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at Northeastern University

Platforms for Advanced Wireless Research

PAWR + Colosseum: Federating Physical and Virtual Wireless Testbeds to accelerate 5G and Beyond Research

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Slices-RI Summer School
07/20/2022

COLOSSEUM
at Northeastern University

Team (PIs)

Tommaso Melodia

Principal Investigator

Tommaso serves as the project Principal Investigator, with responsibilities of overall project leadership, coordination, outlining new research directions, and evolution of the capabilities of Colosseum.

Stefano Basagni

Co-PI

Stefano serves as Director of Community Outreach and Engagement. His responsibilities include coordinating with the communities of Colosseum stakeholders, event organization and supervision, as well as engaging the Colosseum community for feedback and guidelines on continuous development, management and usage of the system.

Kaushik Chowdhury

Co-PI

Kaushik serves as Director of Research Planning. He is responsible of managing the capabilities of the system concerning external access for research. He is also involved in Colosseum enhancements for supporting advanced studies on machine learning in wireless.

Abhimanyu (Manu) Gosain

Co-PI

Manu Gosain serves as the project manager for the Colosseum team. He manages engagement with Academic, Industry, SME, and federal agency users to customize research topics and deployment on Colosseum. He also serves as the main interface with PAWR platforms for consistence and integration of the experimenter frameworks.

Team (continued)

Northeastern Team

- Leonardo Bonati
- Salvatore D'Oro
- Pedram Johari
- Francesco Restuccia
- Subhramoy Mohanti
- Miead Tehrani Moayyed
- Chineye Tassie
- Michele Polese

DevOps Team

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

Technical Consultants

- Kurt Yoder
- Mario Jao-Ng

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PAWR is a public-private partnership funded by the National Science Foundation and 35 leading companies

A $100M program started by the **National Science Foundation** to create four city-scale testbeds for the purpose of accelerating fundamental research on wireless communications and networking technologies.

Researchers	Industry	Smart & Connected Communities
Enhance research efforts in line with national priorities and speed up the transfer rate from university lab to industry end users.	Accelerate potentially disruptive new technologies and speed time to market through an expanded pool of experts and resources.	Build core wireless capabilities through creative partnerships, attract funding and local jobs, and use advanced capabilities to enhance city services.

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Platforms for Advanced Wireless Research

NEW NATIONAL RESOURCE FOR WIRELESS SYSTEMS RESEARCH

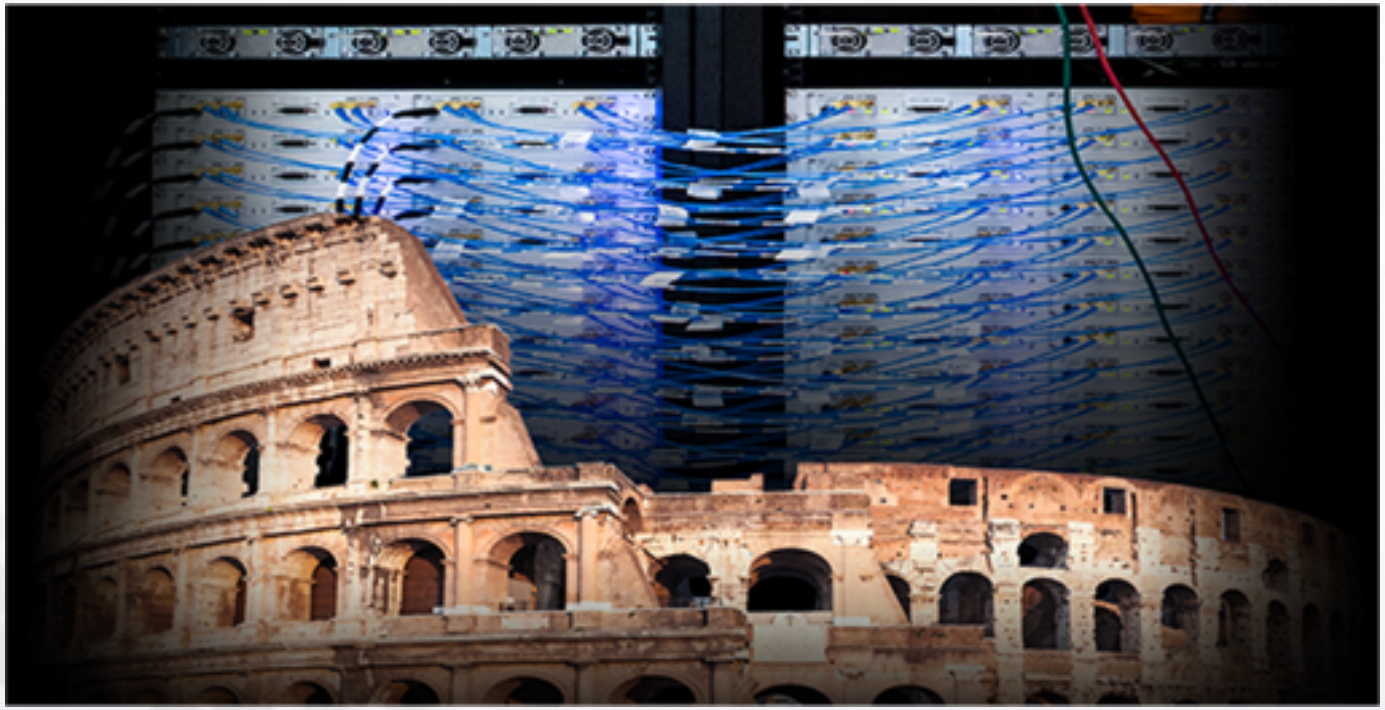
- Colosseum, a massive $20M wireless systems testbed developed by DARPA, has already been transferred to Northeastern University and is currently up, operational, and open to the NSF community
- Transfer to Northeastern funded by NSF CCRI grant
  - 256 x 256 100 MHz RF channel emulation, 128 Programmable Radio Nodes
  - Computing resources (CPU, GPU, FPGA)
  - Access control and scheduling infrastructure
- Supports remote shared access
  - Spectrum Sharing
  - AI + Wireless
  - 5G (softwarization, slicing, security)
  - IoT

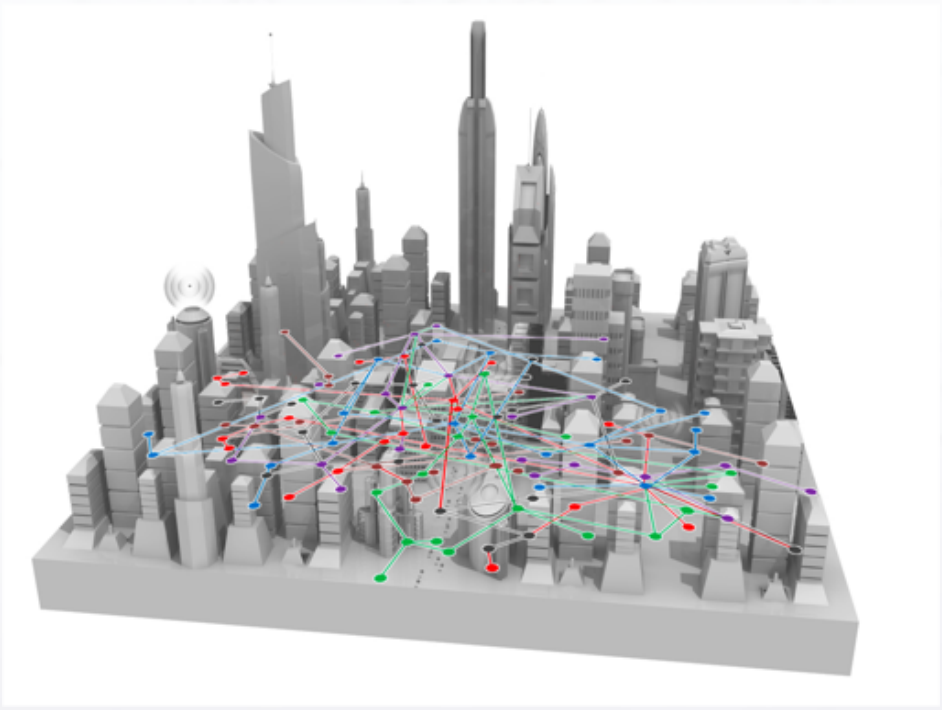
COLOSSEUM: Much More Than a Supercomputer

- Colosseum has RF hardware in the loop
- Not only a simulation environment: real-time emulation with real wireless signals and emulated channels
- Combines in a SINGLE instrument
  - Fidelity of hardware channel emulators
  - Flexibility of a virtualized data center,
  - Scale of a network simulator
- Fully programmable
- $20M+ investment by DARPA
- $6M investment by NSF
- $2M investment by Northeastern

COLOSSEUM: The World's Largest Wireless Emulator

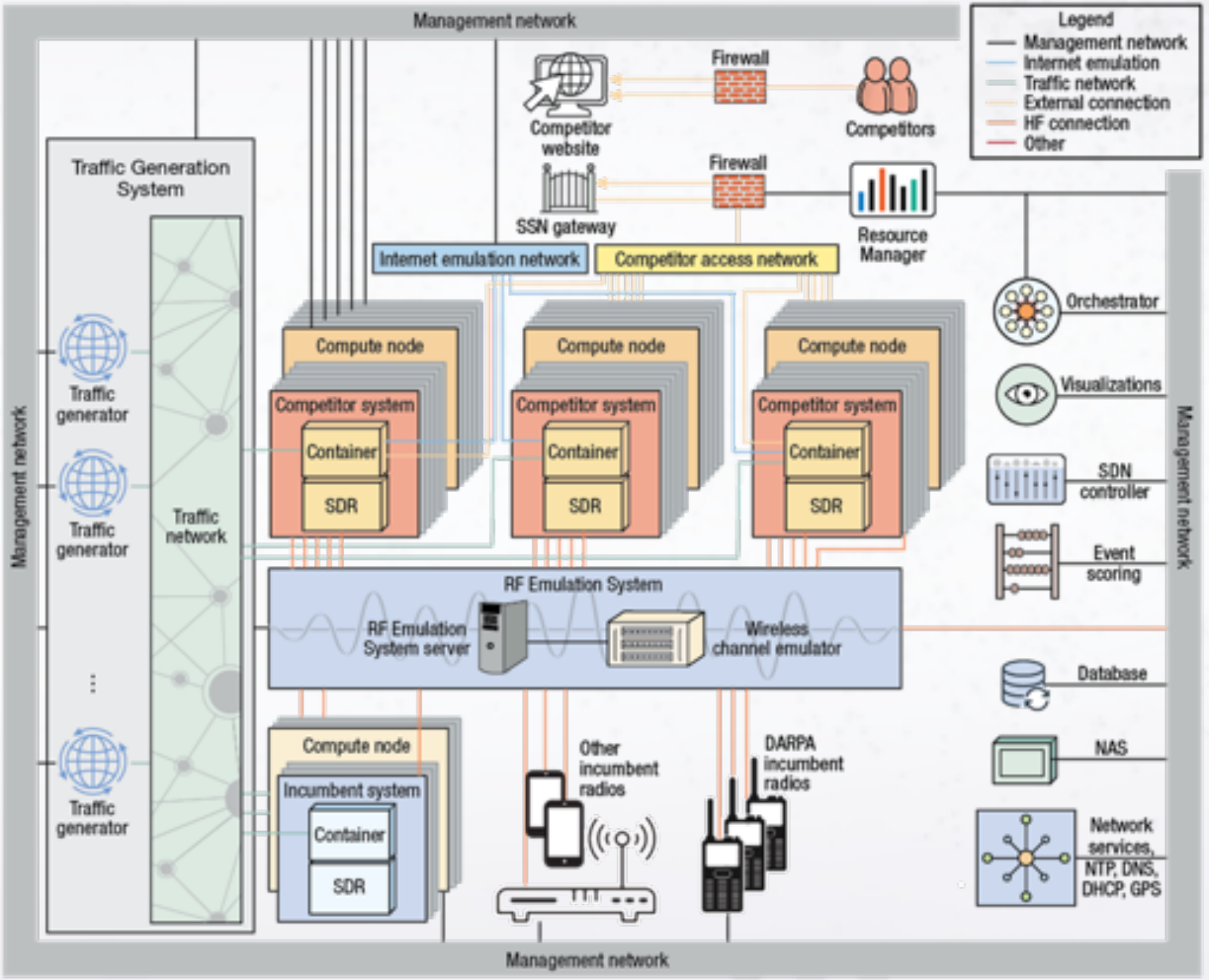
- 256 software defined radios (fully programmable)
- Fabric of field programmable gate arrays - > 65k channels emulated in real time
- 128 servers w/ hardware in the loop, remotely available for user experiments
- Diversified scenarios for better generalization of ML / AI models
- Large-scale experimentation of wireless RF systems with spectrum in the loop





COLOSSEUM Architecture

https://www.spectrumcollaborationchallenge.com/about/technology/



COLOSSEUM: Much More Than a Supercomputer

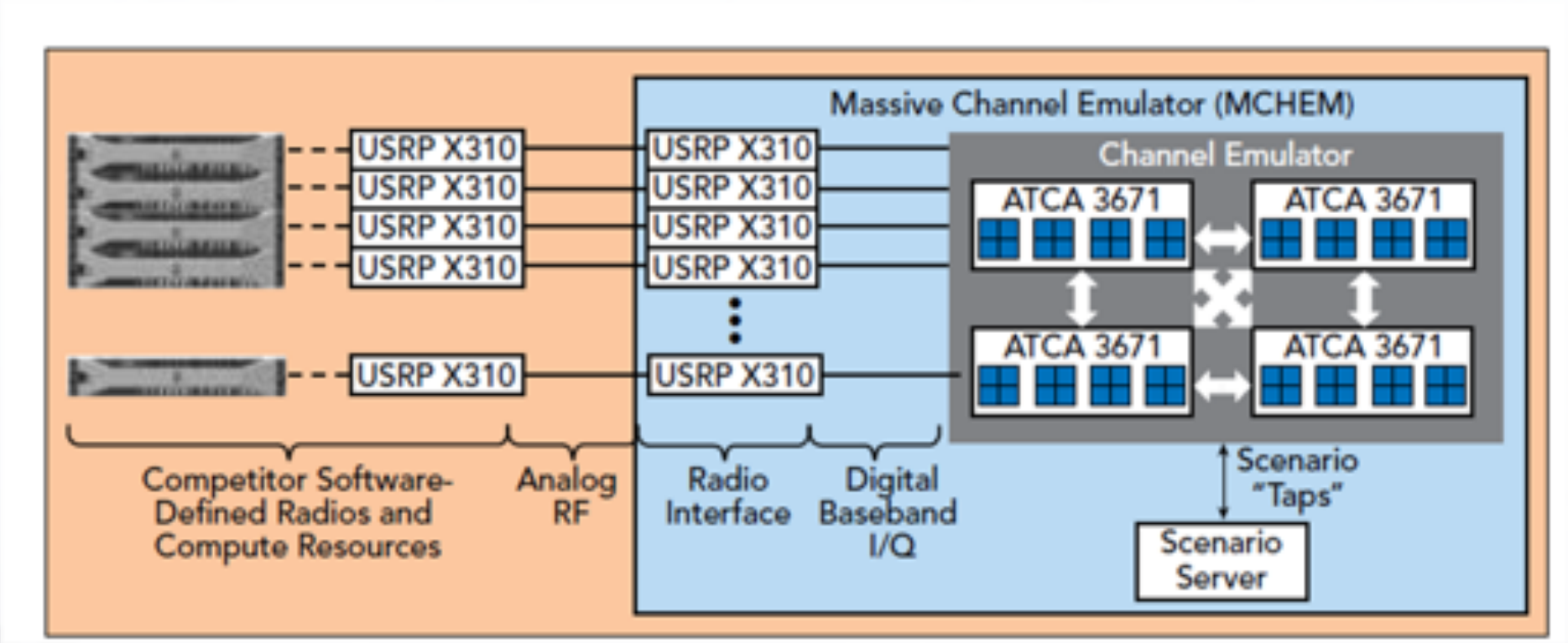
- Colosseum differs from existing supercomputers in that it combines massive RF hardware, and programmable hardware to emulate in real time and with high fidelity complex RF scenarios, including spectrum sharing, radar, etc.

- The complex realistic modeling with RF hardware in the loop enabled by Colosseum is not possible with any of the existing simulation models available on supercomputers

- In Colosseum, RF transmissions are generated by real programmable RF hardware, and RF channels are emulated through a unique fabric of programmable field programmable gate arrays, able to emulate 65k channels between each individual radio pair in real time.

Massive Channel Emulator (MCHEM)

- Emulates in real time channels between 256 independent transmitters (65k channels)
- 512-tap channel model (sparse, 4 nonzero)
- Scenarios



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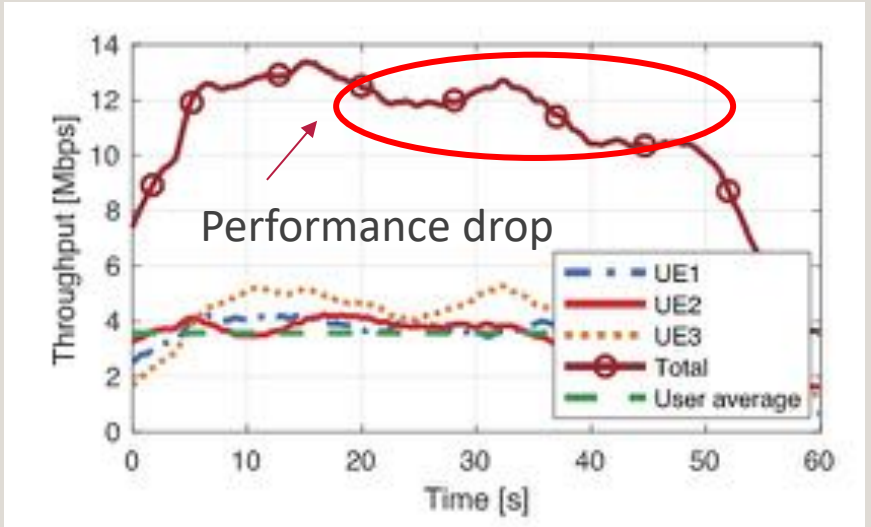
Scenarios – The Colosseum Way

- RF / traffic scenarios are **deterministic**: Experiments w/ same scenario execute the same way
- Will be extended w/ stochastic distributions in the filter taps

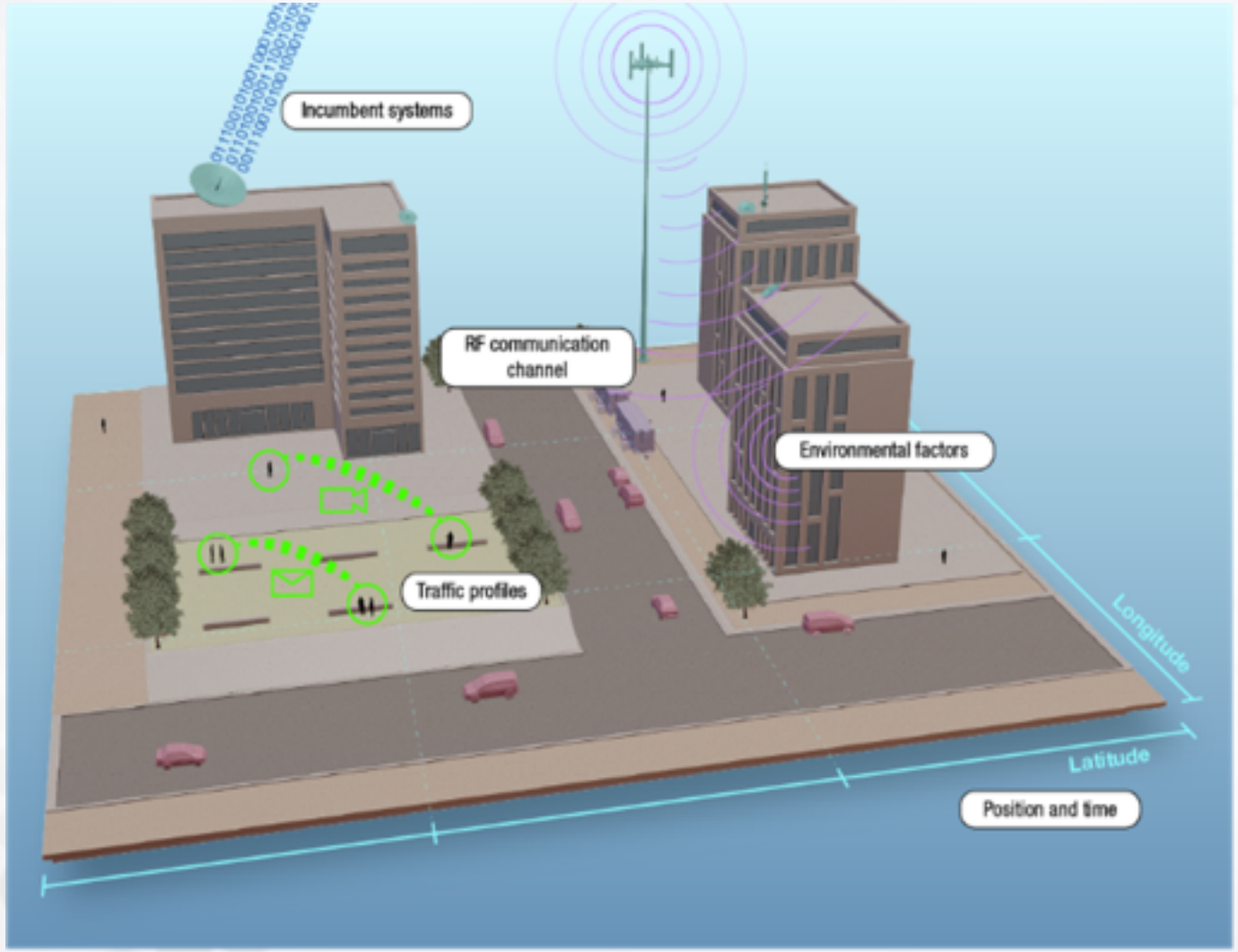
- Colosseum enables:
  - **Full control** over the wireless channel
    - non stationarity in the **distribution**
    - only keep **desired** channel effects
  - **Reproducibility** / **repeatability**
  - **Easy comparison** between algorithms



*Is the performance drop due to the **channel** or **bad algorithm design**?*

An example: performance drop

Example Scenario (Alleys of Austin)



- A platoon from the Texas Army National Guard at Camp Mabry is practicing urban maneuvers and communications in Austin.
  - The platoon is split into five squads consisting of 9 squad members and one UAV.
  - The scenario is designed to run for 930 seconds, with 300 seconds per stage for 900 seconds of competitive time and 15 seconds appended on either end. The scenario

DARPA produced scenario video:
https://youtu.be/0p-b6TZP6DI

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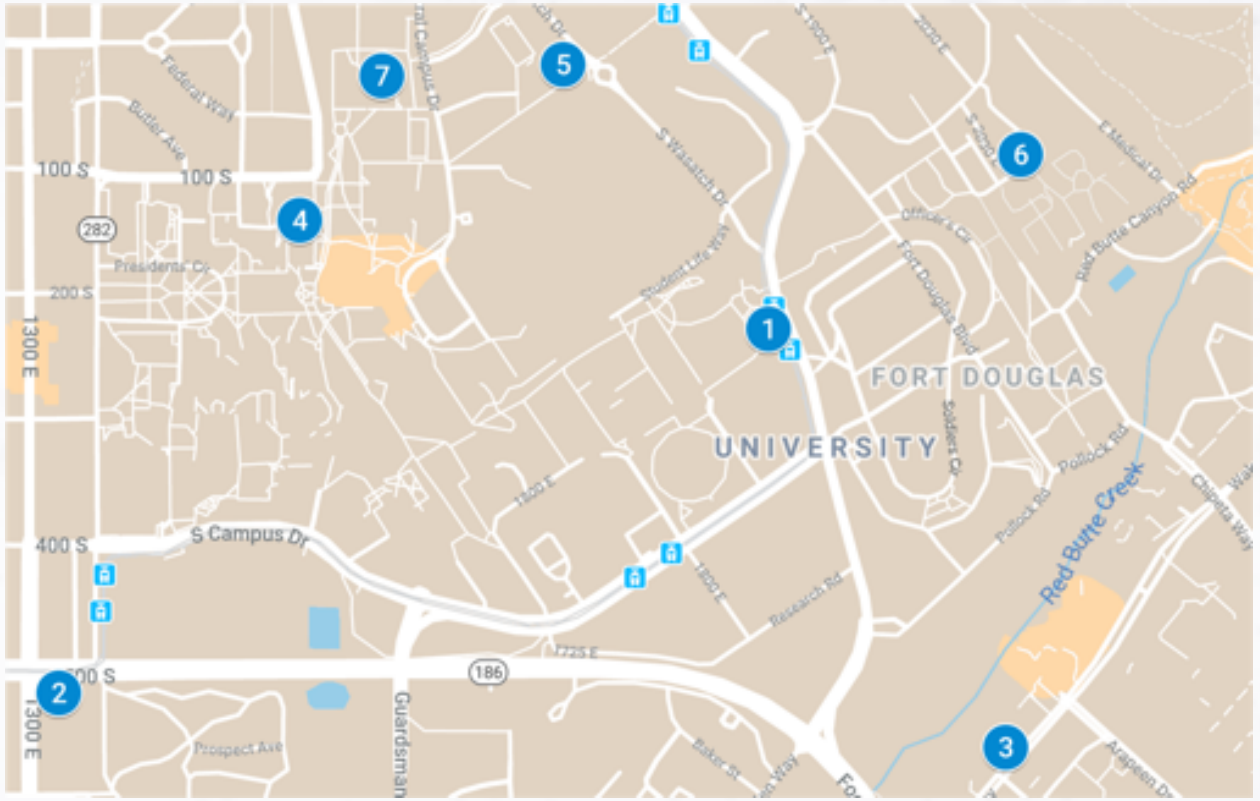
Additional Colosseum 5G Scenarios

Boston Public Garden, Boston, MA



POWDER PAWR – University of Utah Campus, Salt Lake City, UT

* Blue circles represent the base station locations

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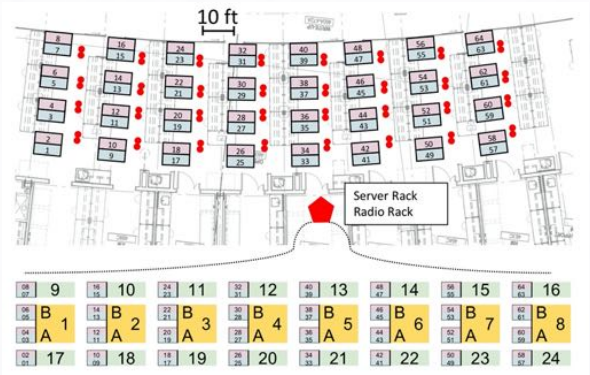
Experiment-as-a-Service Over Multiple Testbeds

One container to rule them all:

- Initial design and testing at-a-scale on Colosseum w/ different scenarios
- Validate on real-world indoor environment on Arena
- Experiment into the wild on PAWR city-scale platforms

Test at-a-scale on emulated scenarios

Validate in real wireless environment



Test large-scale capabilities

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5G And Beyond Use Cases

- Provide an overview of use-cases and applications

- Map your research with what can be done on Colosseum

COLOSSEUM: Serving Diverse Communities

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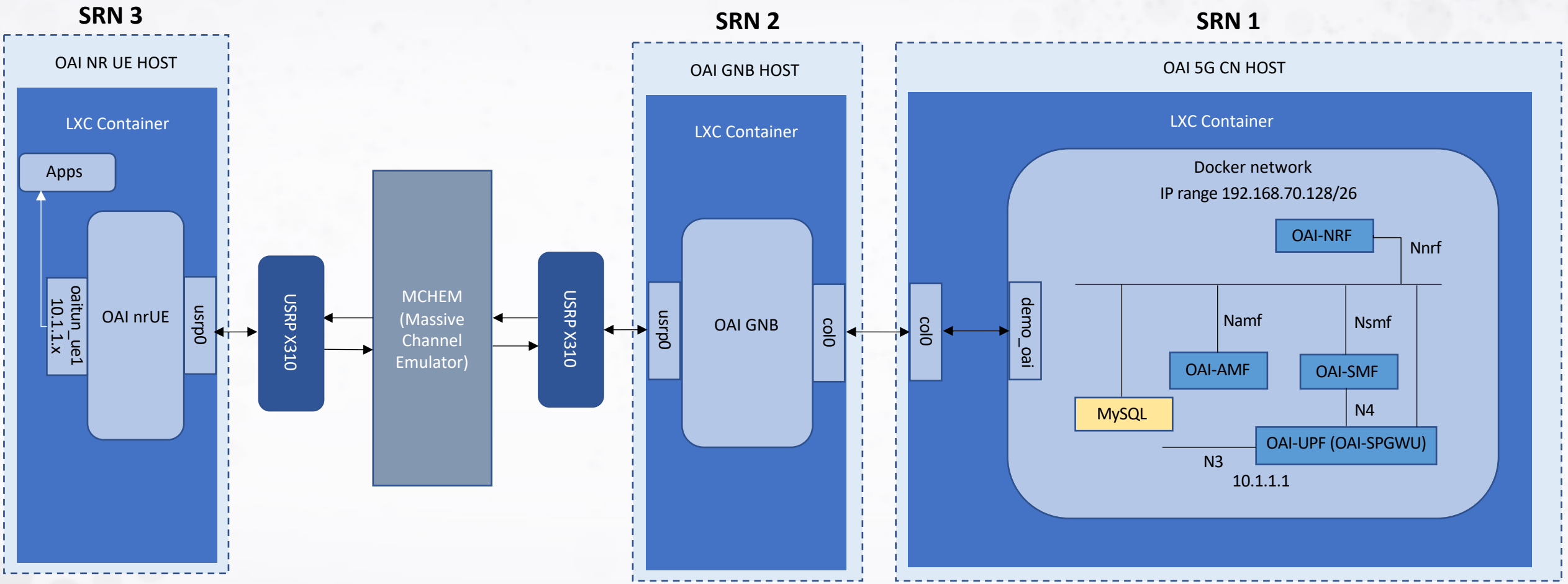
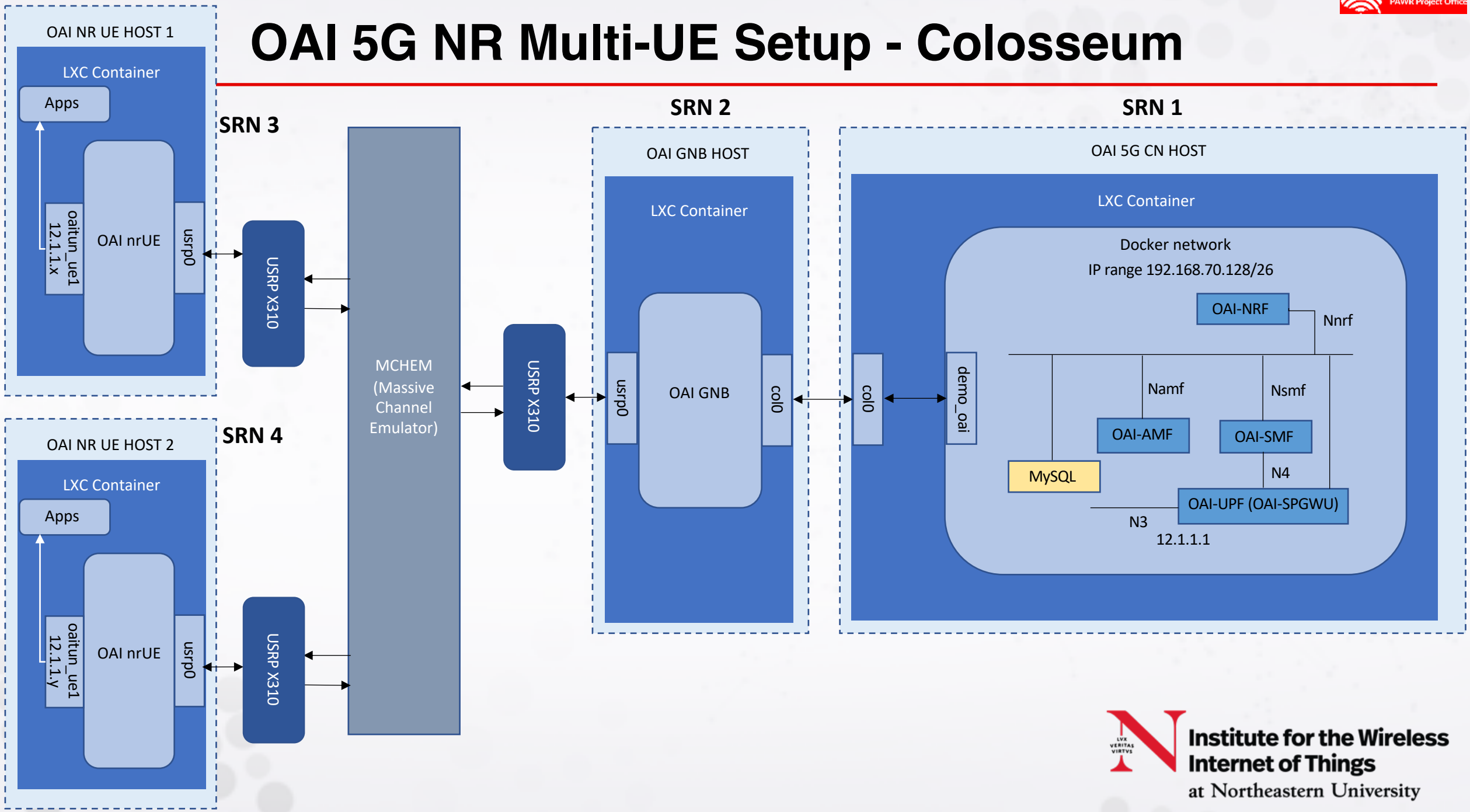
OAI 5G NR SA Setup - Colosseum



OAI 5G NR Multi-UE Setup - Colosseum



PAWR Project Office

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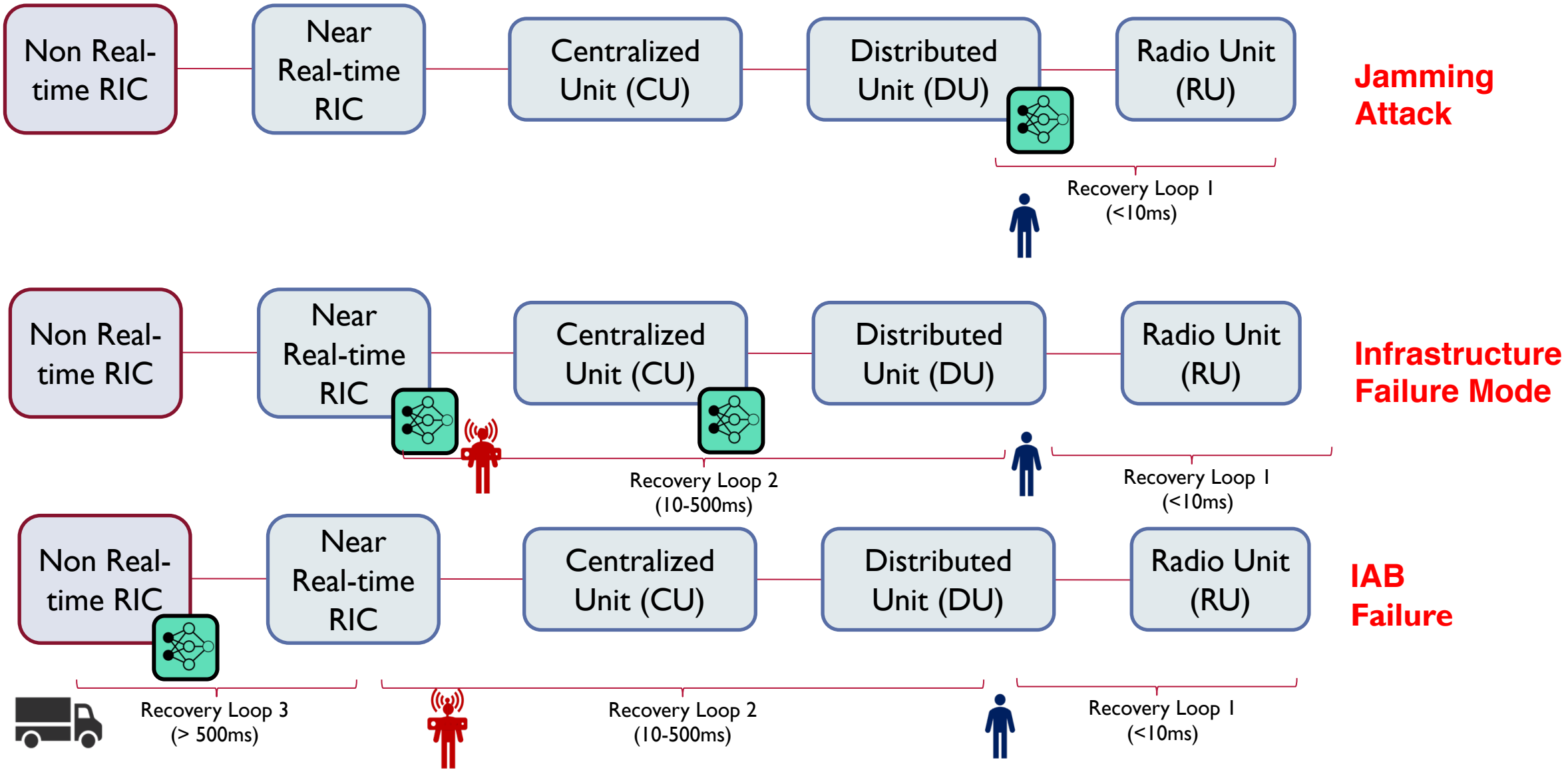
Tactical Edge w/ 5G + O-RAN



OpenRAN Gym

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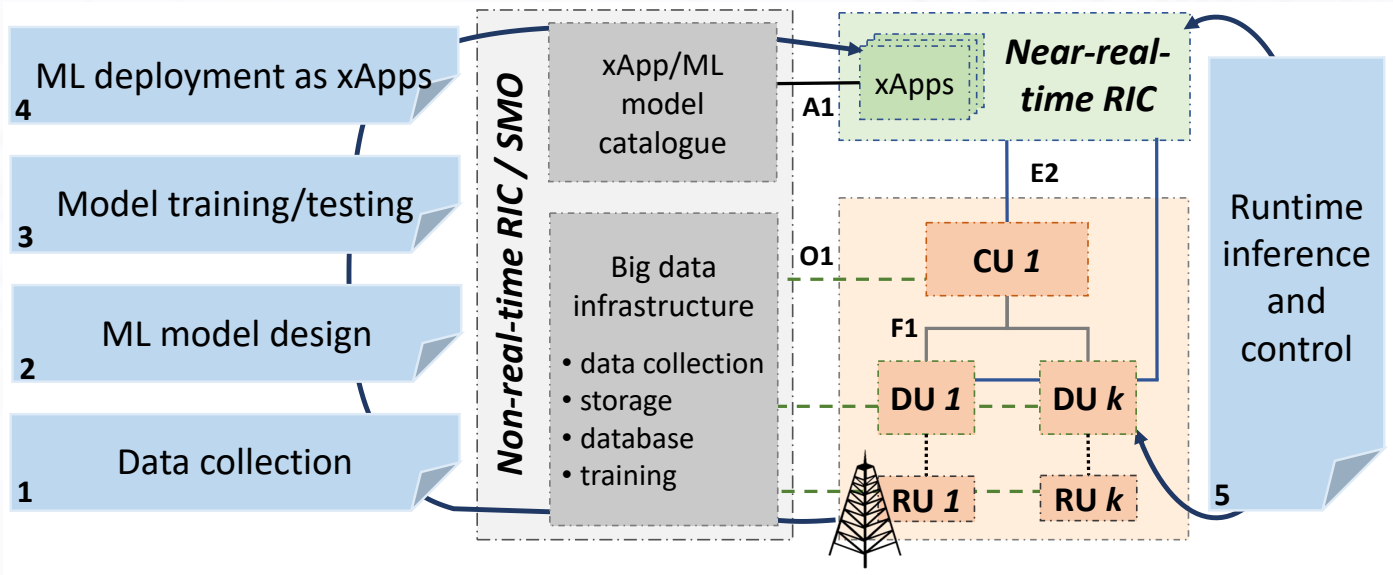
OpenRAN Gym

*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



M. Polese, L. Bonati, S. D'Oro, S. Basagni, T. Melodia, "*ColO-RAN: Developing Machine Learning-based xApps for Open RAN Closed-loop Control on Programmable Experimental Platforms*", arXiv:2112.09559 [cs.NI]

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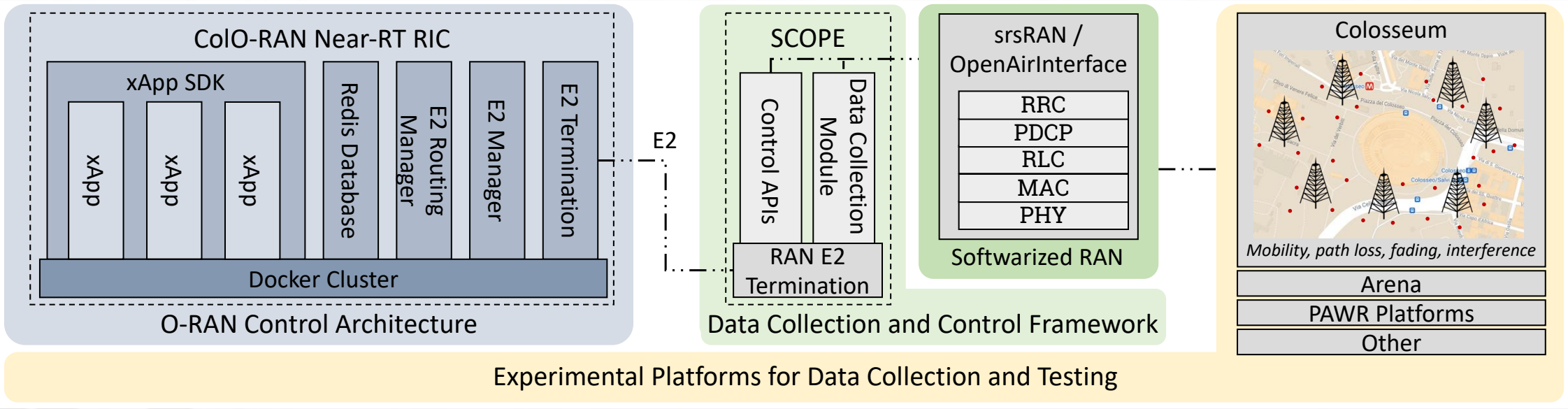
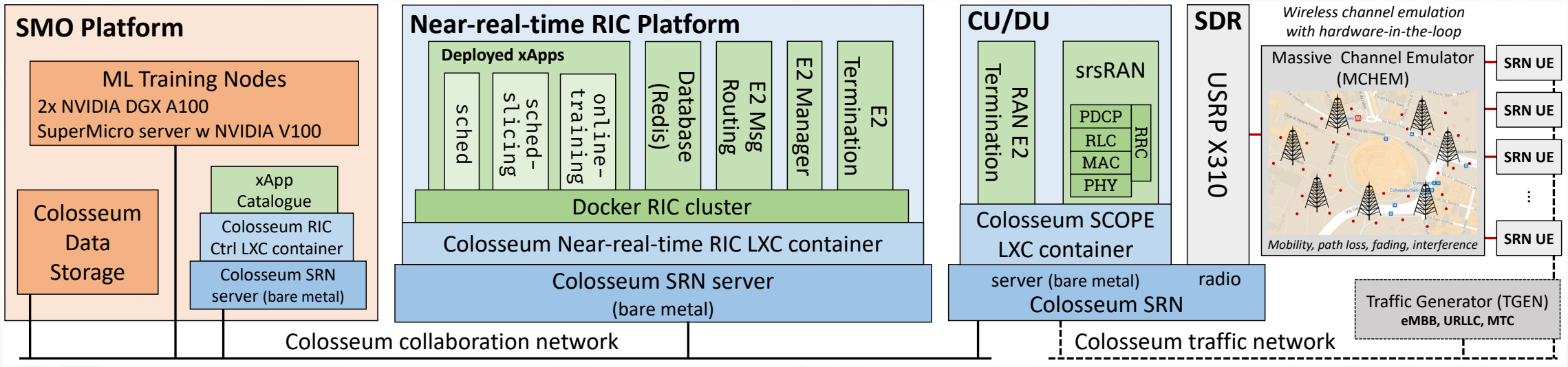
OpenRAN Gym Components

- 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)



O-RAN Near-real-time RIC: ColO-RAN

- O-RAN-compliant implementation of OSC near-real-time RIC, adapted to work on Colosseum
- Runs custom xApps w/ control loops for network control and performance optimization
- Connects to the softwarized RAN through the O-RAN E2 interface



M. Polese, L. Bonati, S. D'Oro, S. Basagni, T. Melodia, "*ColO-RAN: Developing Machine Learning-based xApps for Open RAN Closed-loop Control on Programmable Experimental Platforms*", arXiv:2112.09559 [cs.NI]

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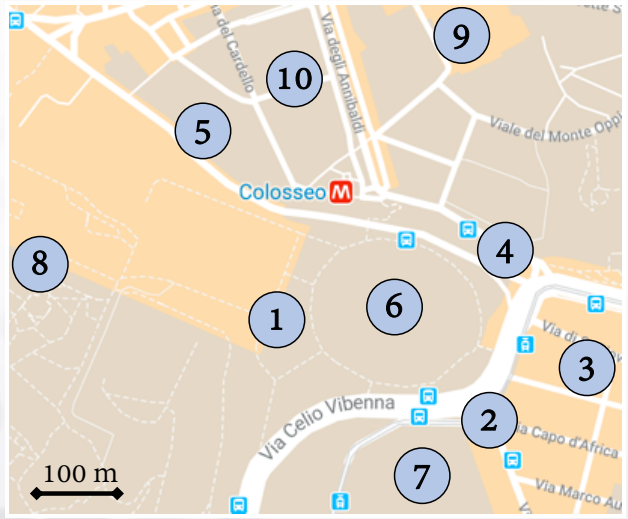
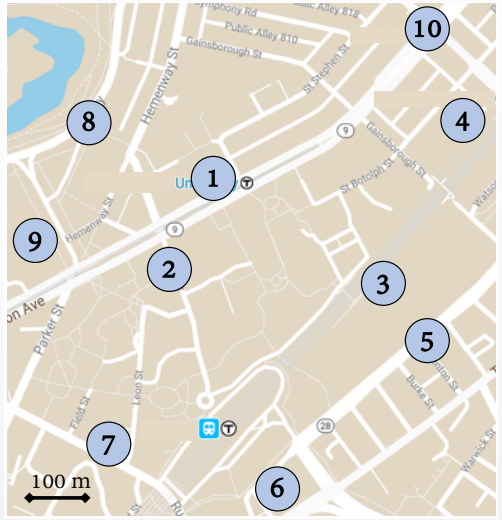
Softwarized RAN & Data Collection Framework: SCOPE

L. Bonati, S. D'Oro, S. Basagni, and T. Melodia, "*SCOPE: An Open and Softwarized Prototyping Platform for NextG Systems,*" in Proceedings of ACM MobiSys, Virtual Conference, June 2021

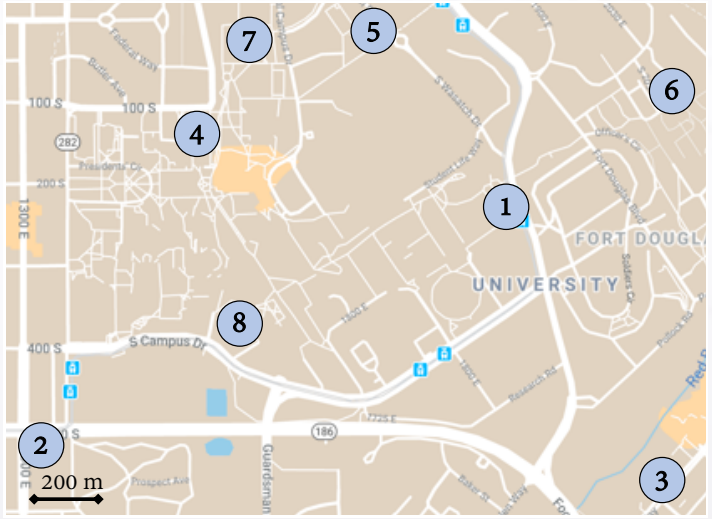
- Data collection and control framework (currently based on srsRAN)
- Paired w/ Colosseum allows to collect data in:
  - Different RF scenarios (specify effects such as path loss, position/distance of BSs/UEs, mobility/speed)
  - Traffic flows and types among nodes
- Exemplary scenarios representative of cellular deployments in:



Rome, Italy

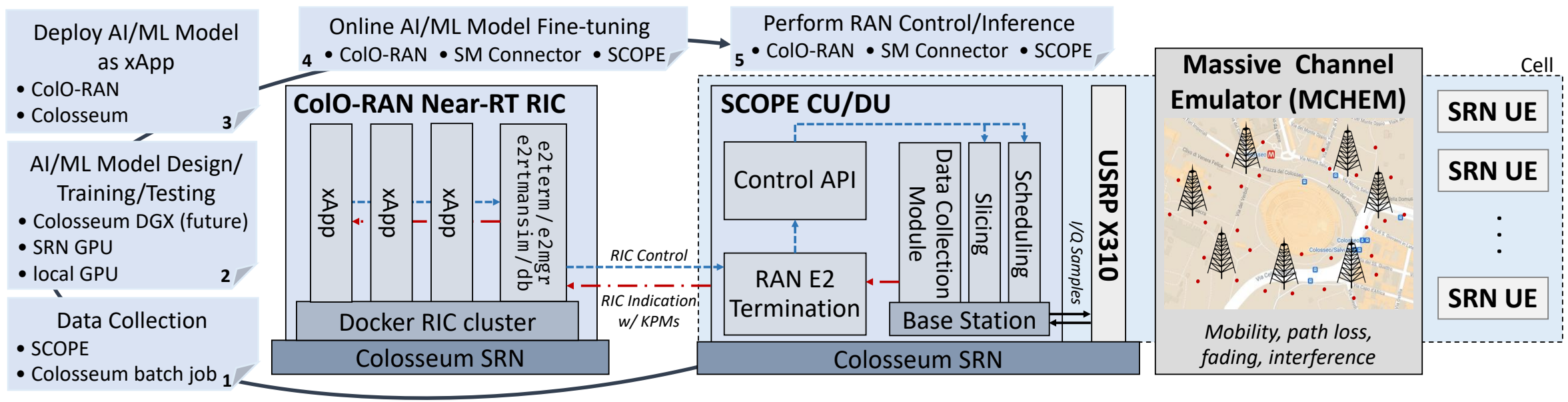


Boston, MA



Salt Lake City, UT (POWDER)

xApp Development Workflow



./setup-scripts/setup-ric.sh <eth-interface> → Host 1: start near-RT RIC

python3 ./radio_api/scope_start.py --config-file radio.conf
./radio_code/colosseum-scope-e2/run_odu.sh → Host 2: start base station and subscribe to RIC

./setup-scripts/setup-sample-xapp.sh <basestation-id> → Host 1: start xApp w/ base station control loop

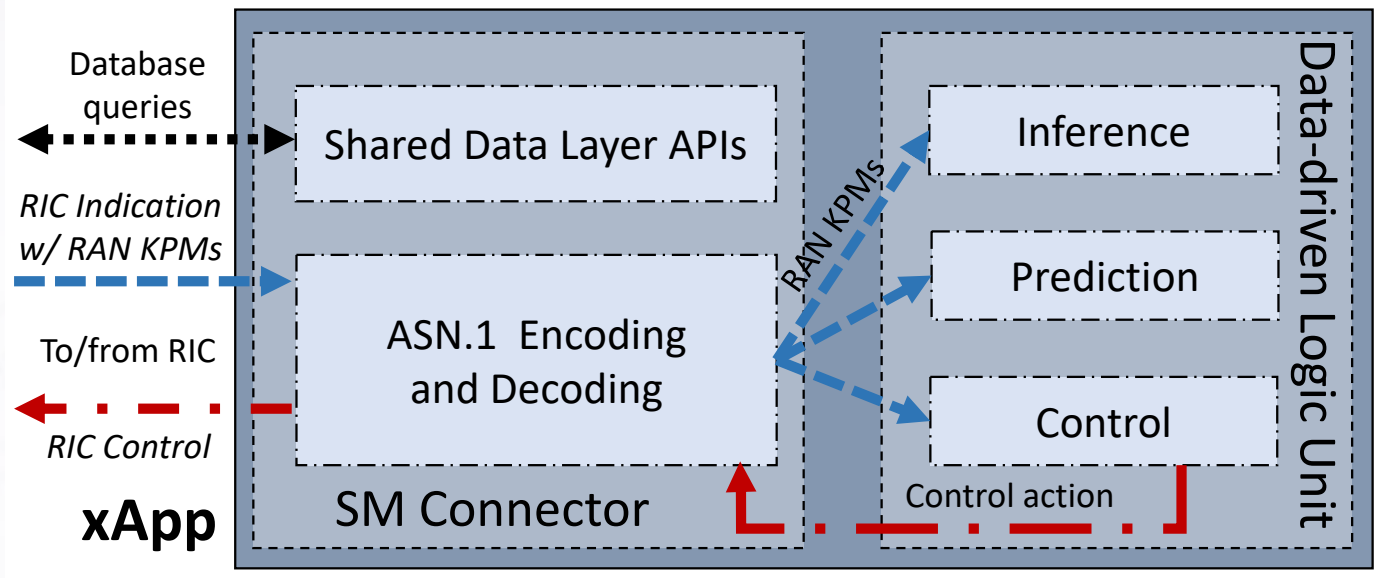
xApp Structure

Data-driven logic unit:

- Process RAN data and compute control action

SM Connector:

- Interface w/ the RIC and get data from the RAN
- Forward RAN data to data-driven logic unit
- Send computed control actions to RAN through RIC and E2 termination



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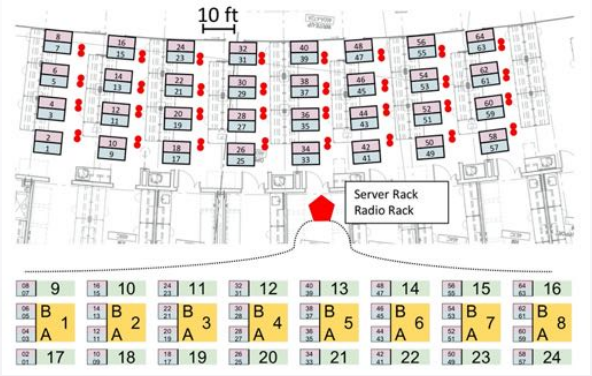
Prototype At-scale, Test in the Wild

- Prototype with OpenRAN Gym on Colosseum
- Validate in real environment (e.g., Arena testbed)
- Test large-scale capabilities on city-scale platforms (e.g., PAWR platforms)

Test at-a-scale on emulated scenarios

Validate in real wireless environment



Arena

Test large-scale capabilities

OpenRAN Gym on PAWR

- Transfer containers from Colosseum within minutes

Testbed	SCOPE w/ E2 (1.7 GB)	ColO-RAN near-RT RIC, prebuilt (6.5 GB)	ColO-RAN near-RT RIC, to build (1.6 GB)
Arena	1 m 27.413 s	5 m 41.487 s	1 m 25.002 s
COSMOS	1 m 28.631 s	5 m 39.704 s	1 m 27.352 s
POWDER	1 m 30.787 s	5 m 43.704 s	1 m 28.546 s

- Start containers within minutes (seconds for the base stations)

Testbed	SCOPE w/ E2 (1.7 GB)	ColO-RAN near-RT RIC, prebuilt (6.5 GB)	ColO-RAN near-RT RIC, to build (1.6 GB)
Arena	0.887 s	1 m 11.483 s	46 m 18.110 s
COSMOS	25.463 s	2 m 34.905 s	26 m 4.410 s
POWDER	30.139 s	2 m 55.654 s	21 m 11.220 s

only when building from scratch (e.g., if modifying RIC code)

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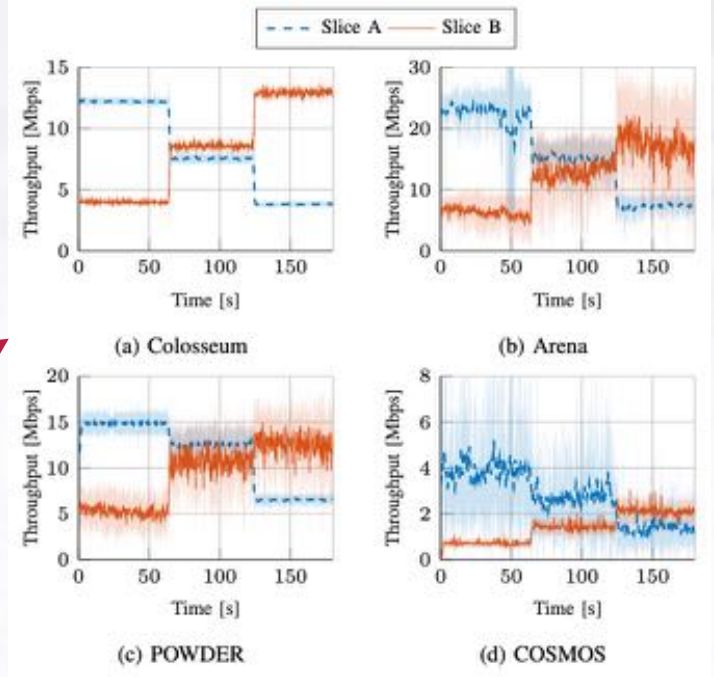
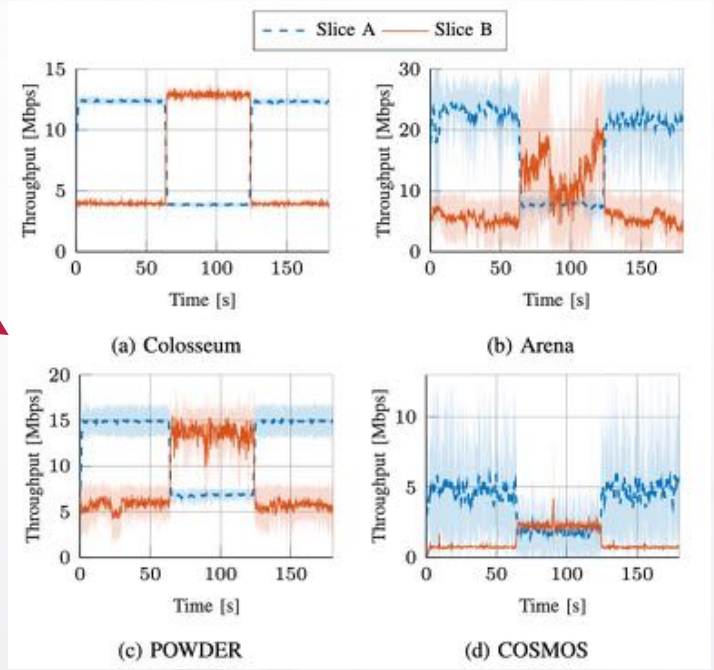
OpenRAN Gym on PAWR

- **Dynamic slice allocation** according to the following configurations

Slice	First Minute	Second Minute	Third Minute
Slice A	75% RBGs	50% RBGs	25% RBGs
Slice B	25% RBGs	50% RBGs	75% RBGs
Slice A	75% RBGs	25% RBGs	75% RBGs
Slice B	25& RBGs	75% RBGs	25% RBGs



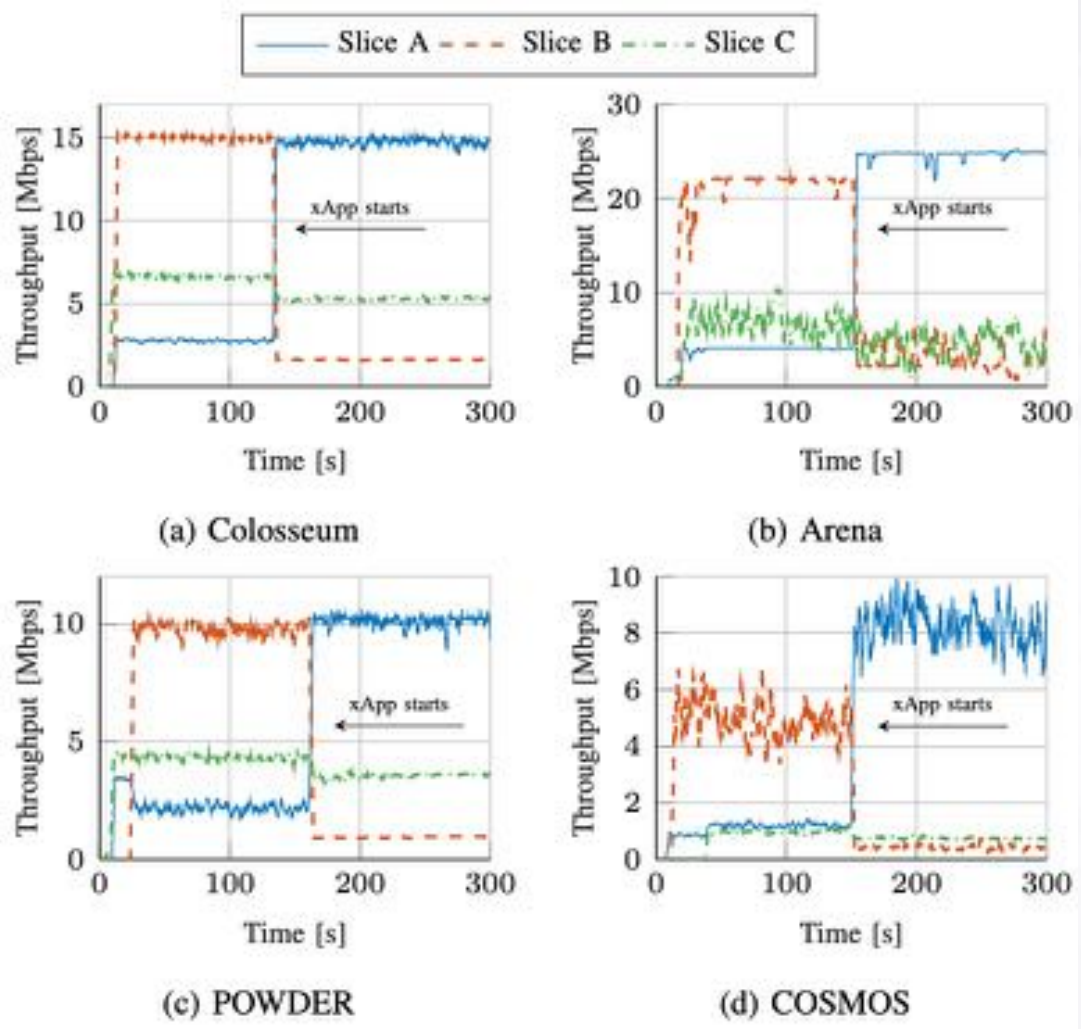


- Results are consistent across **very different platforms** with **heterogeneous environments**

OpenRAN Gym on PAWR

- **Closed-control loops** through xApp instantiated on the near-real-time RIC

- xApp tunes the network to **reach operator's intent** (e.g., prioritize users of slice A)



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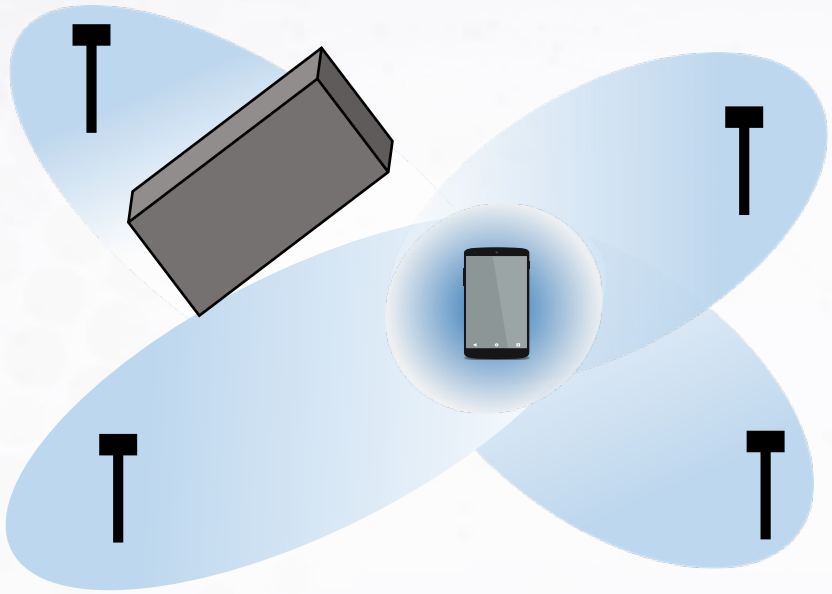
Beamforming/Massive MIMO on Colosseum



Advantages:

- Spatial diversity
- Increased SNR / channel hardening
- Anti-jamming

Challenges:

- Coordinate and synchronize the transmission from the different antennas
- Channel estimation

Existing studies lack **experimental large-scale** evaluation of the benefits and challenges of beamforming / massive MIMO

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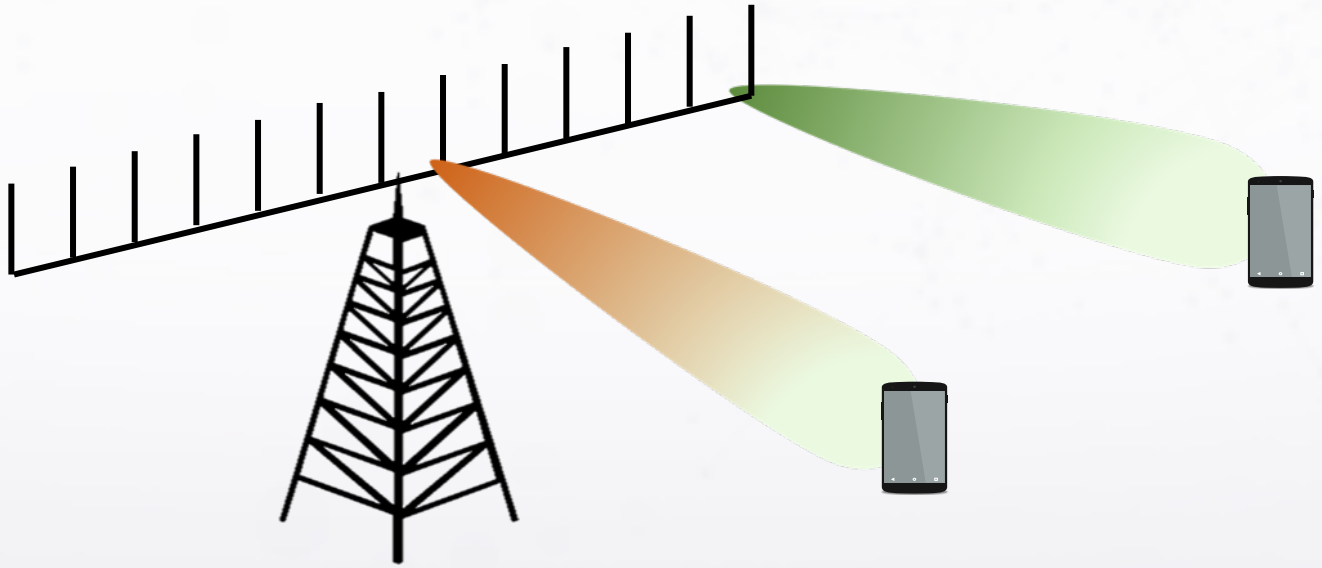
Beamforming/Massive MIMO on Colosseum

Use multiple SRNs to transmit / receive pre-coded signals

1. Colosseum supports this thanks to synchronization infrastructure in Quadrant 1
2. The scale of Colosseum enables new **massive MIMO** studies



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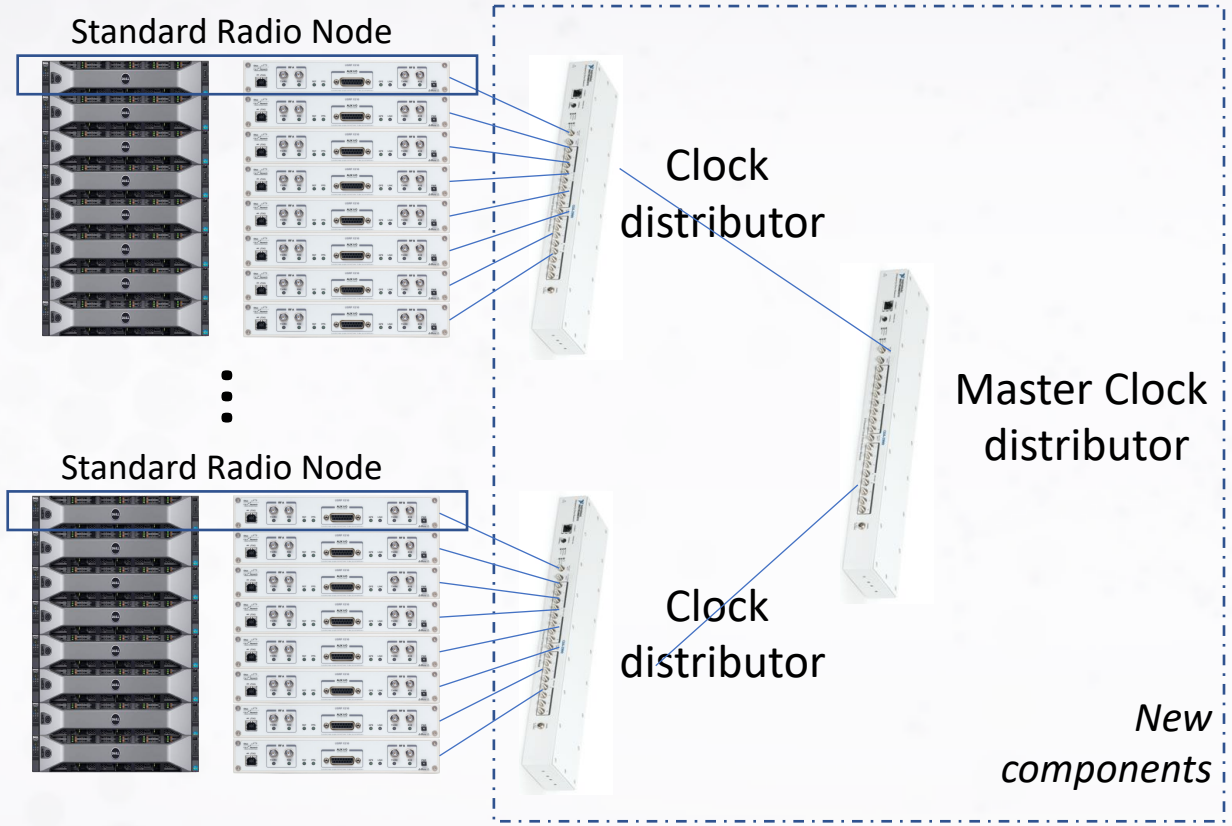
Beamforming on Colosseum - Infrastructure



- Initial deployment with
  - One Colosseum quadrant 32 Standard Radio Nodes (Server + USRP X310)
  - Synchronized clock/PPS with 5 Octoclocks
  - Using UHD drivers to synchronize I/Q samples among different SRNs

- Work in Progress: The container is currently being developed

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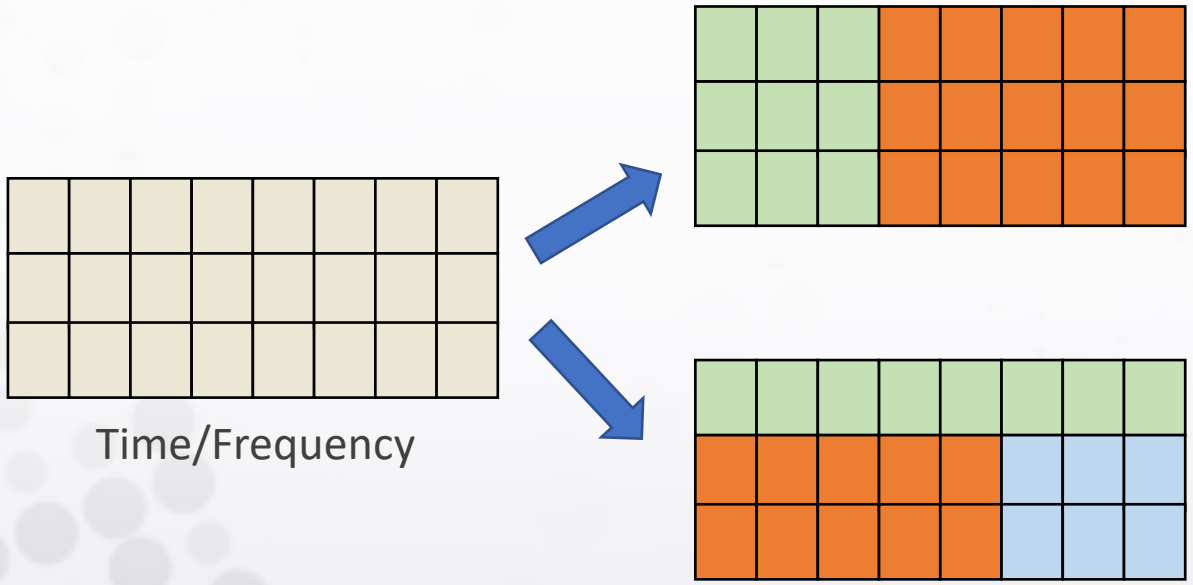
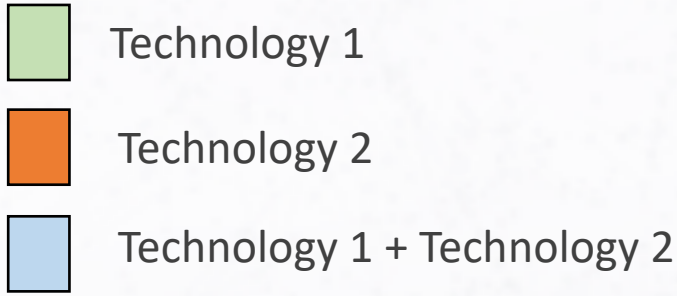
Spectrum sharing

- **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**?
  - **Licensed/Unlicensed**
  - **Cognitive** radio



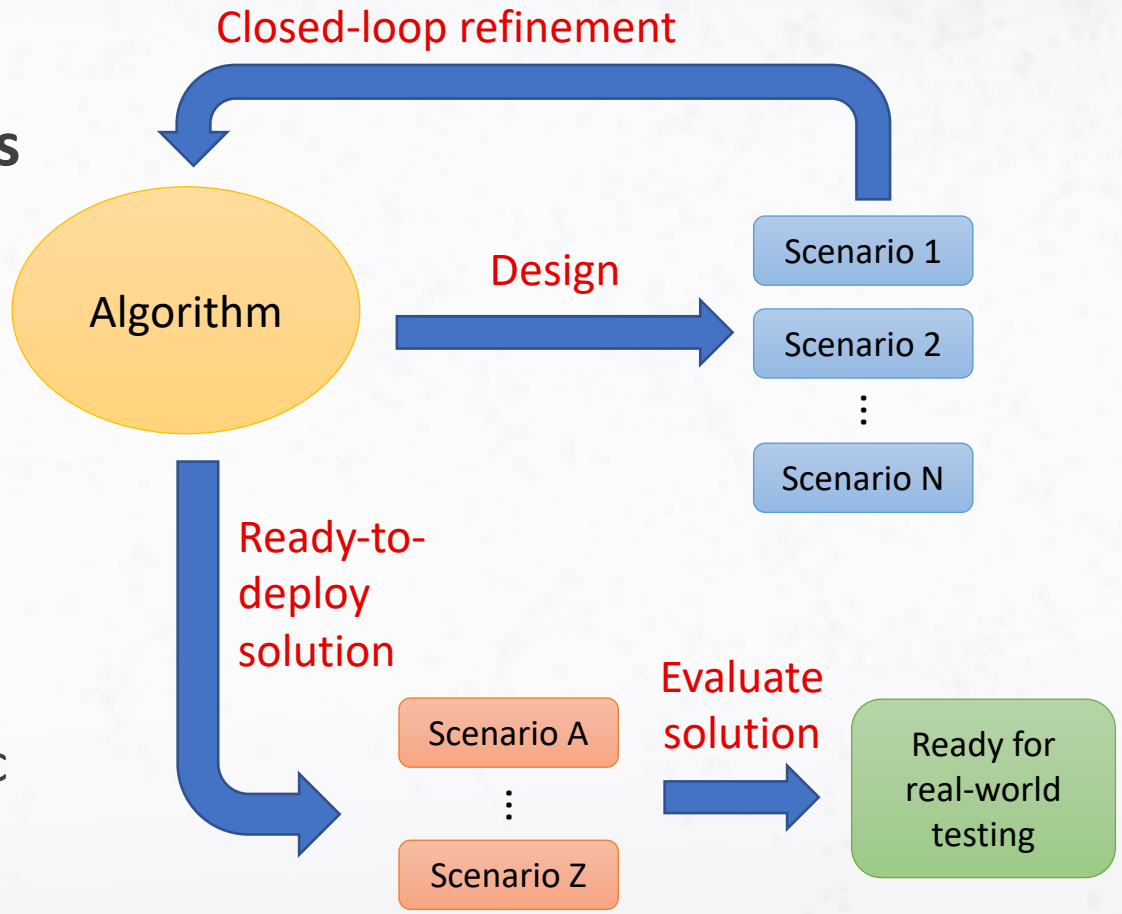


Which one is **better**?

Spectrum sharing on Colosseum

Opportunity:

- Generate **heterogeneous RF/traffic scenarios**
- **Design adaptive** solutions:
  - Optimization / Data-driven
  - Minimize impact on licensed users
  - Spectrum hole detection
- **Validate** algorithms on unseen scenarios
  - Ensure algorithms are not scenario-dependent
  - Test different algorithms on the same RF/traffic scenarios for fair comparison



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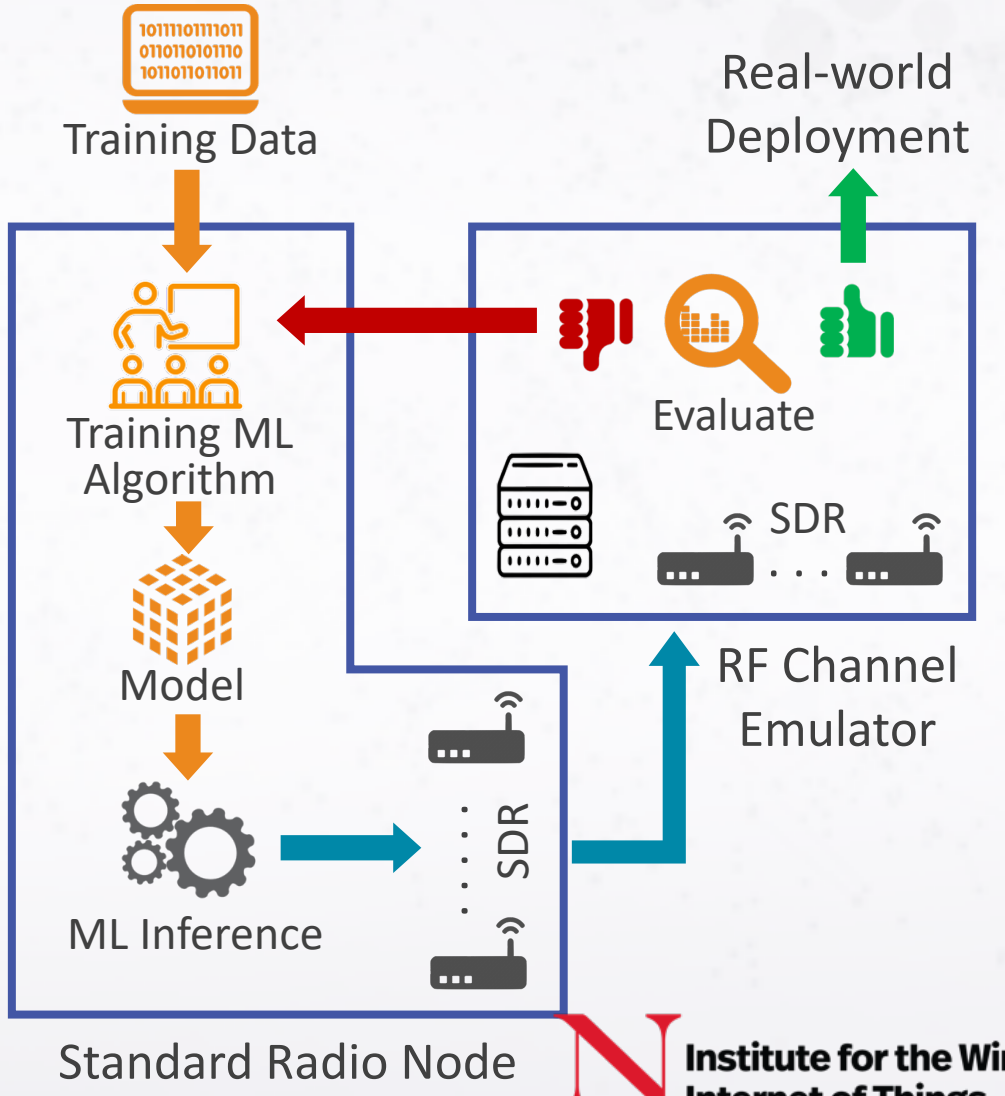
Fusion of Artificial Intelligence and Internet of Things

- **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 WiFi, Cellular or LPWAN
  - X310 Software Defined Radio
  - Powerful computation nodes equipped with GPUs
  - FPGAs for embedded AI-IoT testing



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Who Can Use Colosseum?

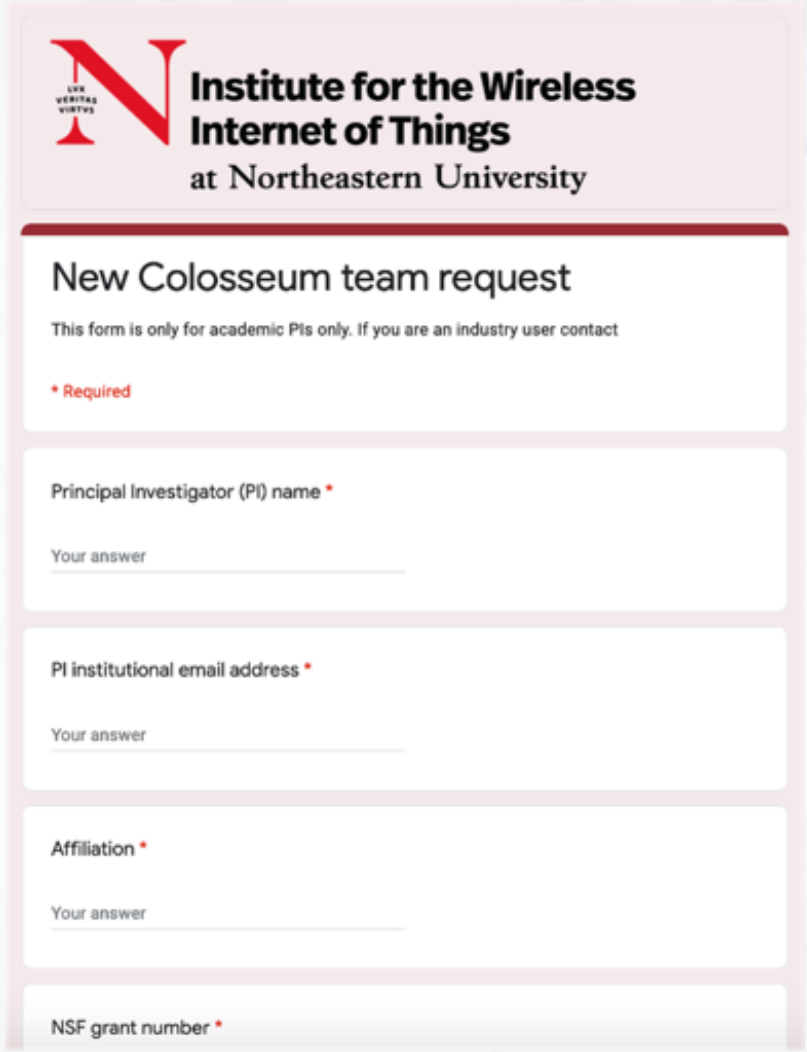
- **NSF-supported researchers** can access Colosseum free of charge
- We provide basic support and documentation, scenario creation on a best effort basis
  - Tell us what you are trying to accomplish, and we will direct you to an existing scenario, or we will try to work with you to develop a new one (resources permitting)

- **DoD researchers (i.e, ARL, AFRL, NRL)** can access Colosseum for free for two years

- Industry and other researchers: talk to us (colosseum@northeastern.edu), we are developing a fee structure for use by communities that are not currently contributing to Colosseum

Getting Started with Colosseum

- PIs can submit new team requests at:
  - Colosseum.net under useful links
- PIs need to be either supported by NSF or a DoD researcher
- Useful links:
  - Colosseum website: colosseum.net
  - Knowledge base: colosseumneu.freshdesk.com/support/solutions
  - Help desk: https://colosseumneu.freshdesk.com/support/tickets



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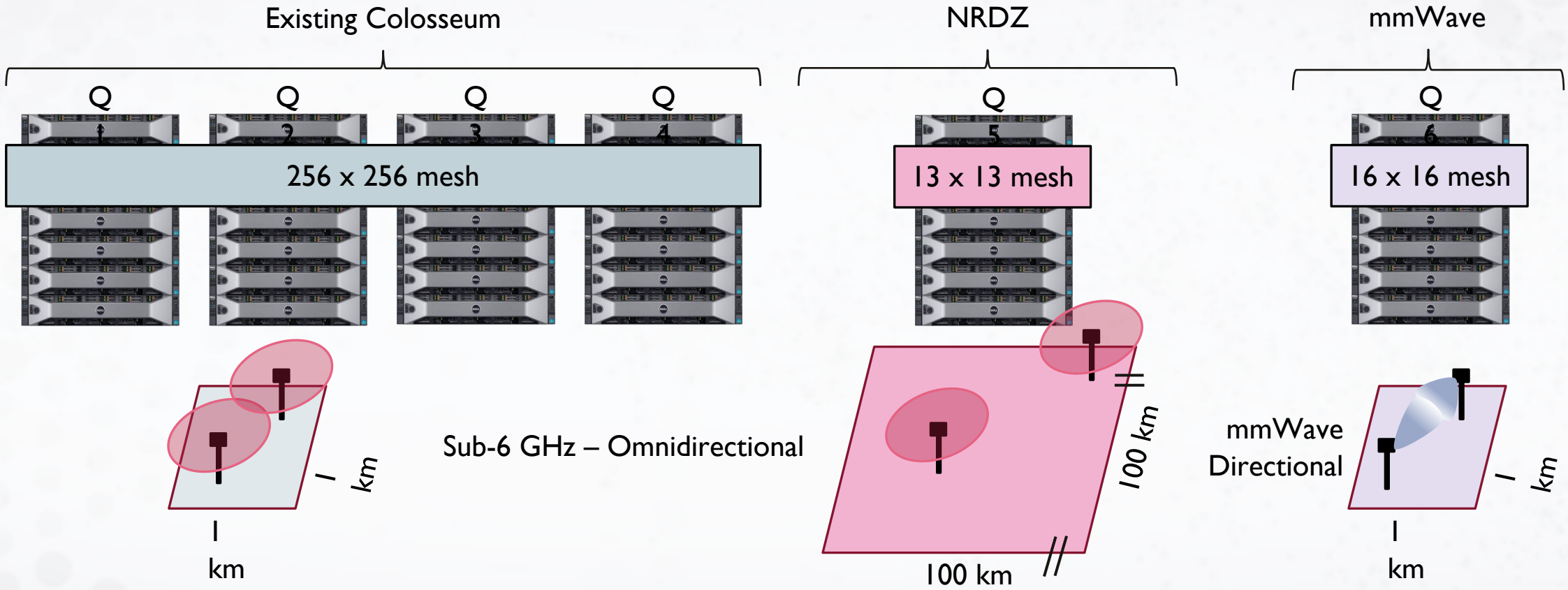
Evolution of Colosseum



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Thank You !!

- Questions ?

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