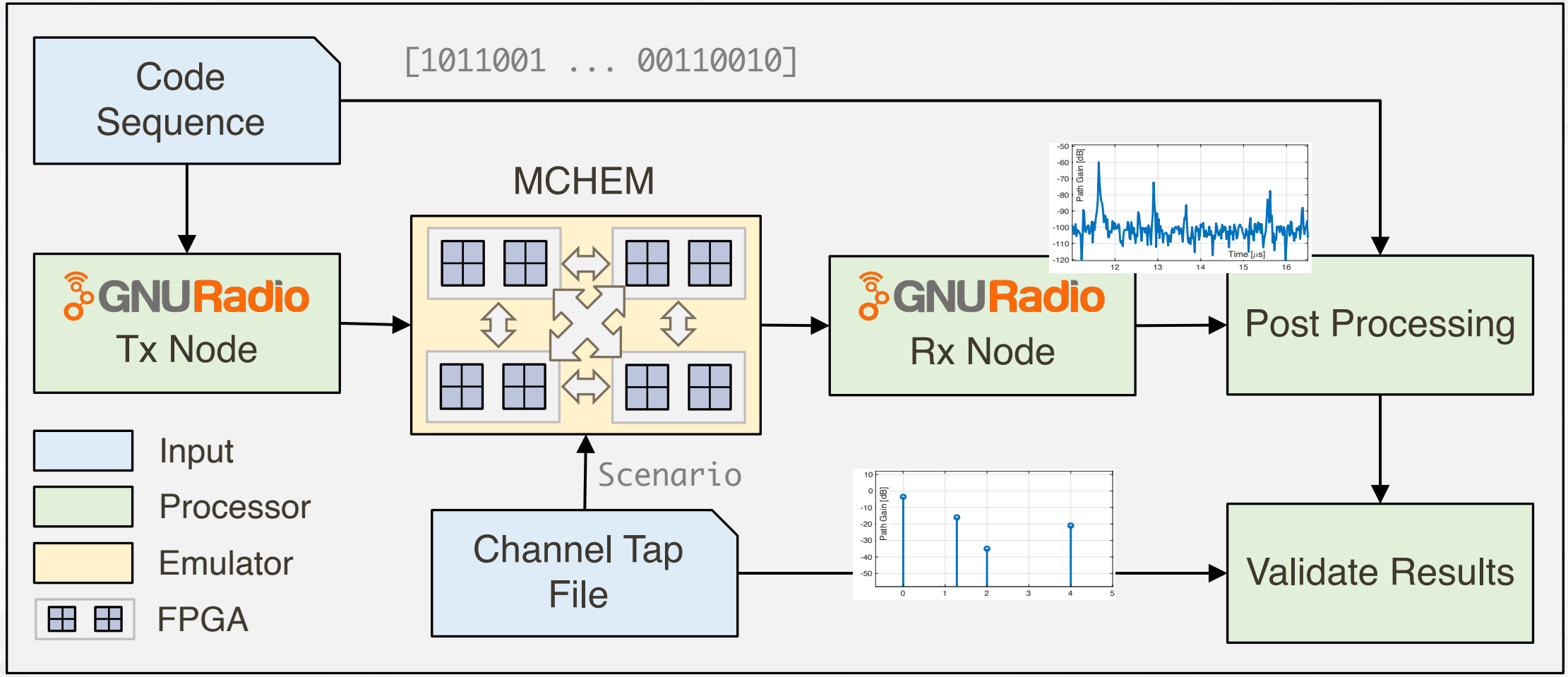
Channel Sounding



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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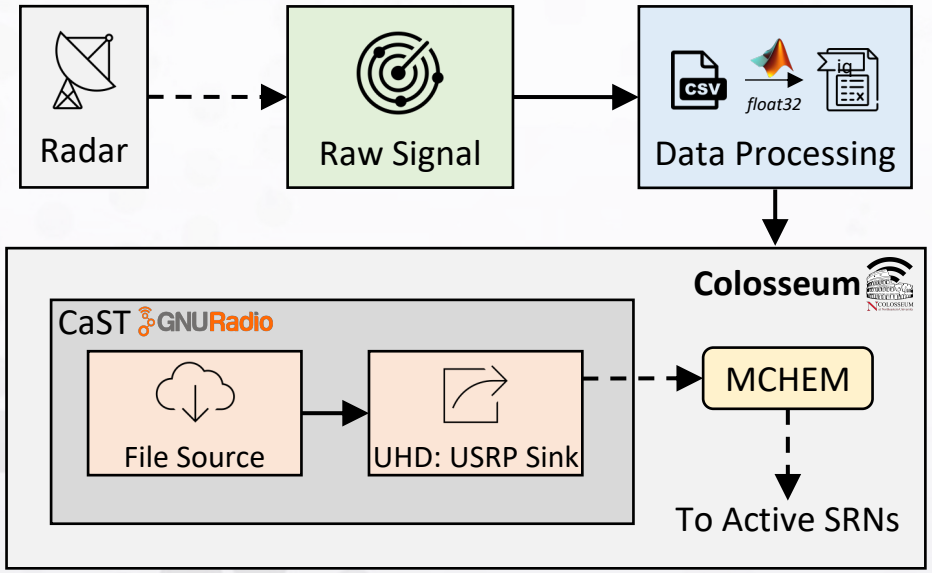
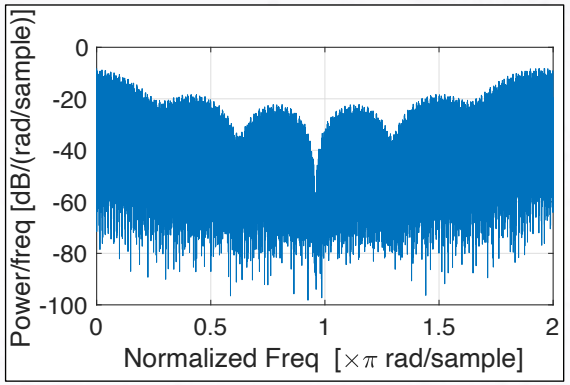
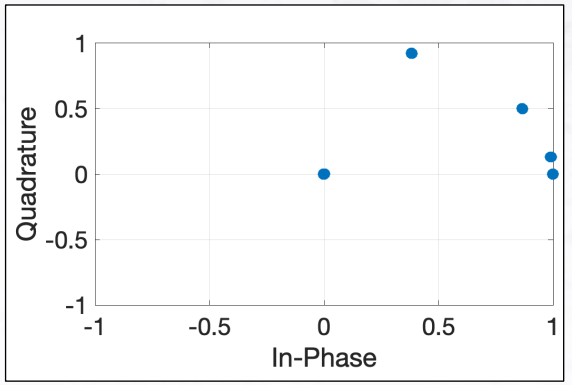
Radar Characterization

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

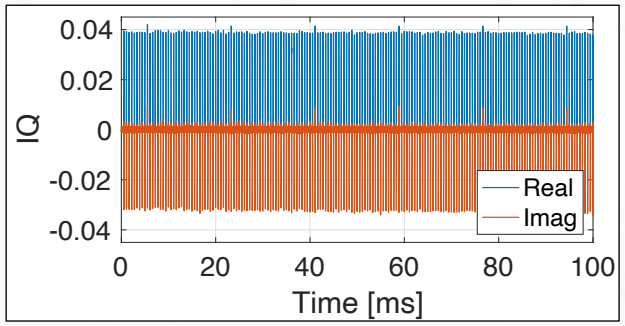




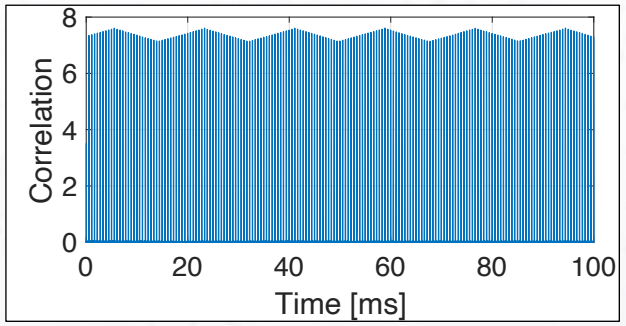
Radar PSD



Radar constellation



Received radar waveform



Radar correlation

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

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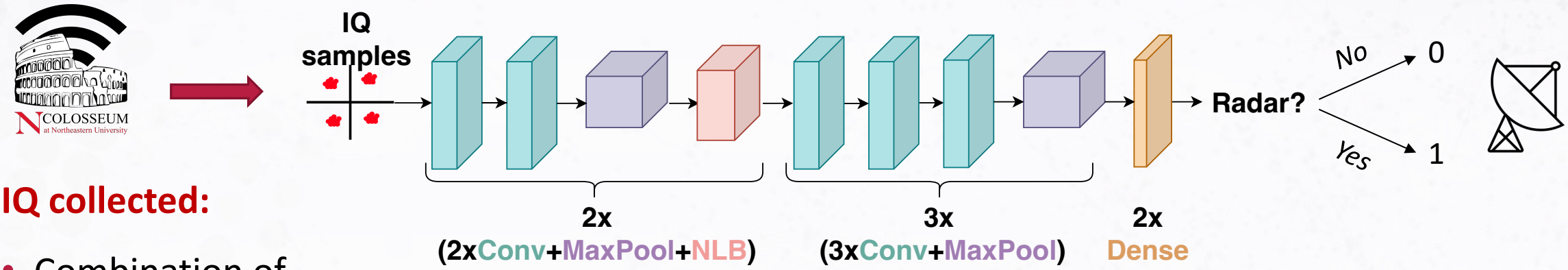
Intelligent Radar Detector

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

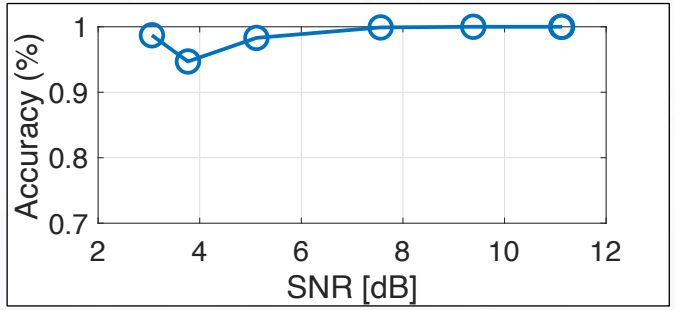


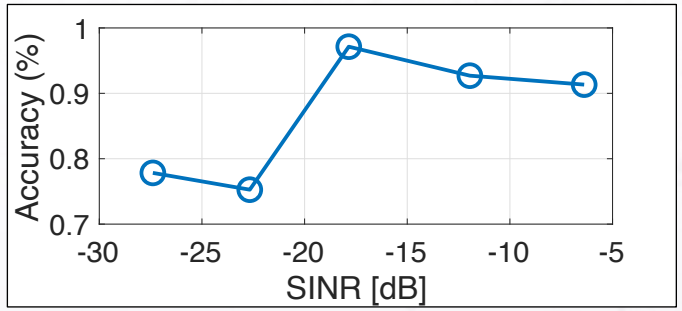
IQ collected:

- 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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Open RAN on Colosseum

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Twinning O-RAN Systems in Colosseum

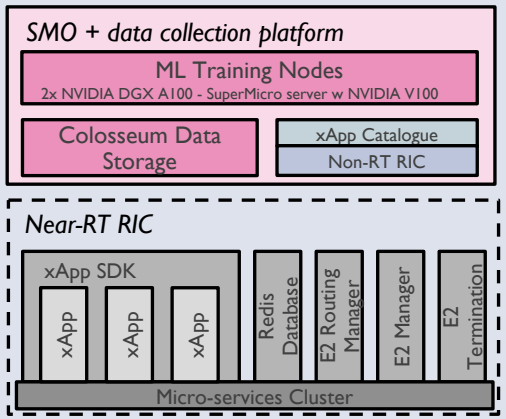
O-RAN ALLIANCE

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

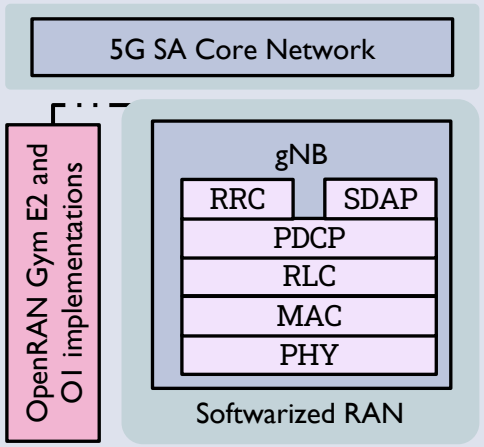
Automated end-to-end digital twin for AI/ML in O-RAN

OpenRAN Gym

RICs and AI/ML for O-RAN



OPEN AIR INTERFACE



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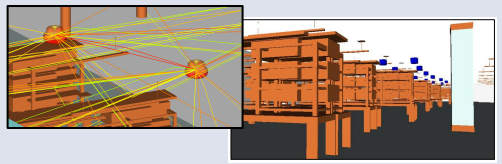
RF Digital Twin



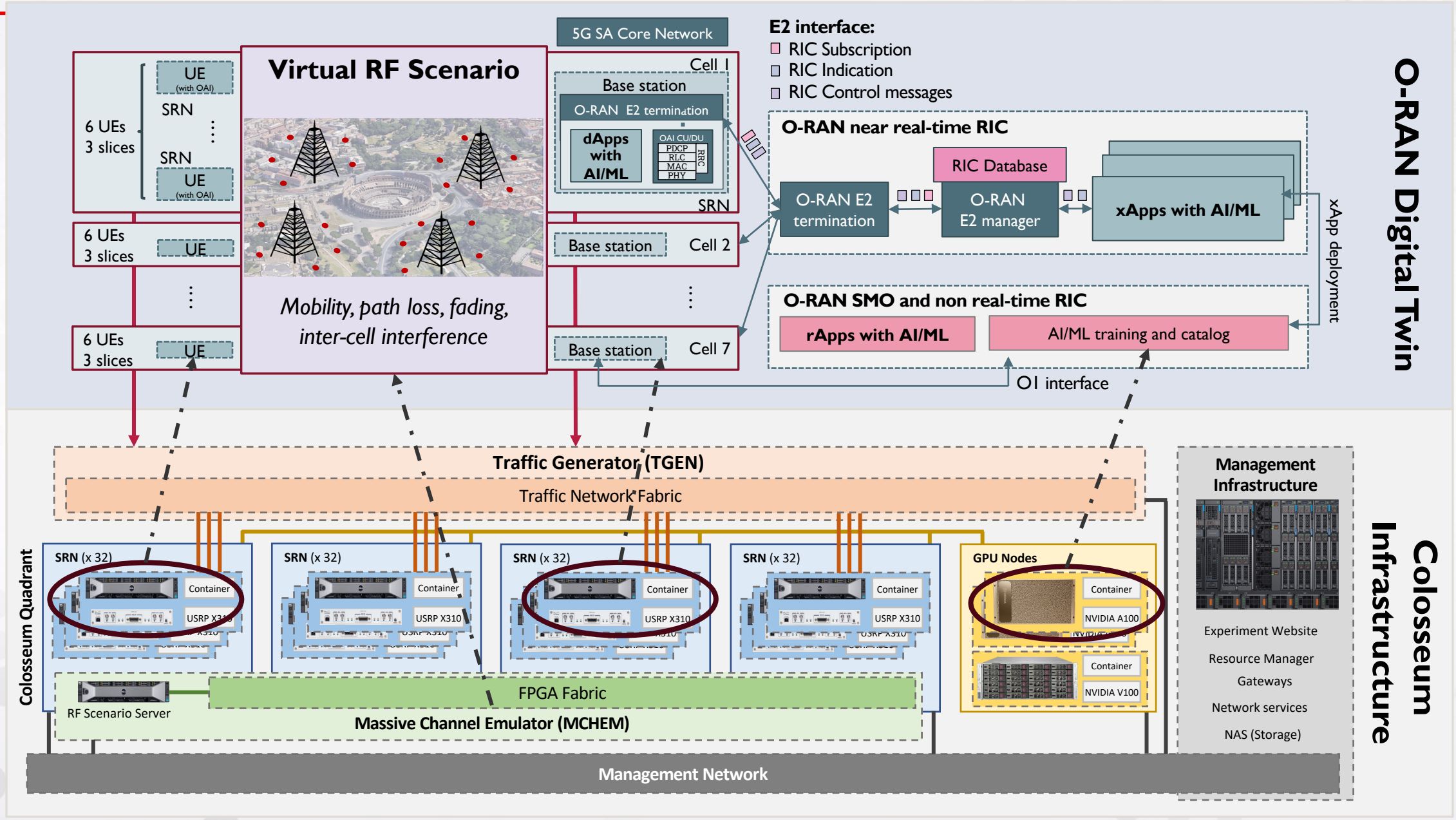
CI/CD/CT

Large-scale Experiment Orchestration

Data Collection

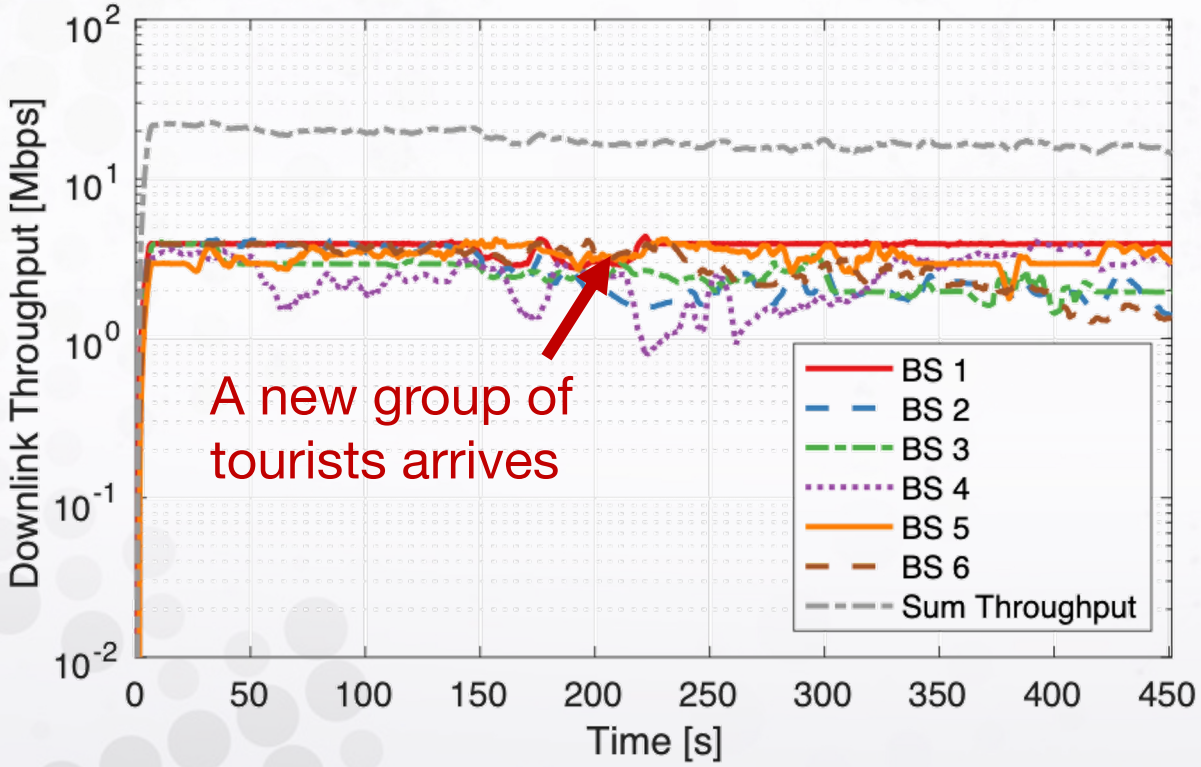
AI/ML Validation

Colosseum: The Open RAN Digital Twin

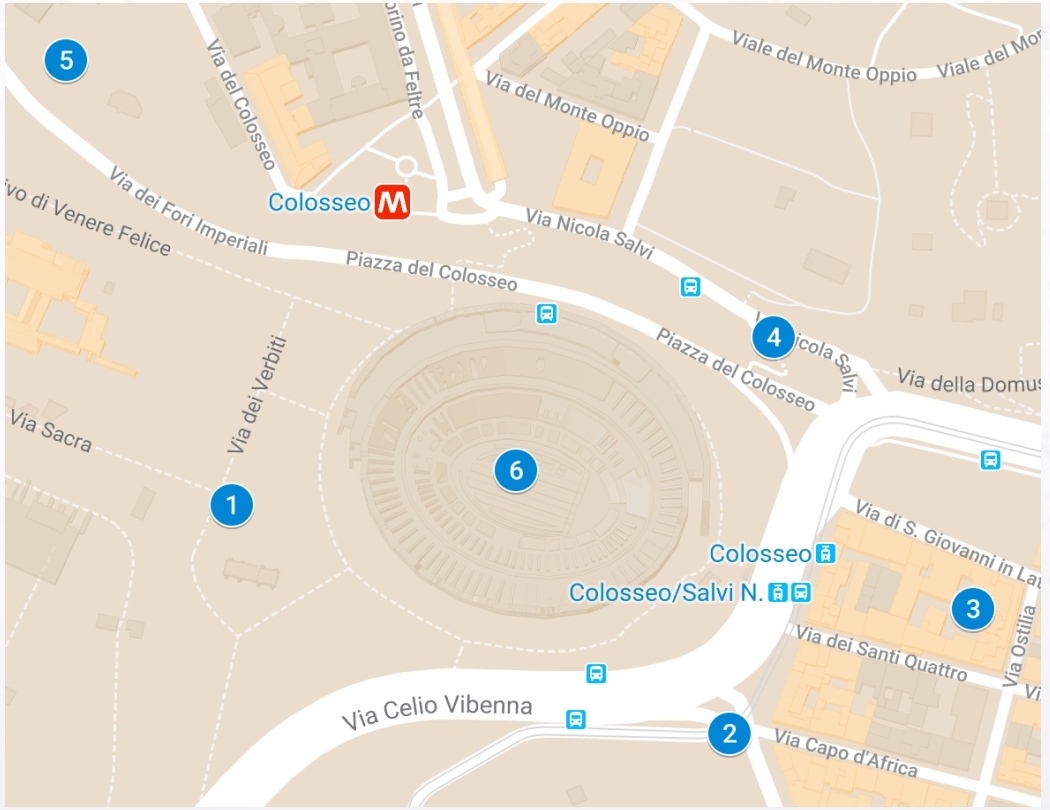


Colosseum 5G Capabilities

- 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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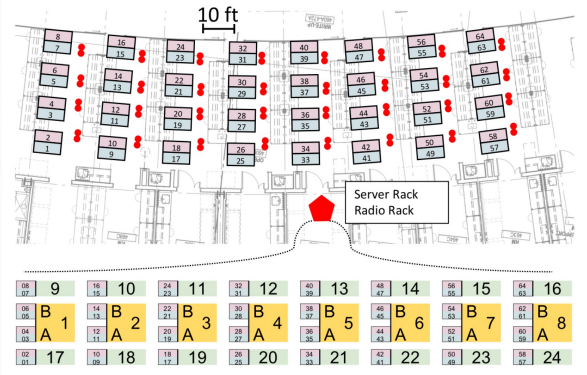
Validate in real wireless environment



Arena

Test large-scale capabilities

Platforms for Advanced Wireless Research

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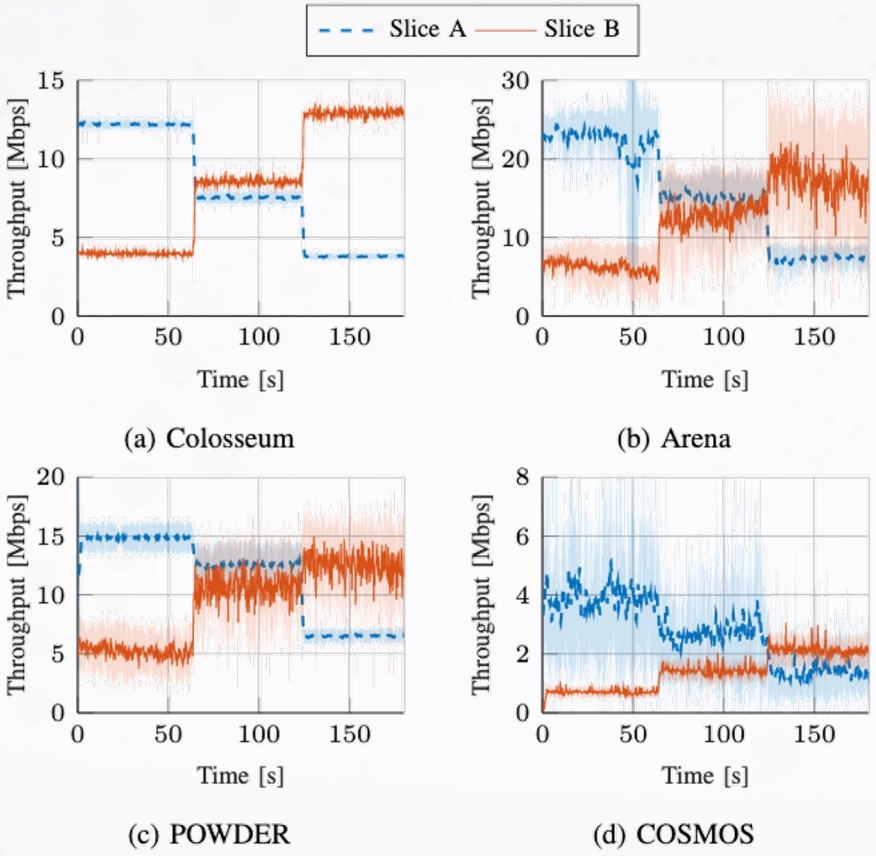
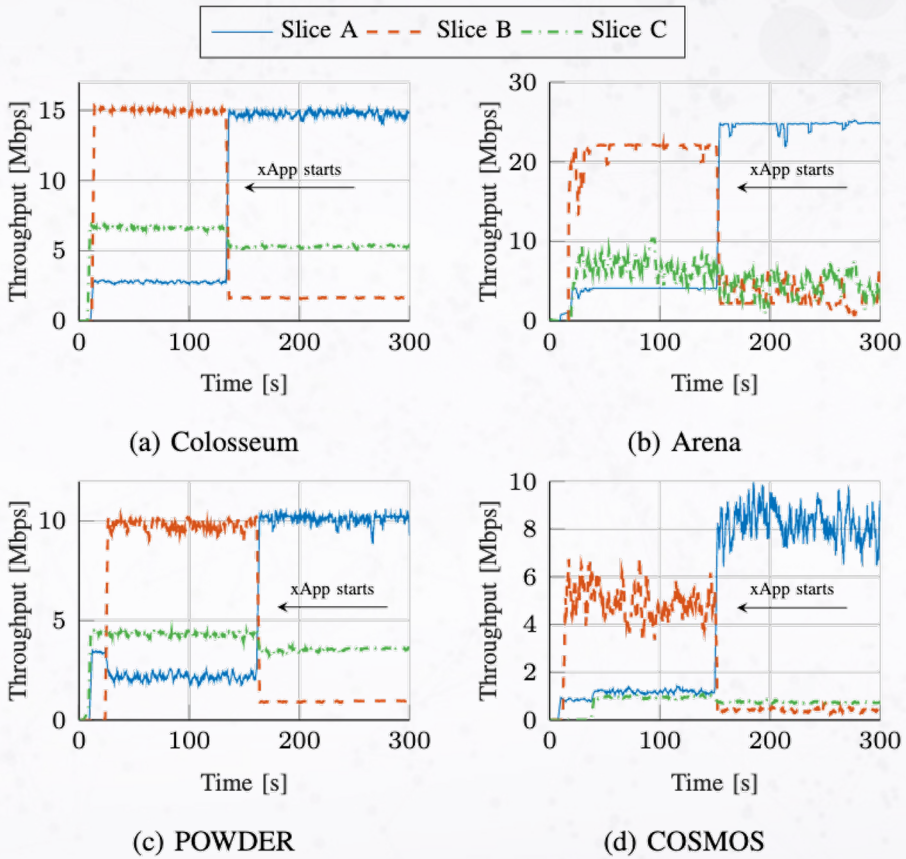
From Colosseum to PAWR

Periodic change of slicing resources



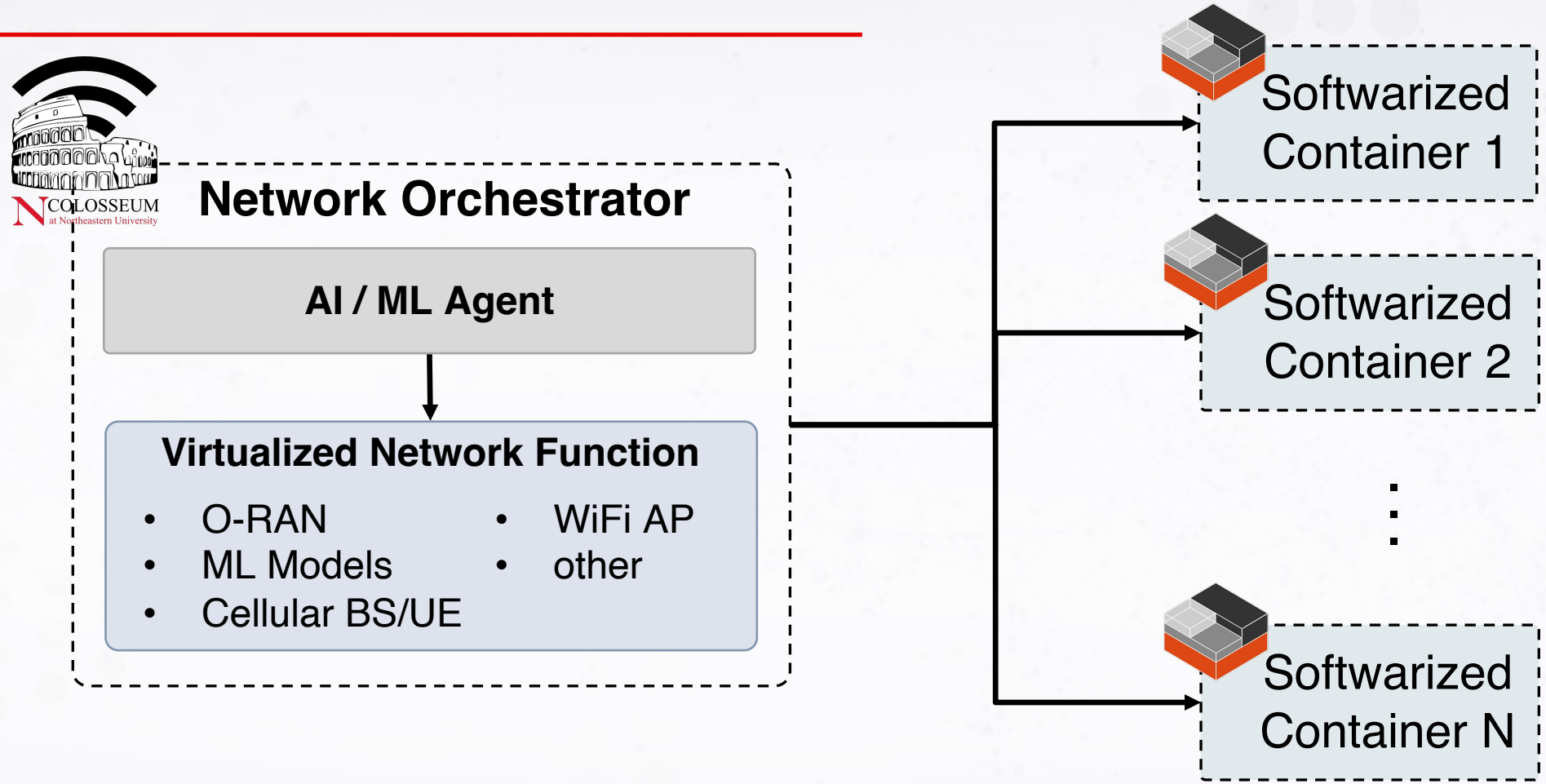
xApp closed-control loop



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

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

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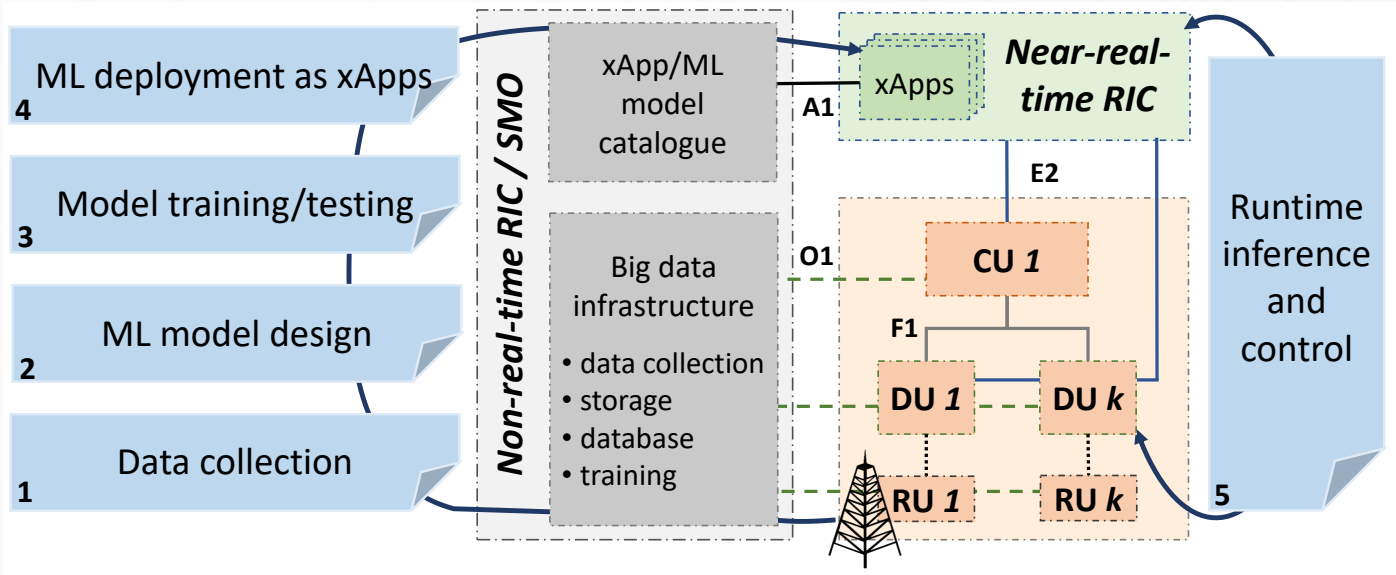
OpenRAN Gym

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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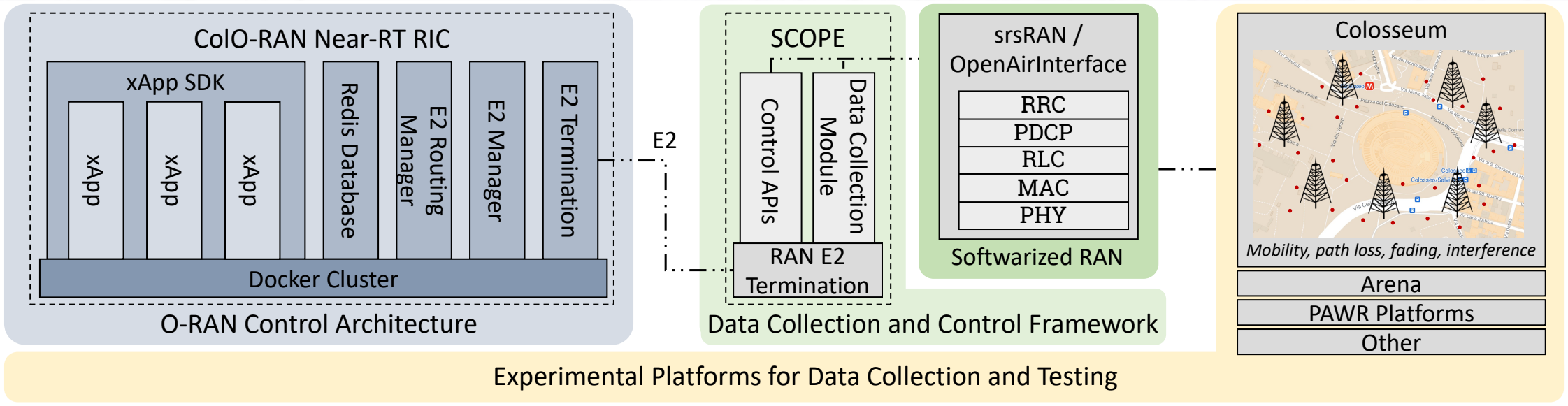
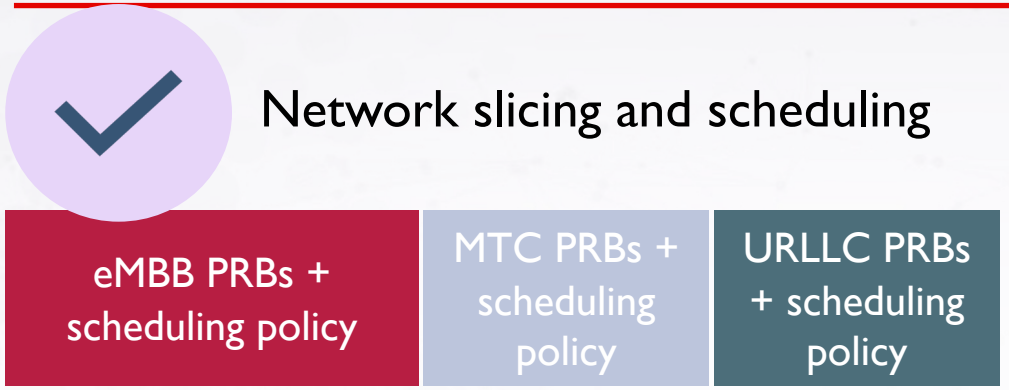
OpenRAN Gym Components

- 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)

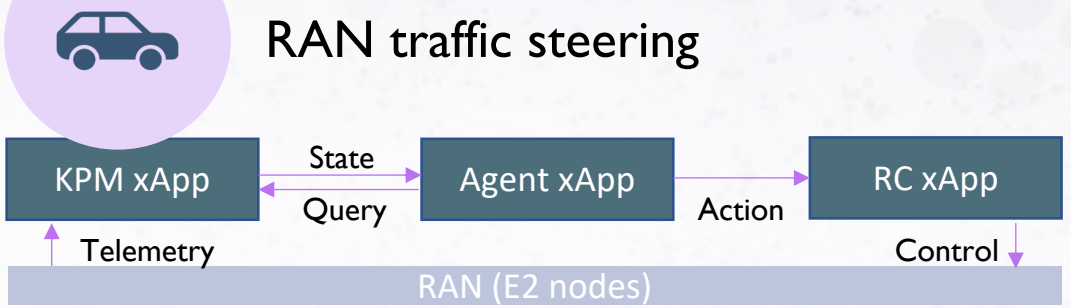


Developing Open, Programmable, and Intelligent Networks

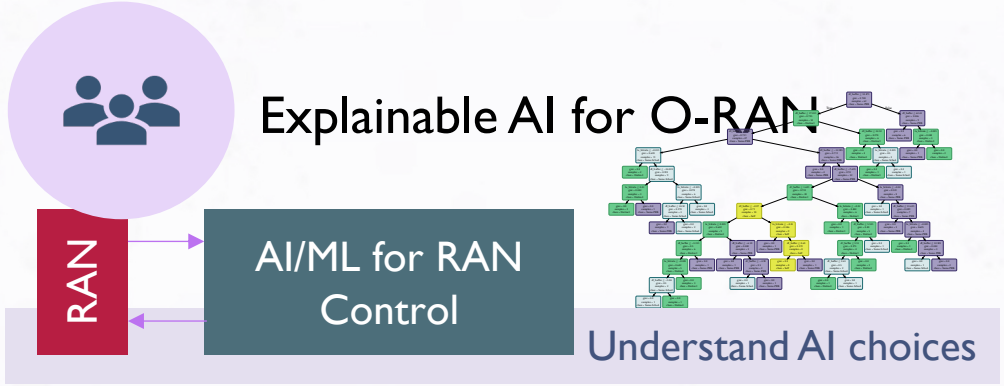
Network slicing and scheduling



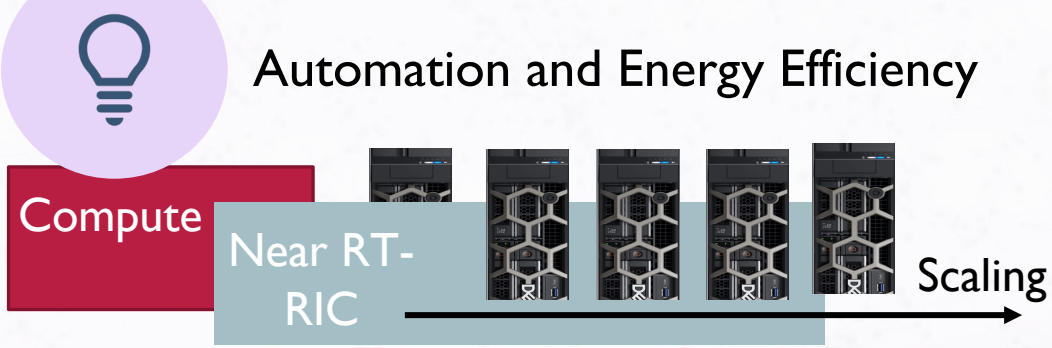
RAN traffic steering



Explainable AI for O-RAN



Automation and Energy Efficiency



dApps – closing the real-time loop in Open RAN

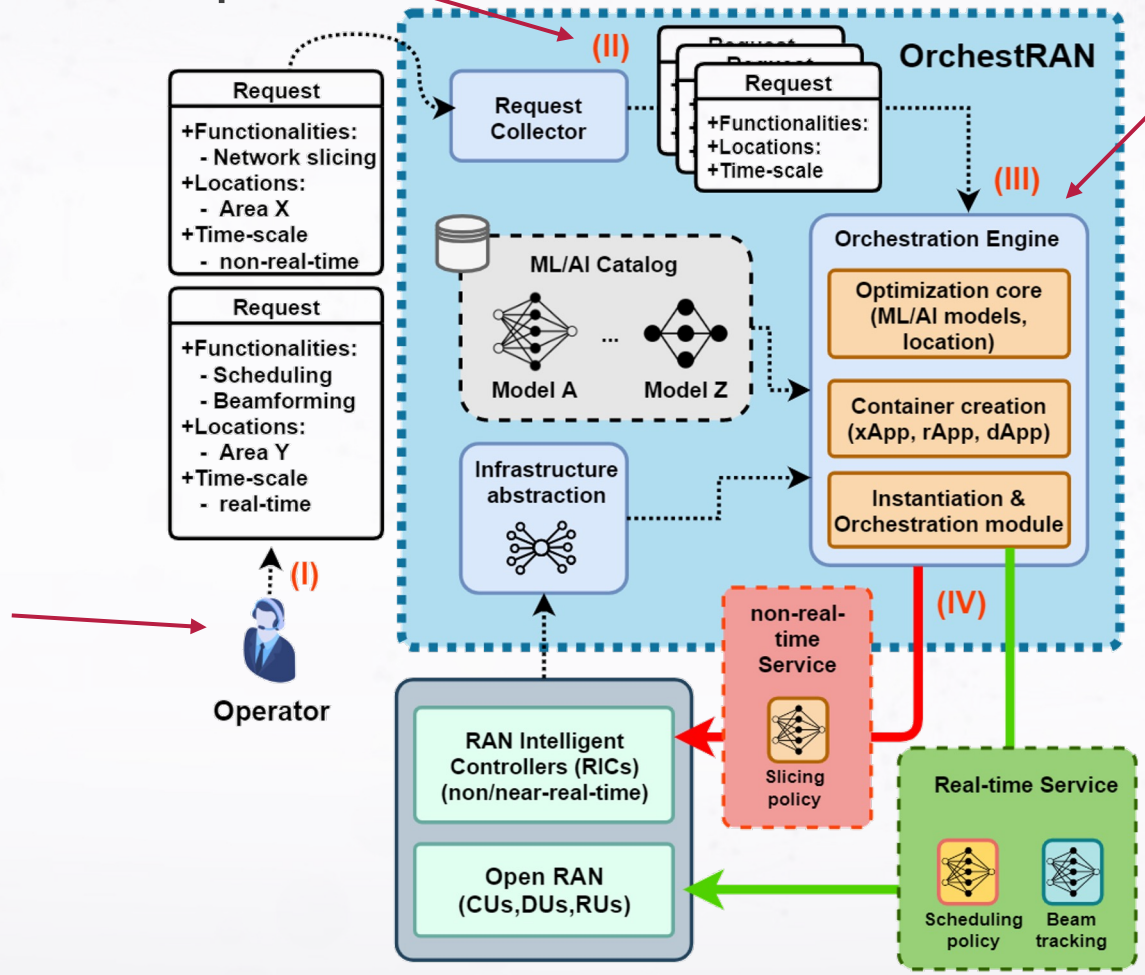
- Programmable elements in DUs and CUs
- Spectrum sharing, beam management, inference on user plane
- Now considered in O-RAN ALLIANCE nGRG

Intelligence Orchestration in Open RAN

(II) Collect requests

(III) Compute orchestration policy

- Which model
- Where and when



(I) Submit request:

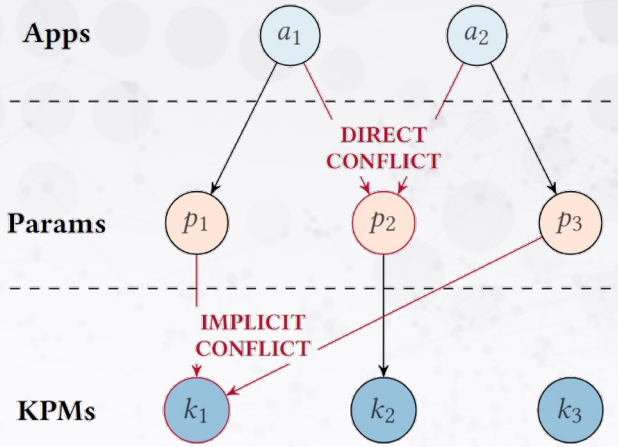
- Functionalities
- Locations
- Time-scale

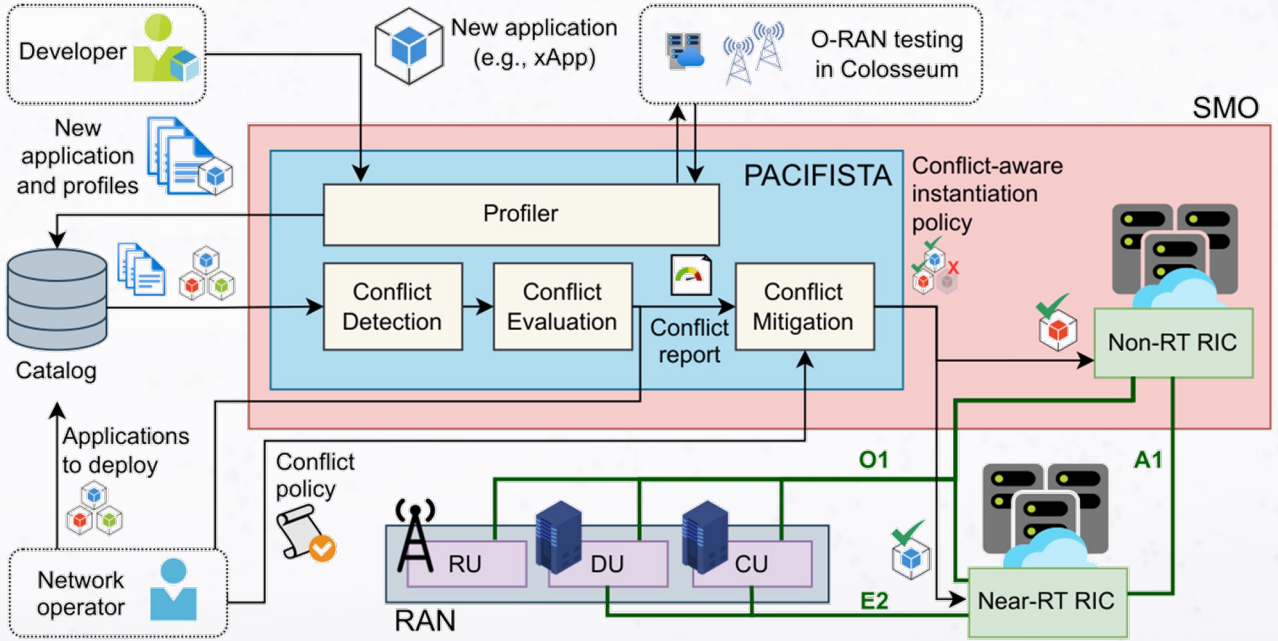
(IV) Deploy intelligence

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



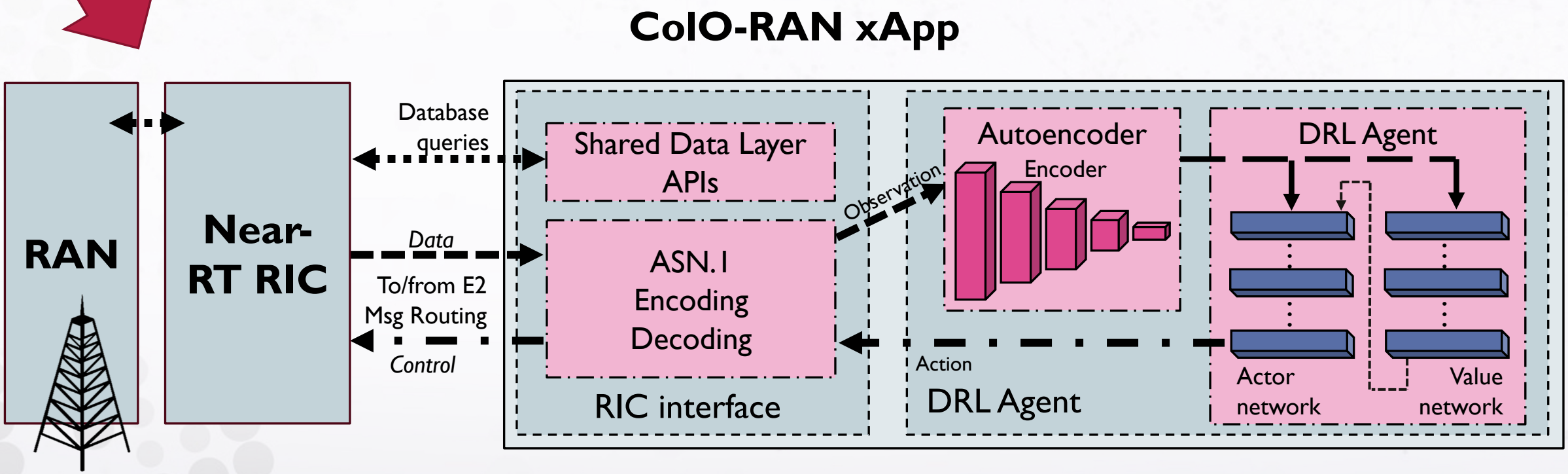


P. Brach del Prever, S. D'Oro, L. Bonati, M. Polese, M. Tsampazi, H. Lehmann, and T. Melodia, "PACIFISTA: Conflict Evaluation and Management in Open RAN" arXiv:2405.04395 [cs.NI], pp. 1-12, May 2024

Design and Testing of DRL Control in Open RAN

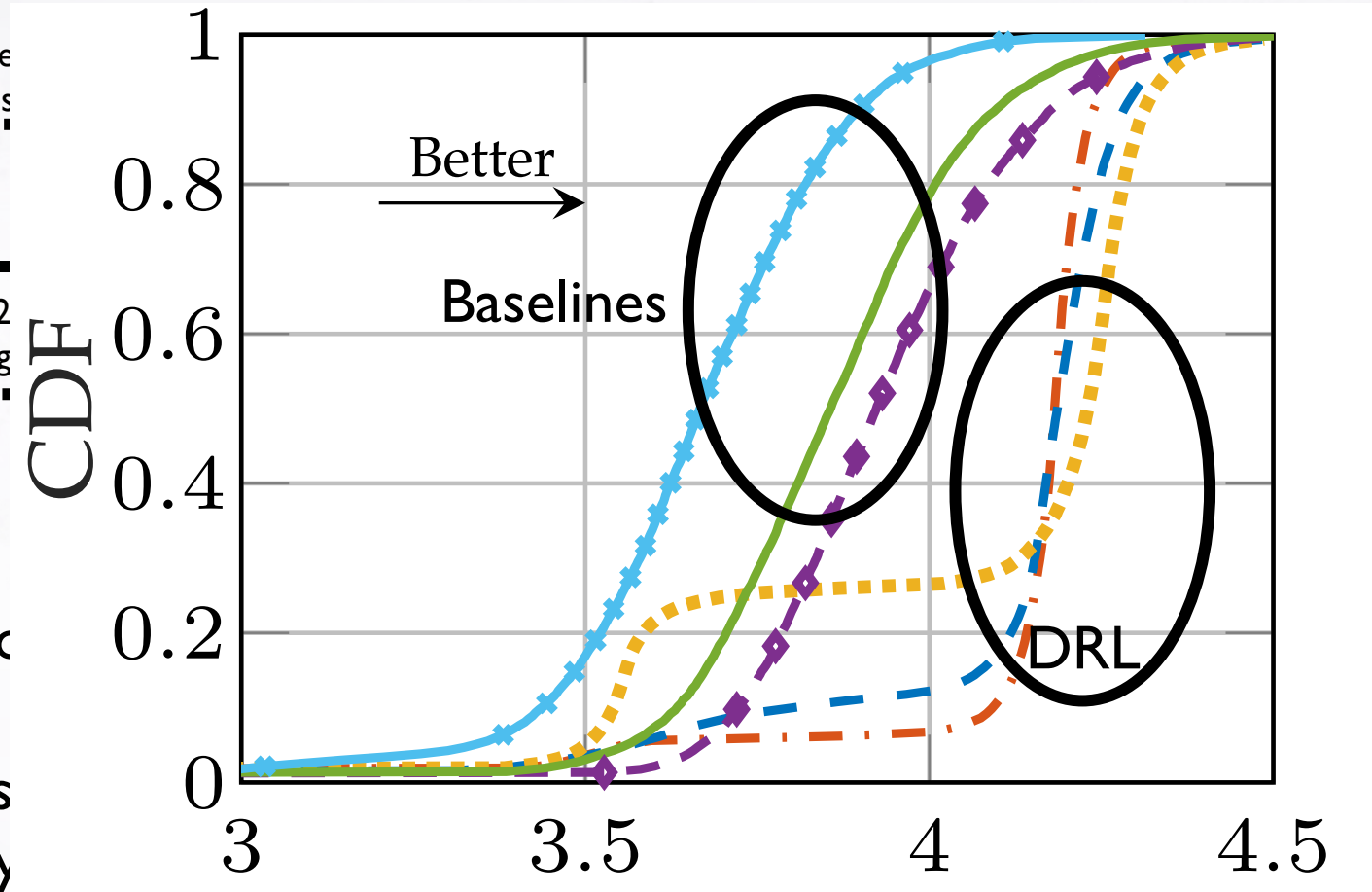
Dataset available: openrangym.com

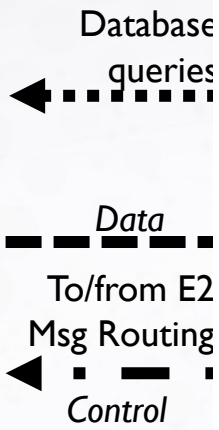
AI/ML that generalizes to different deployments and scenarios

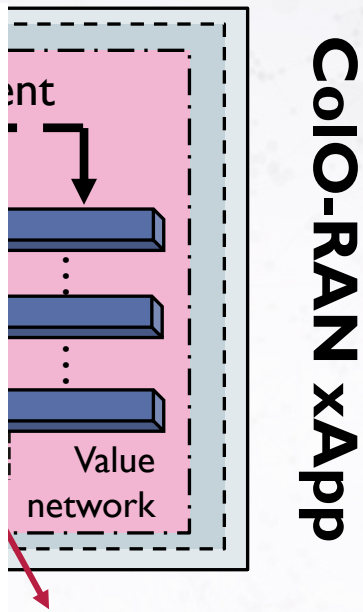


M. Polese, L. Bonati, S. D'Oro, S. Basagni, and T. Melodia, "ColO-RAN: Developing Machine Learning-based xApps for Open RAN Closed-loop Control on Programmable Experimental Platforms", IEEE TMC

Agent Design – Toward Deploying DRL on the RAN







- Generate a cc l 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

- 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

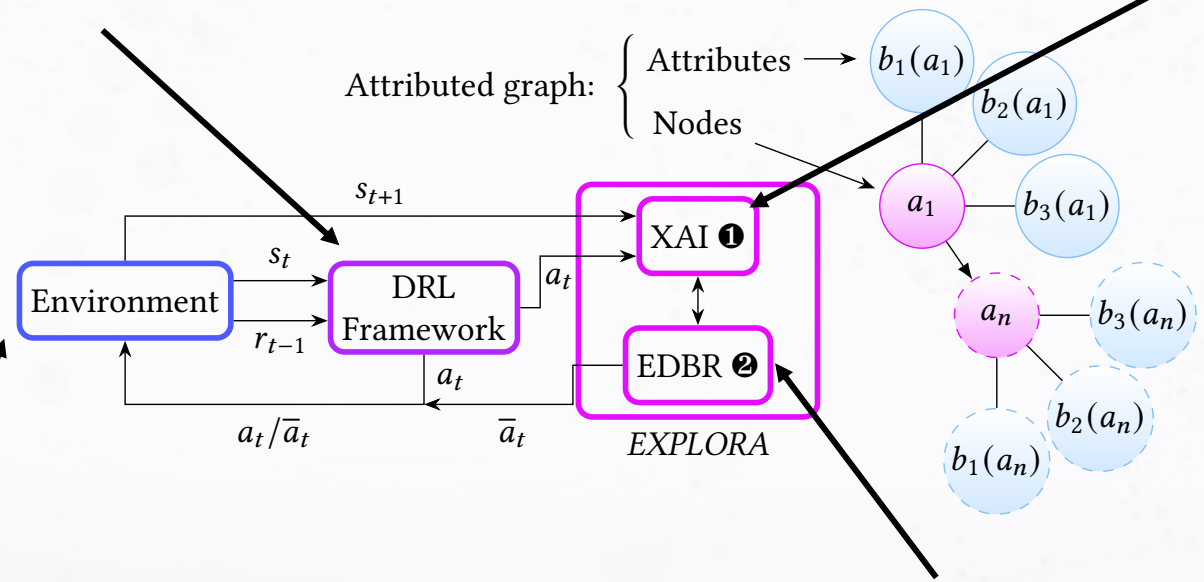
- Challenge: complex input/output relationship (problem for state-of-the-art methods, e.g., SHAP)
- Challenge: memory makes system non-linear
- Challenge: multi-modal control

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

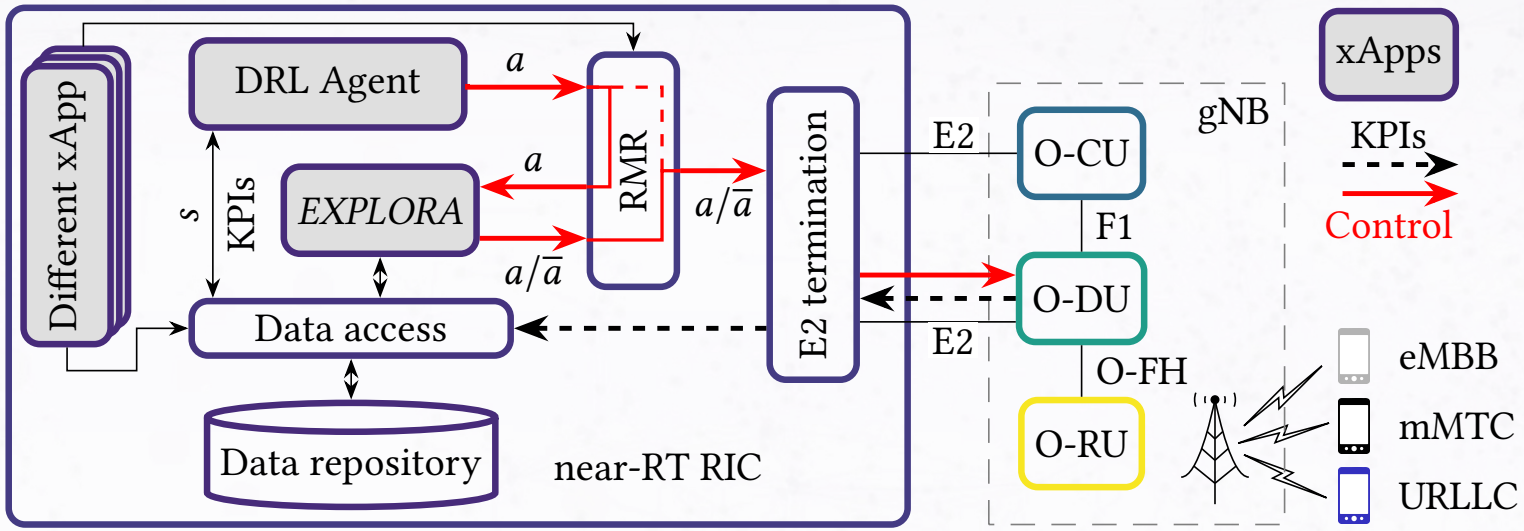
XAI:

- 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

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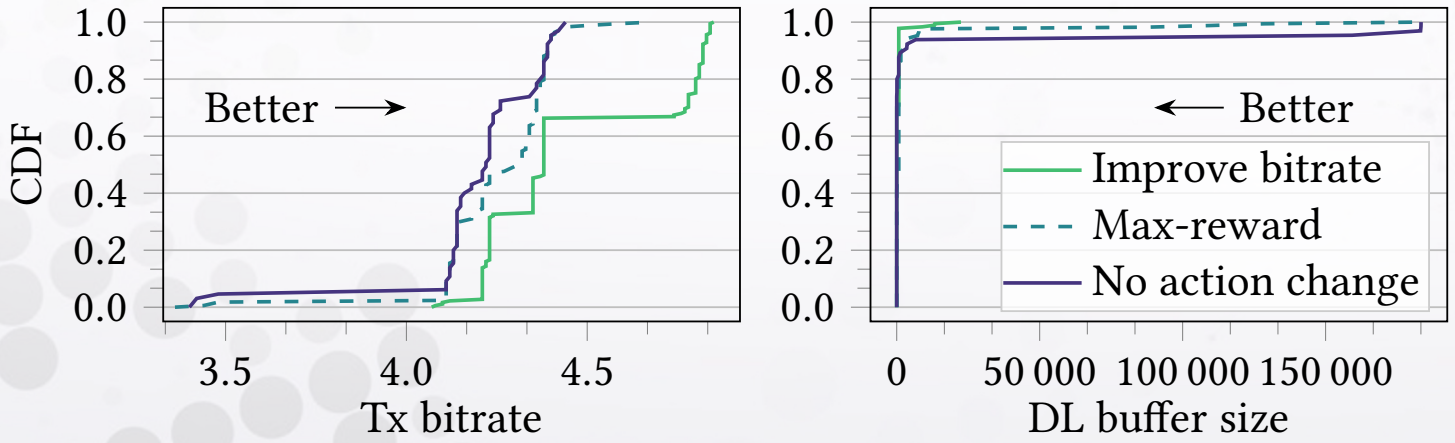
EXPLORA: Explanations and Action Steering

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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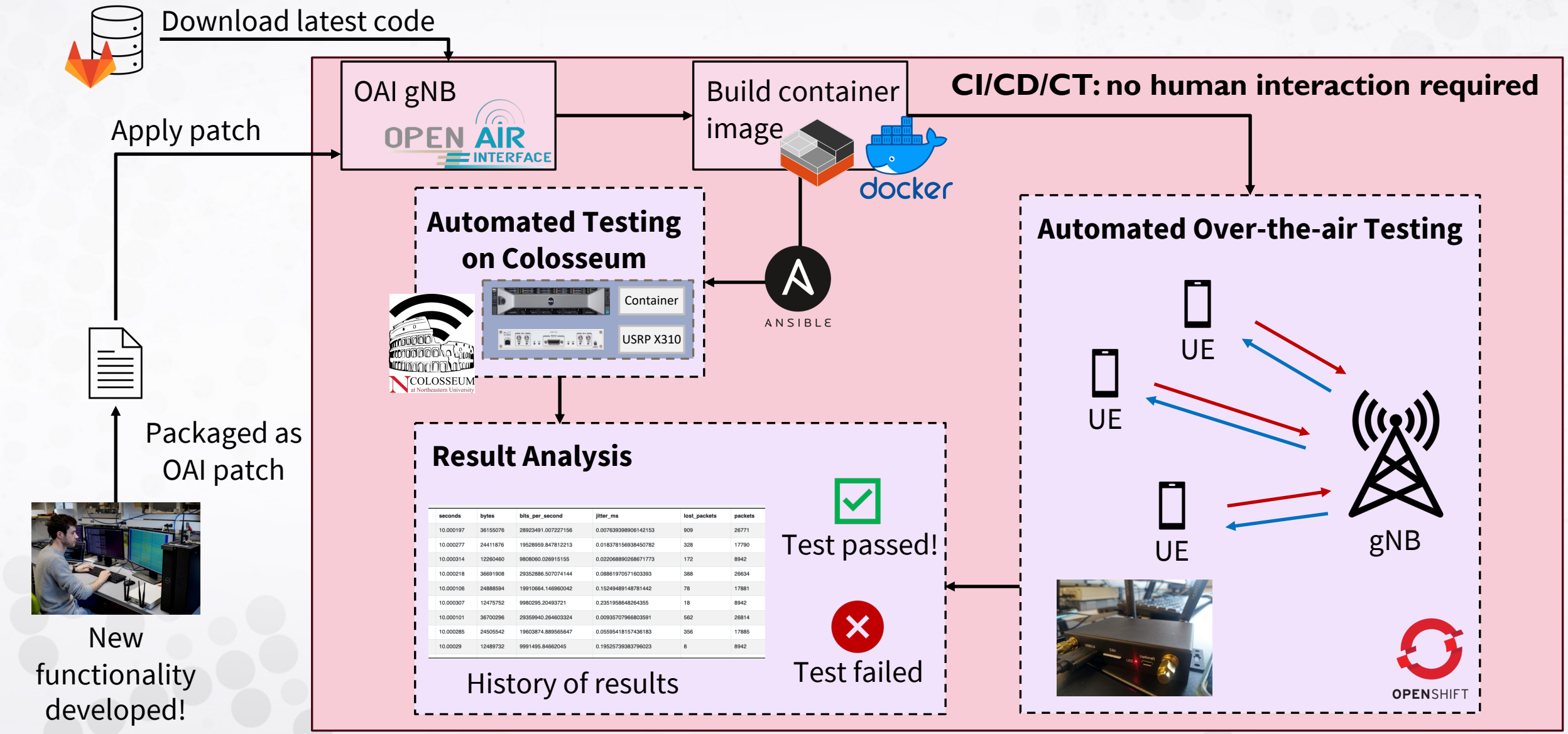
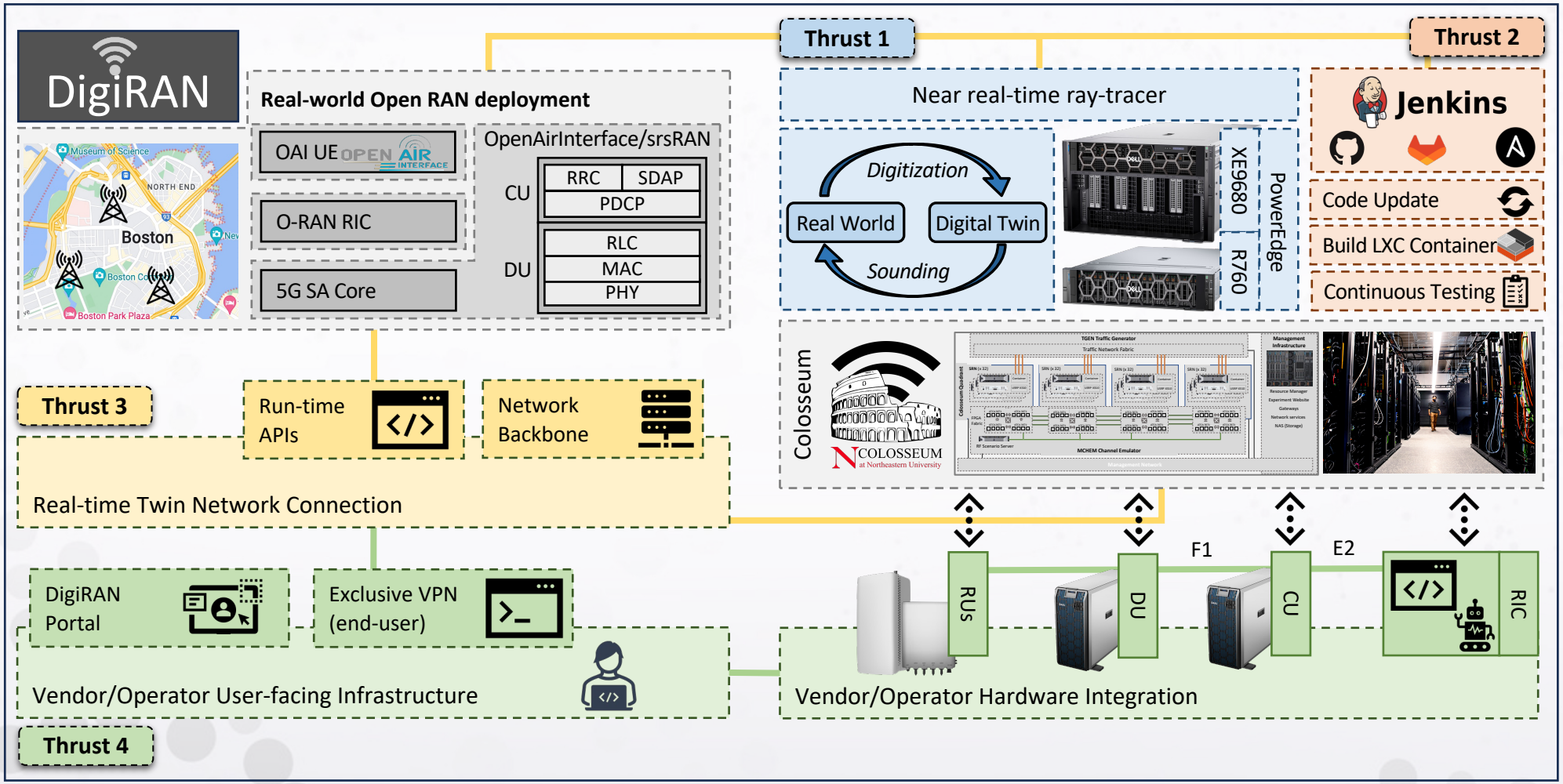
Automated Testing of New Functionality



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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The Colosseum Team

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at Northeastern University

Team (PIs)

Tommaso Melodia
Principal Investigator

Stefano Basagni
Director of Outreach

Kaushik Chowdhury
Co-PI

Abhimanyu (Manu) Gosain
Co-PI

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Team (continued)

Northeastern Team

- Leonardo Bonati
- Davide Villa
- Michele Polese
- Pedram Johari
- Salvatore D'Oro
- Andrea Lacava
- Miead Tehrani Moayyed
- Joshua Groen
- Gabriele Gemmi
- Sakthivel Velumani

Cerbo.io Team

- Michael Seltser
- Ajeet Bagga
- Ventz Petkov
- Paresh Patel

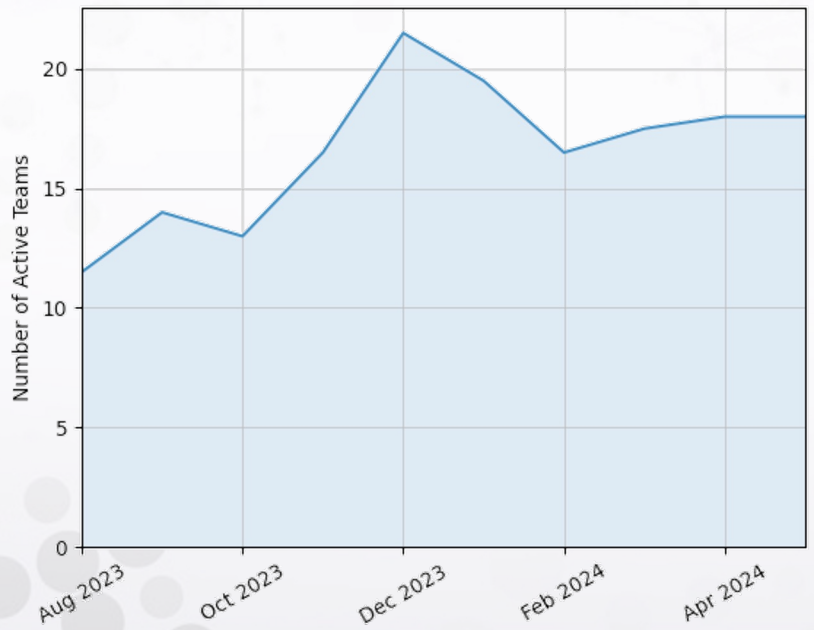
Consultants

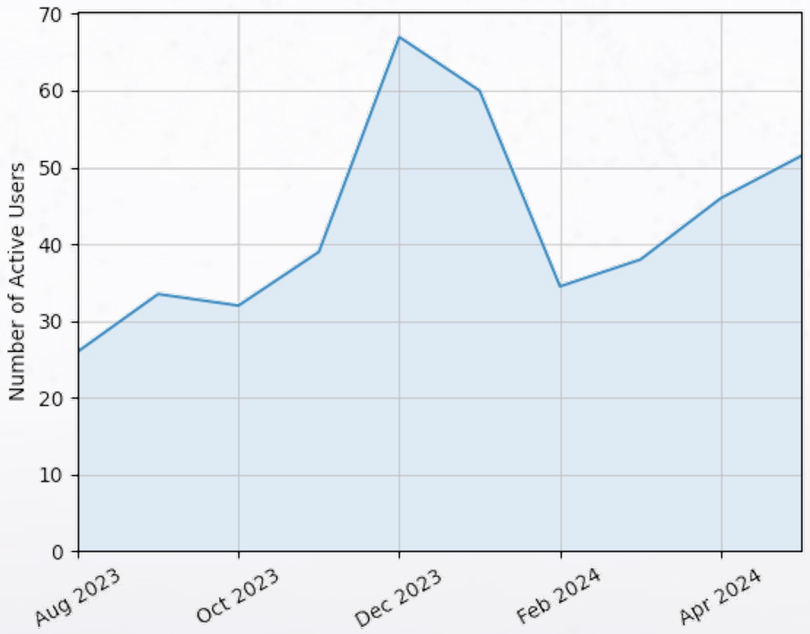
- Kurt Yoder

Colosseum Stats (May 2024)

Colosseum is used by 115 teams and 570 users from:

- 79 academic institutions
- 13 companies (large and small)
- 9 government research laboratories





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Thank You! Q&A

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