Institute for the Wireless Internet of Things at Northeastern University

# Colosseum: The World's Largest Wireless Network Emulator with Hardware-in-the-loop

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

# 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

## Part I

# Introduction to Colosseum

# 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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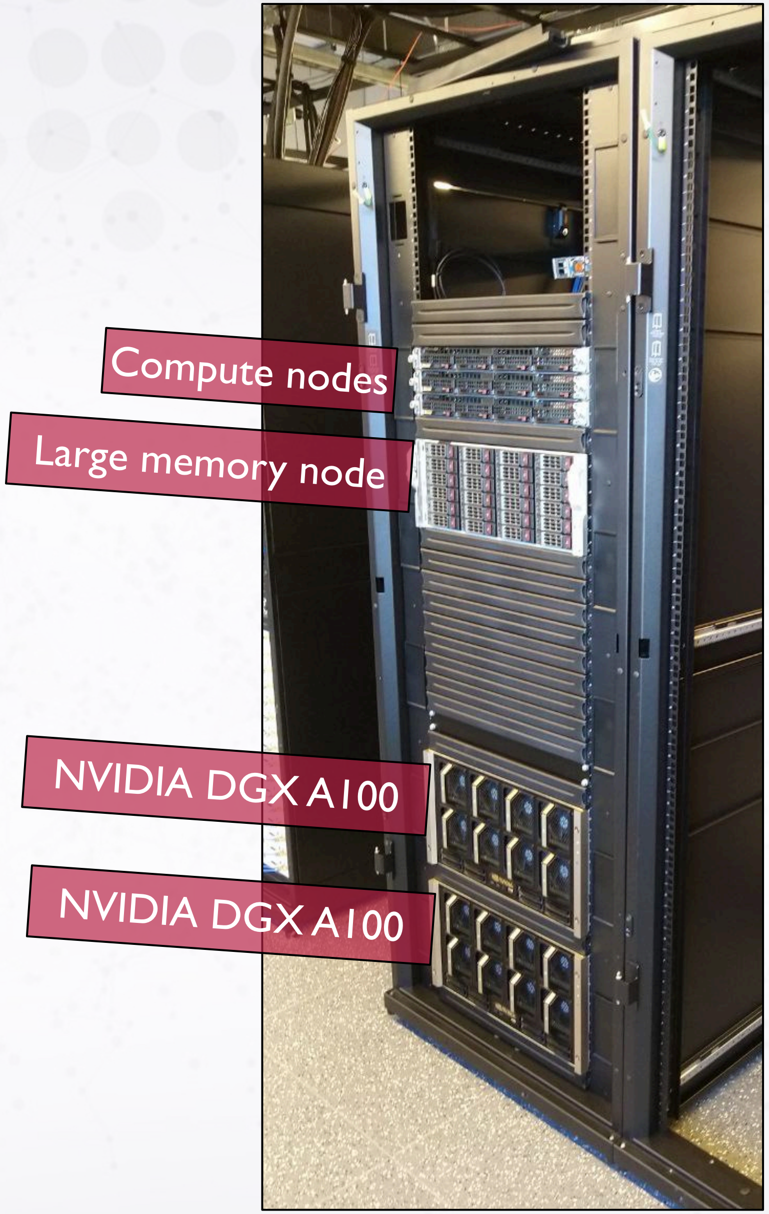
# Colosseum as Enabler for AI/ML

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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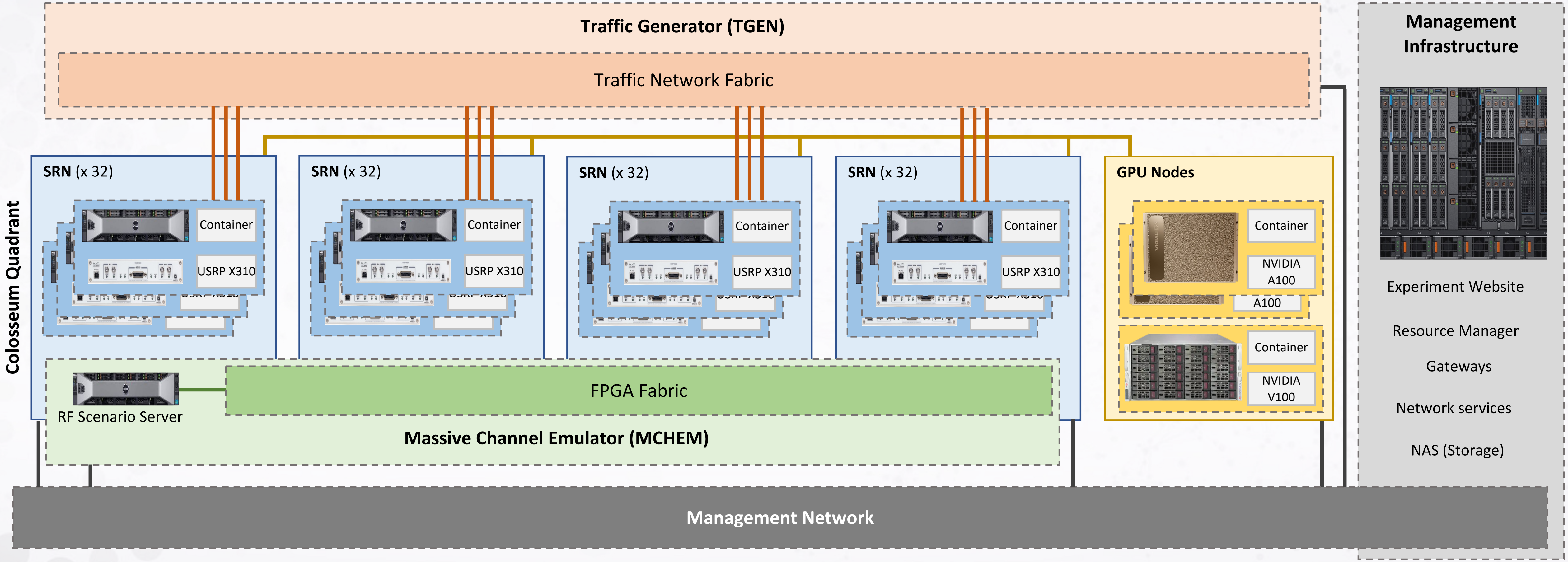
# Colosseum: Much More Than a Supercomputer

- 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 Architecture

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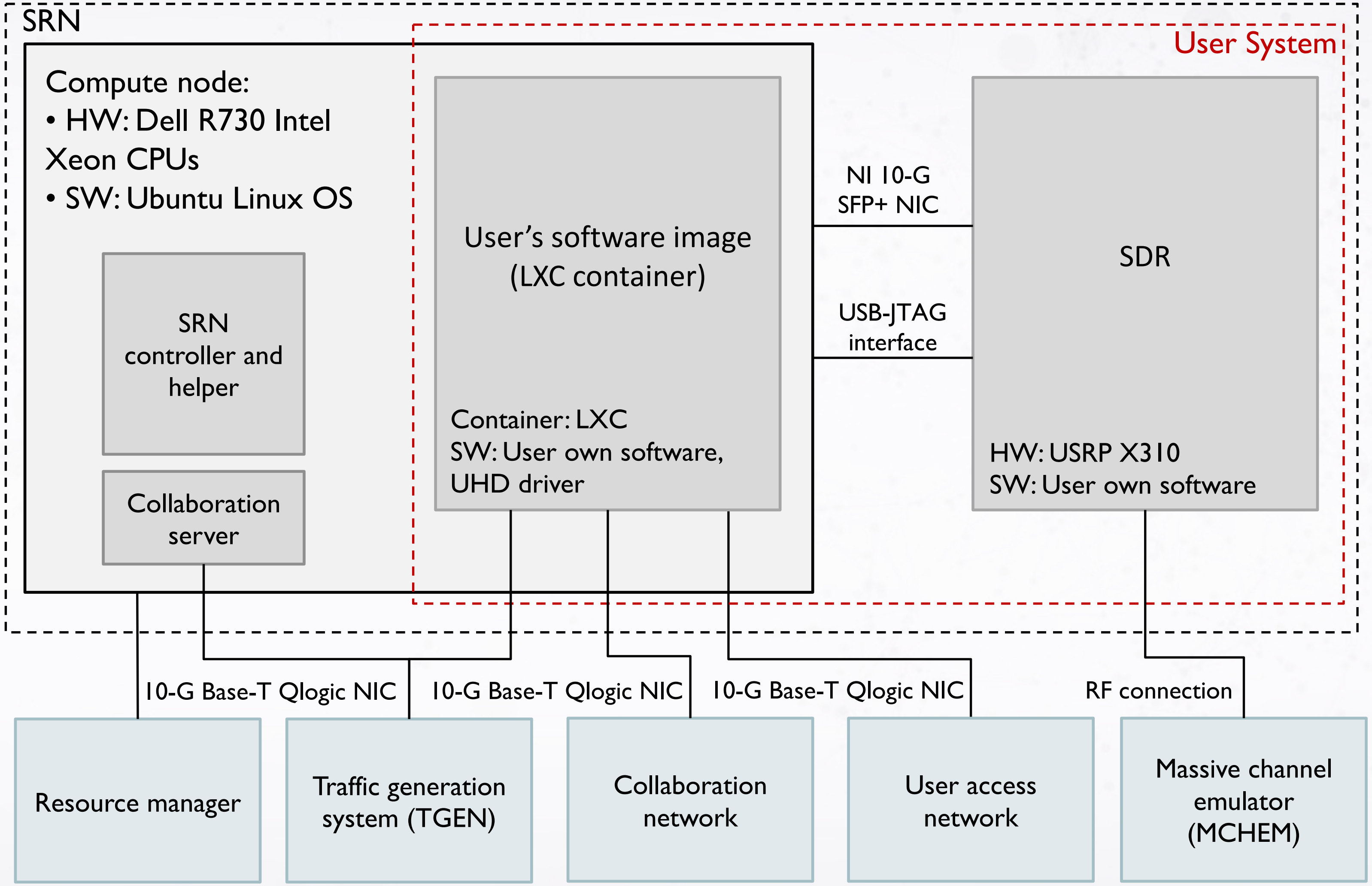
# Standard Radio Node (SRN)



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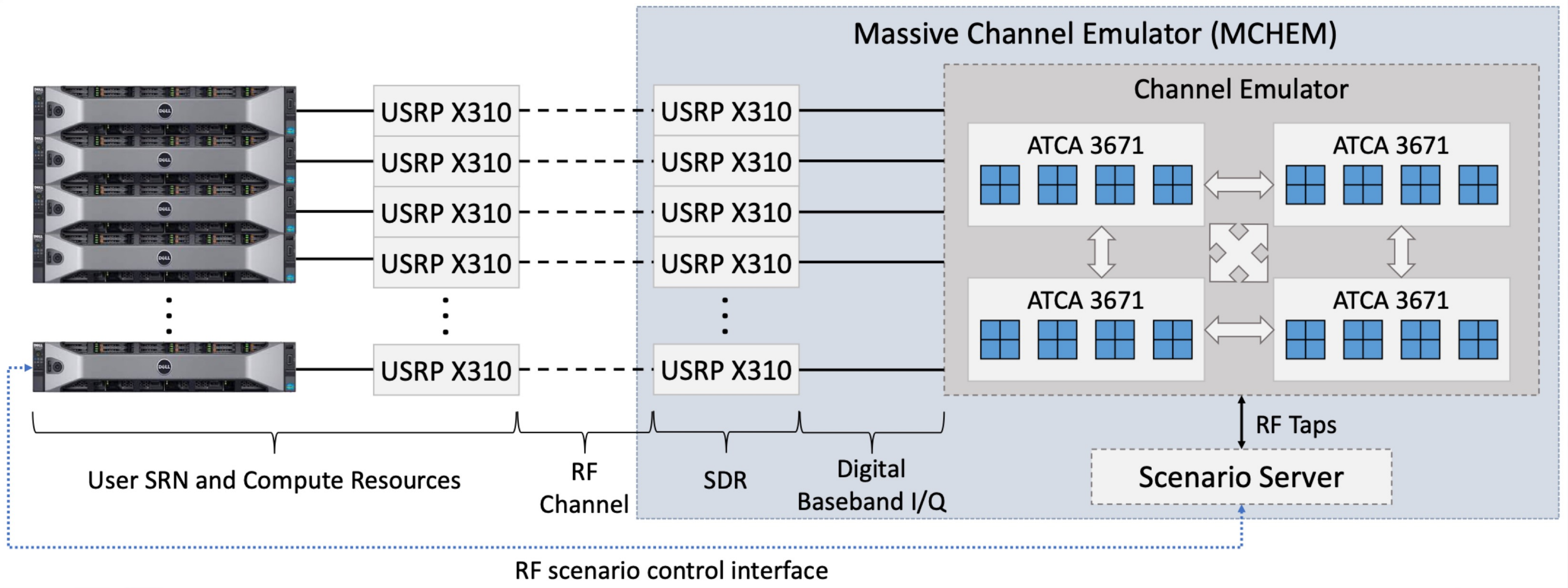
# Massive Channel Emulator (MCHEM)

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



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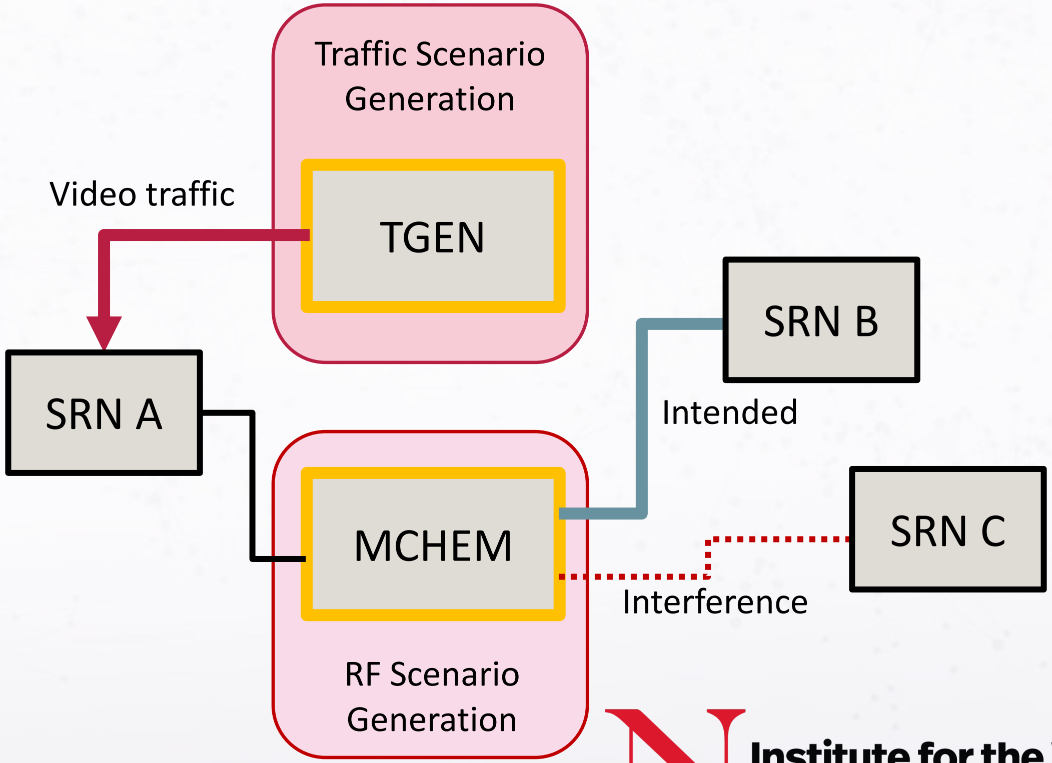
# Scenarios: The Colosseum Way

- RF / traffic scenarios are **deterministic**: Experiments w/ same scenario execute the same way
- Currently being extended w/ stochastic distributions in the filter taps
- **Full control** over the wireless channel
  - Only keep **desired** channel effects
  - Capture **interference** and **superimposition of signals**
- ***Reproducibility*** / ***repeatability***
- **Easy comparison** between algorithms

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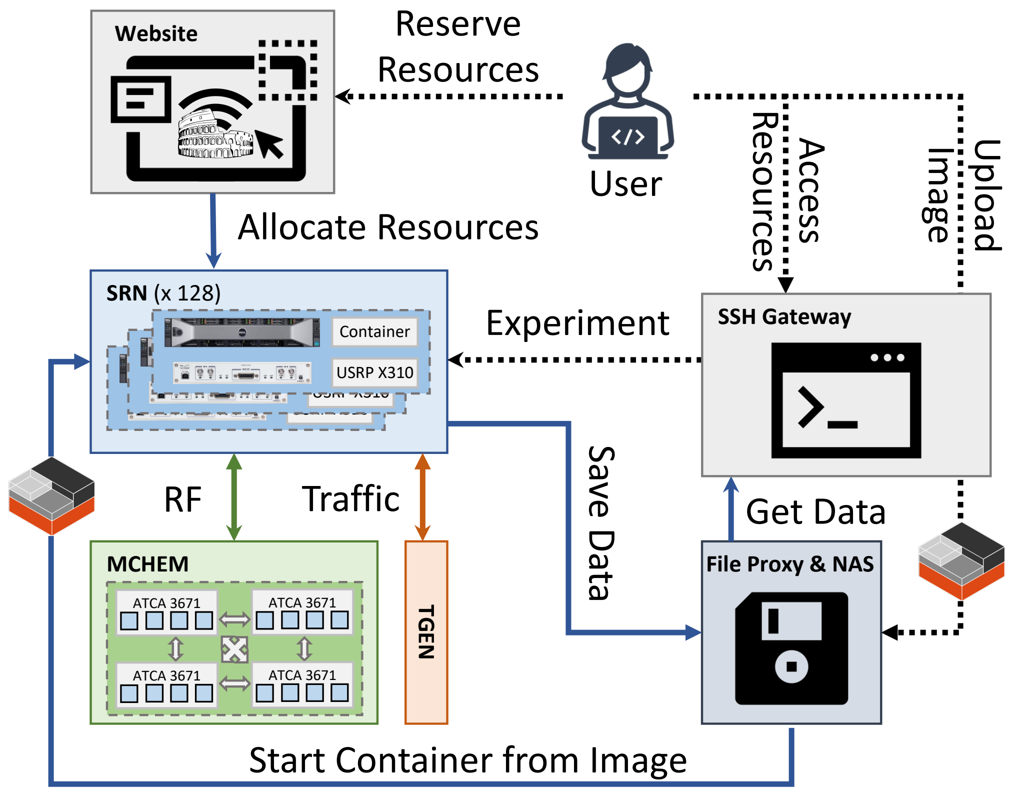
# Open to the Research Community

- Colosseum is **publicly-available** to the research community
- **Multiple users** can access the system and use resources **at the same time**
- **Different experiments are isolated** from each other
- Different **emulation scenarios** can be **used concurrently** on different experiments




How to get access:

- NSF-supported or DoD researchers: fill form at https://tinyurl.com/colosseum-access
- Others: contact colosseum@northeastern.edu

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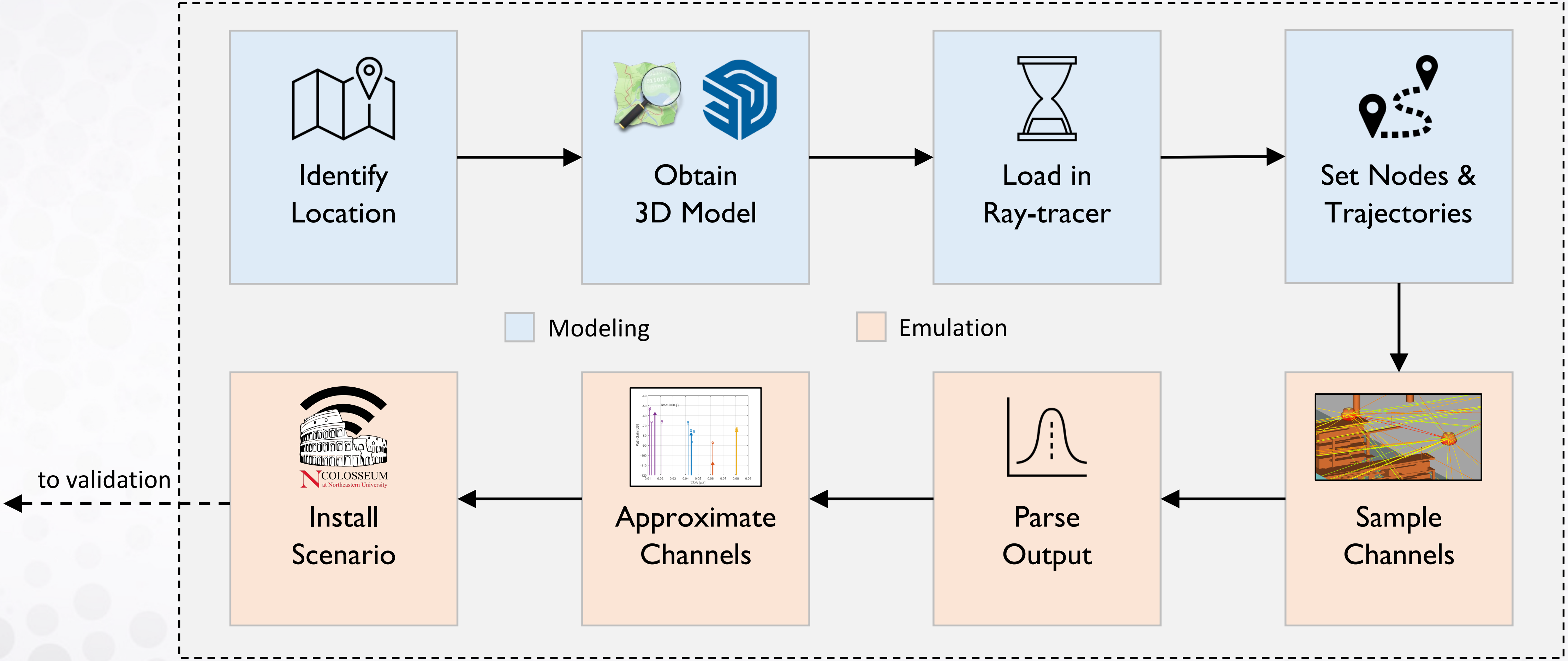
# Scenario Creation Overview

# Scenario Creation Overview



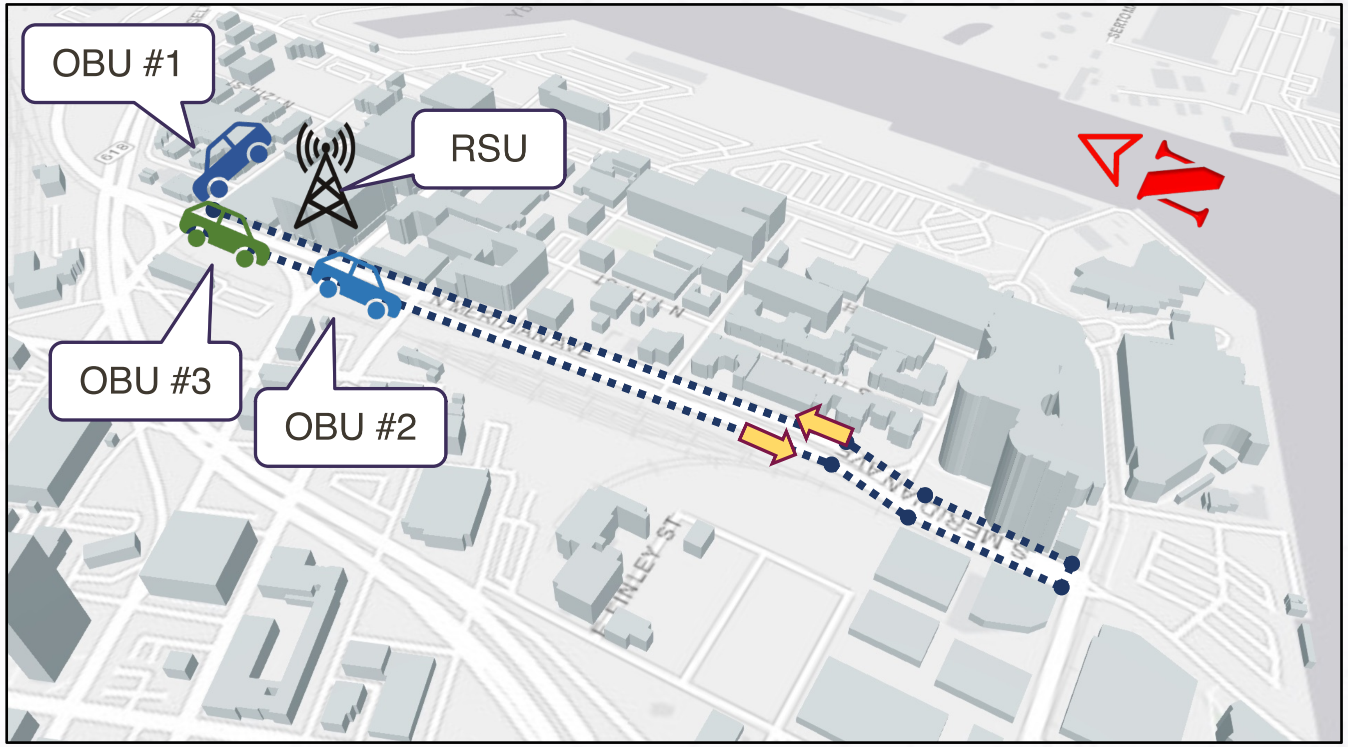

D. Villa, M. Tehrani-Moayyed, P. Johari, S. Basagni, T. Melodia, "*CaST: A Toolchain for Creating and Characterizing Realistic Wireless Network Emulation Scenarios*", Proceedings of ACM WiNTECH 2022, Sydney, Australia, October 2022

M. Tehrani-Moayyed, L. Bonati, P. Johari, T. Melodia, and S. Basagni, "*Creating RF Scenarios for Large-Scale, Real-Time Wireless Channel Emulators,*" in Proceedings of IEEE MedComNet, June 2021

# Creating Mobile RF Scenarios

## Use case V2X Tampa, FL

1. **Identify** scenario location
2. **Obtain** 3D model from OSM
3. **Convert** model in STL to feed Wireless InSite
4. **Define** nodes and trajectory
5. **Sample** the channel using the ray-tracer
6. **Parse** the output to extract channels at each time instant
7. **Approximate** channels
8. **Install** scenario on Colosseum and validate




Tampa, FL mobile scenario

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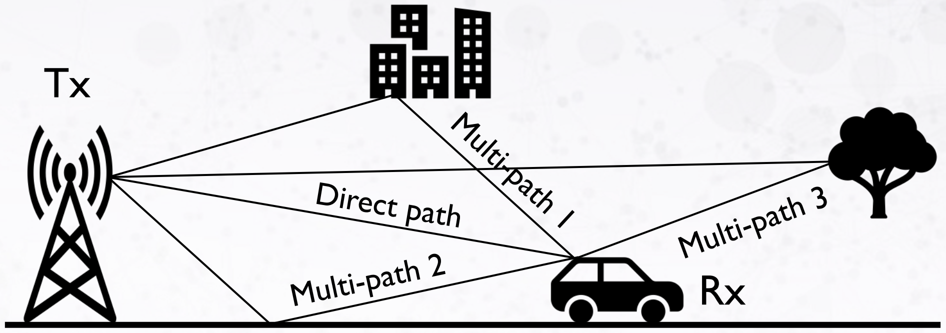
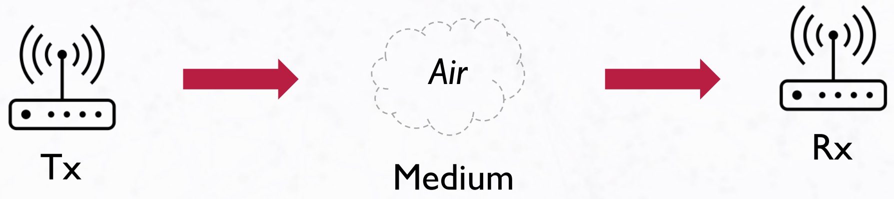
# Scenario Validation

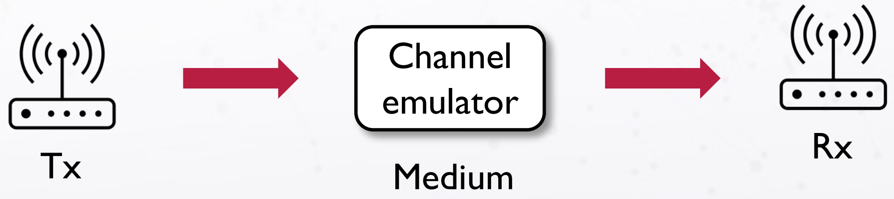
- Channel sounding goals:
  - **Evaluate** an RF channel characteristics
  - **Analyze** the environment
  - **Optimize** the design
- **No over-the-air** communication
- **Emulated** medium
- Sounding goals in emulators:
  - **Validate** original traces:
    - Channel Impulse Response (**CIR**) for Time of Arrivals (ToA)
    - Power Delay Profile (**PDP**) for Pathloss (**PL**)
  - **Understand** emulated behavior




**Communication over-the-air**




**Communication in emulators**

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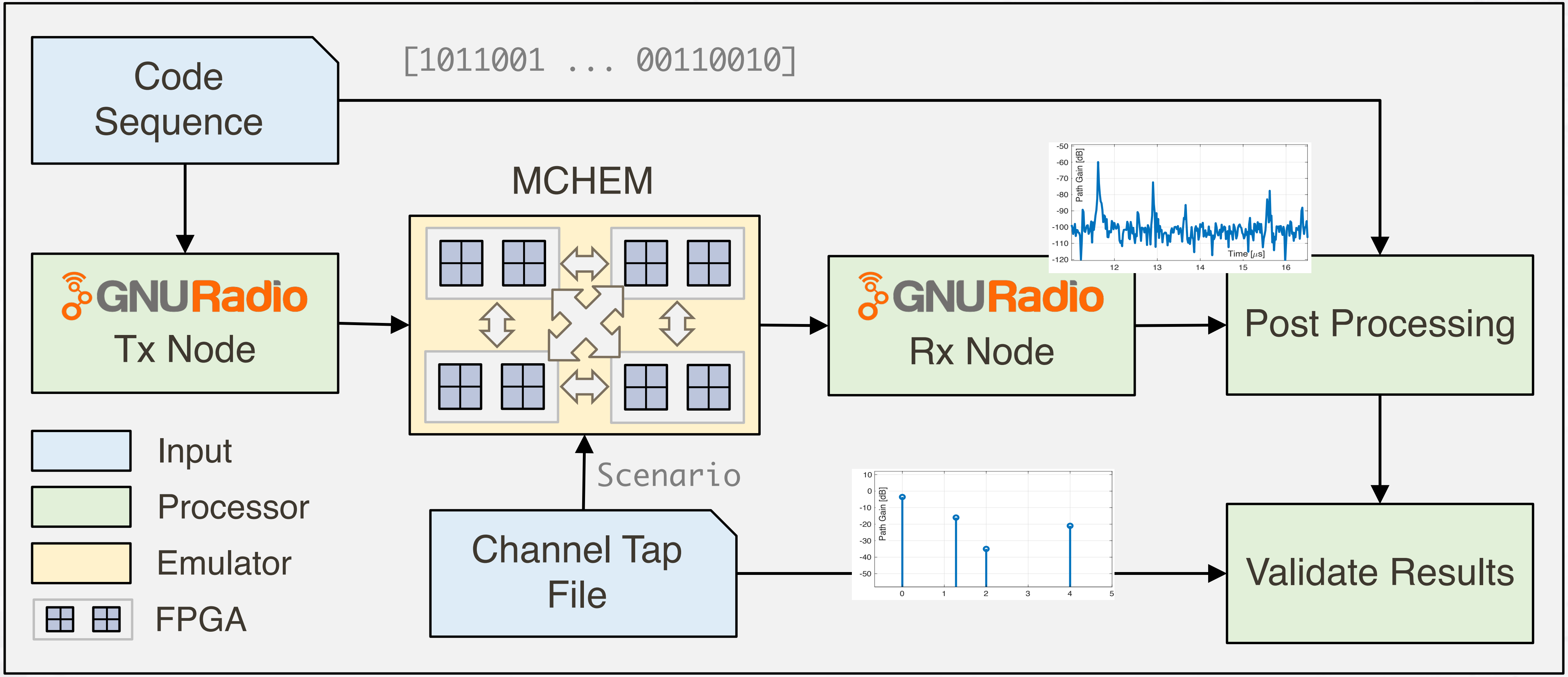
# CaST Channel Sounding Workflow



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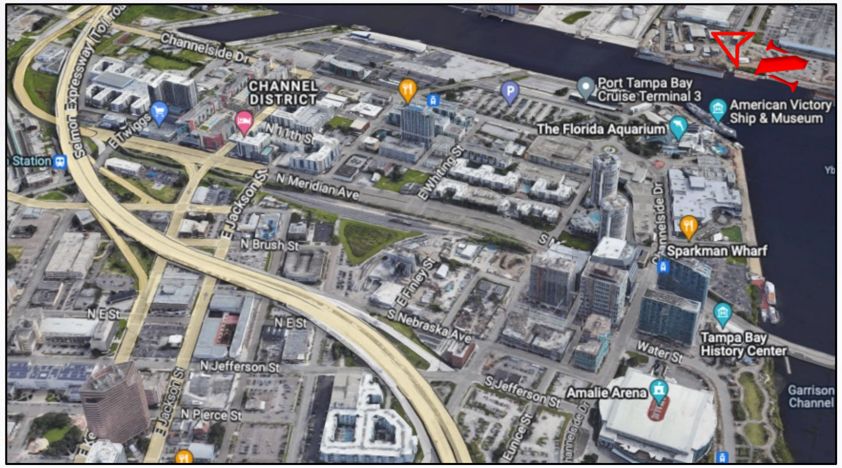
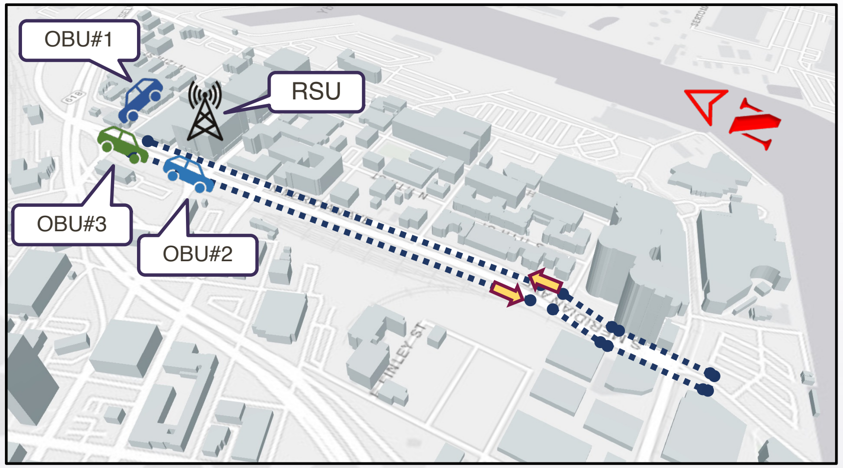
# Some Results: Use Case V2X Tampa, FL



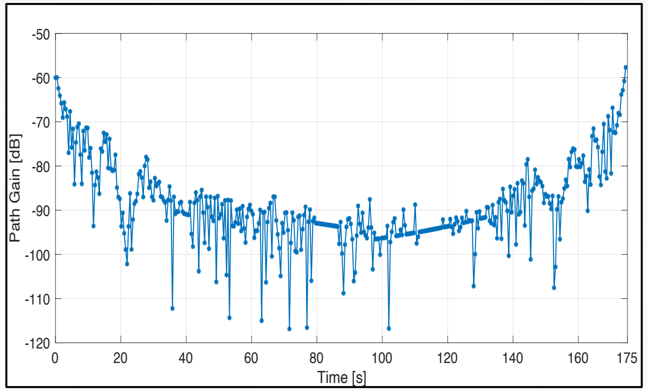

Real Environment

**CaST Framework**

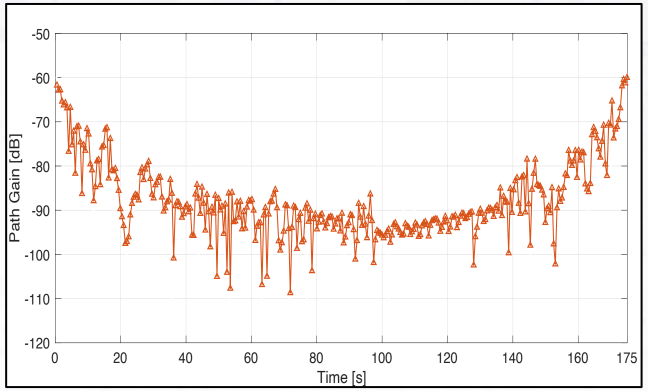
**CaST Sounder**



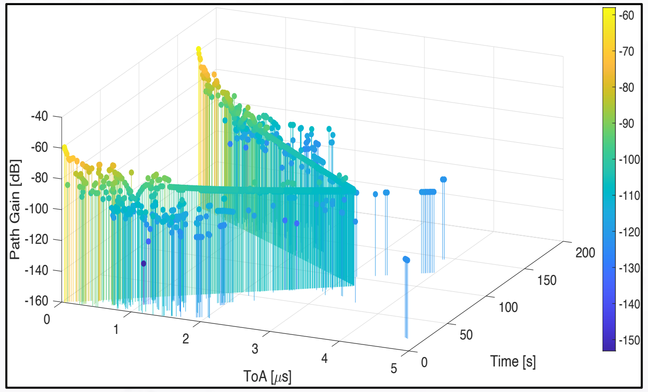

Digital Environment



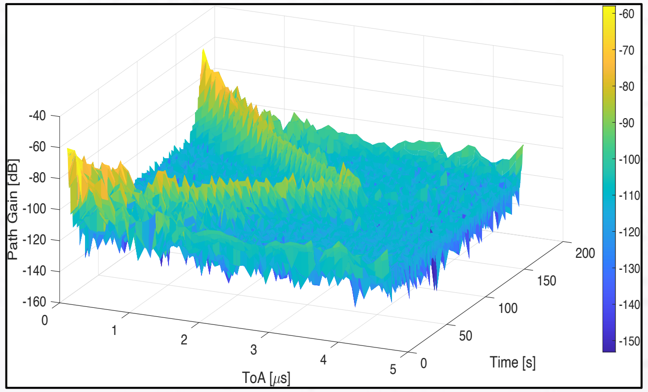

Theoretical path gains RSU-OBU#2




Emulated path gains RSU-OBU#2




Theoretical channel taps RSU-OBU#2




Emulated channel taps RSU-OBU#2

**Good match between real and emulated environment**

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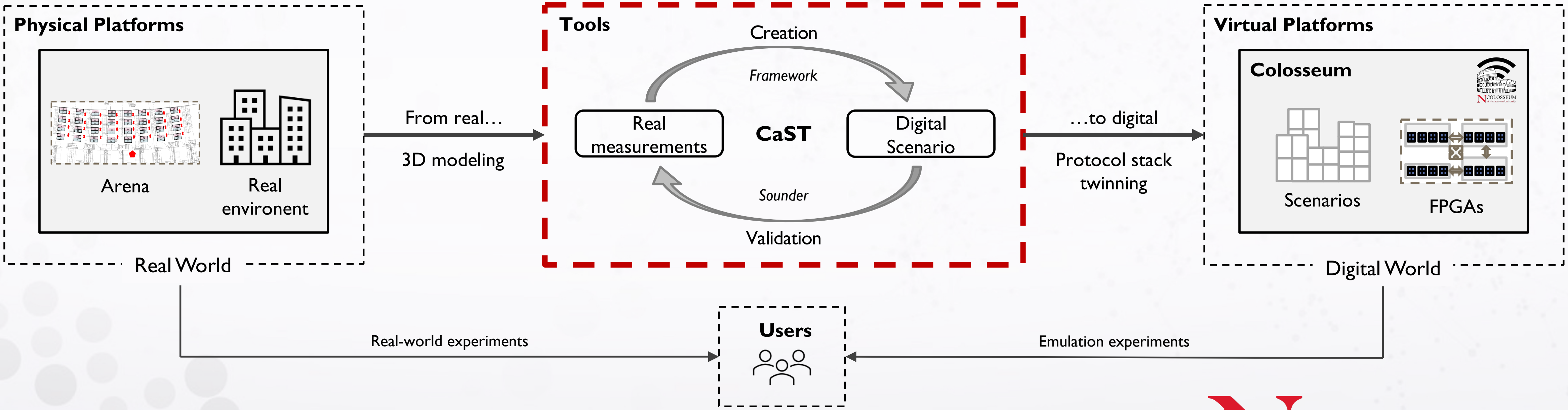
# Colosseum as a Digital Twin

- **Large-scale emulators** are widely used
- **Reliability** of emulations is a key factor
- **Tune** and **Run** experiments as close as possible to reality

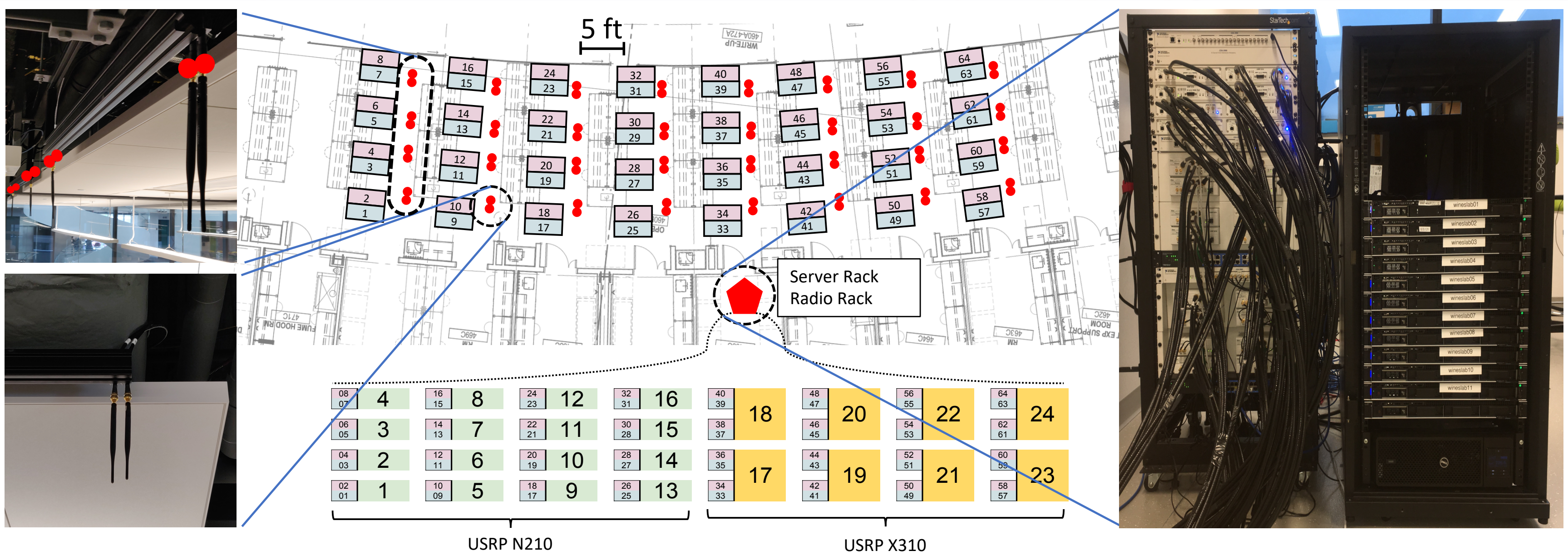





D. Villa, M. Tehrani-Moayyed, C. Robinson, L. Bonati, P. Johari, M. Polese, S. Basagni, T. Melodia, "*Colosseum as a Digital Twin: Bridging Real-World Experimentation and Wireless Network Emulation,*" arXiv:2303.17063 [cs.NI], pp. 1-15, March 2023

# Example of Physical Environment in Digital Twin: Arena

An **open-access** wireless testing platform based on an **indoor 64-antenna ceiling grid** connected to programmable **SDRs** for **sub-6 GHz 5G+** spectrum research.




- **Real-time real-channel** evaluation platform
- **Fully-synchronized** testbed
- Repeatable, flexible, and scalable **high-fi** indoor experiments

L. Bertizzolo, L. Bonati, E. Demirors, A. Al-Shawabka, S. D'Oro, F. Restuccia, and T. Melodia, "*Arena: A 64-antenna SDR-based Ceiling Grid Testing Platform for Sub-6 GHz 5G-and-Beyond Radio Spectrum Research,*" Computer Networks, 2020

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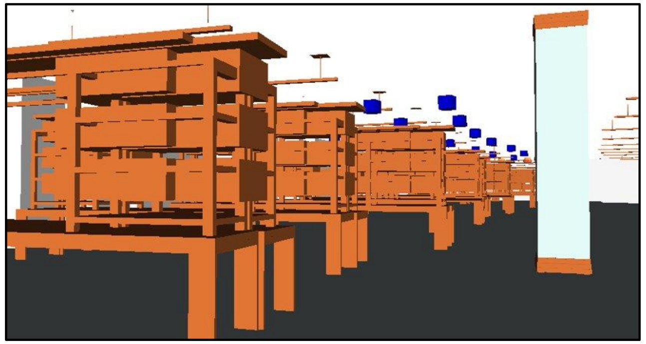
# From Real to Digital

- Create **3D representation** of **real-world location** (e.g., w/ Sketchup, OpenStreetMap)

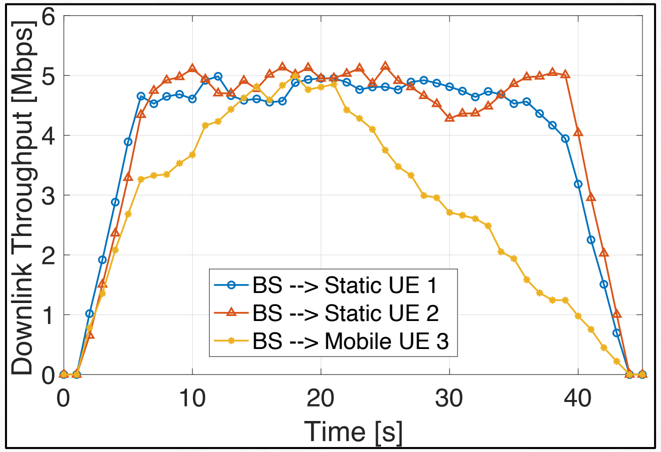
- **Model channels** through ray-tracing (e.g., w/ Wireless InSite, CaST)

- **Validate** through experiments in digital and real world

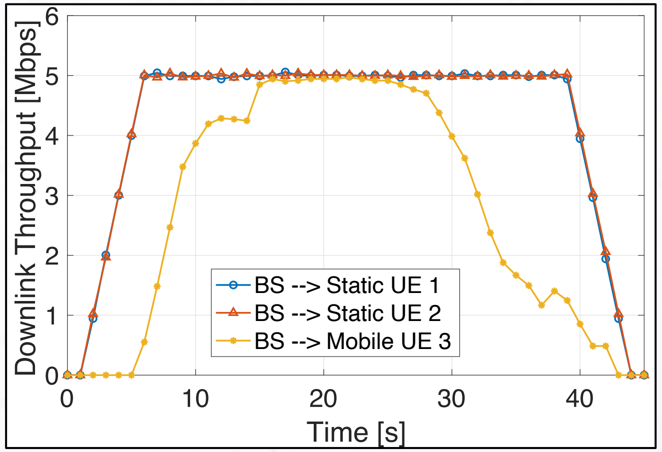
Real world



Digital world




Real world




Digital world

**Good match between real and digital environment**

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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
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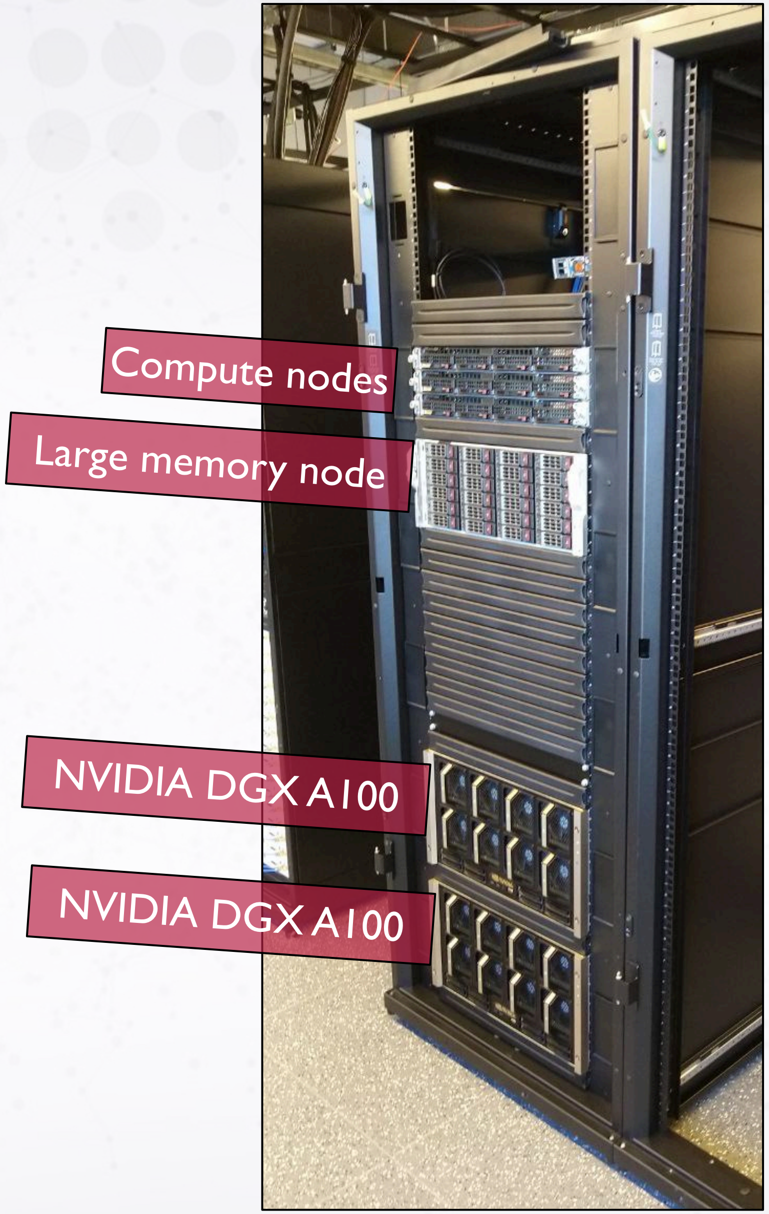
8 NVIDIA A100 GPU 40 GB

Mellanox Infiniband switch

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# Open RAN on Colosseum

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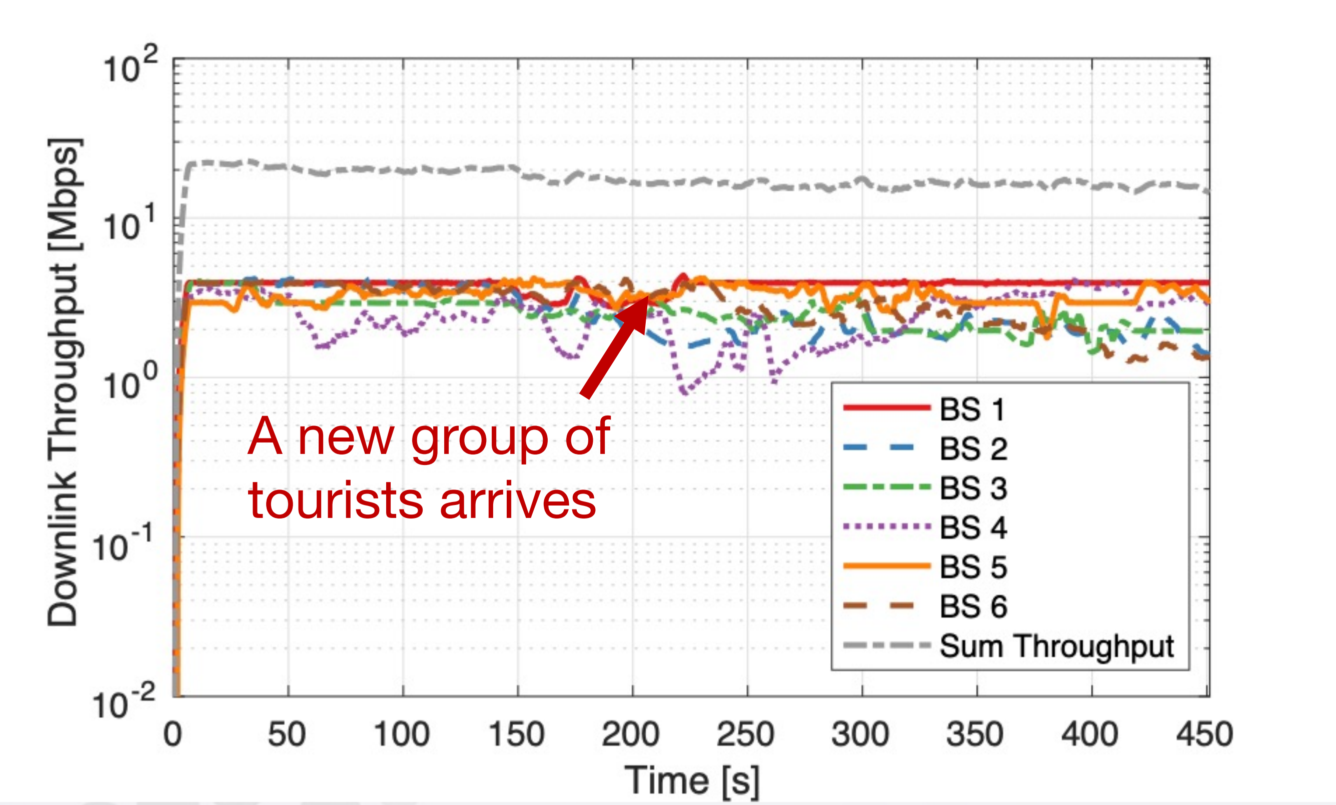
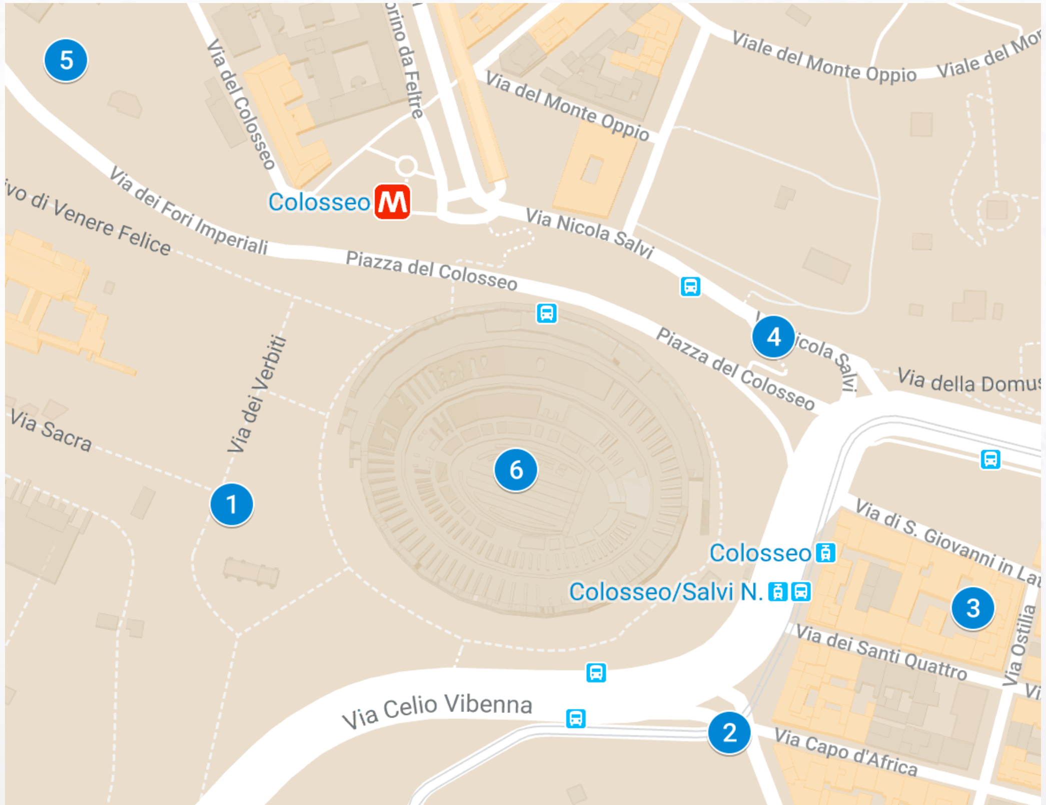
# Colosseum 5G Capabilities

- 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)



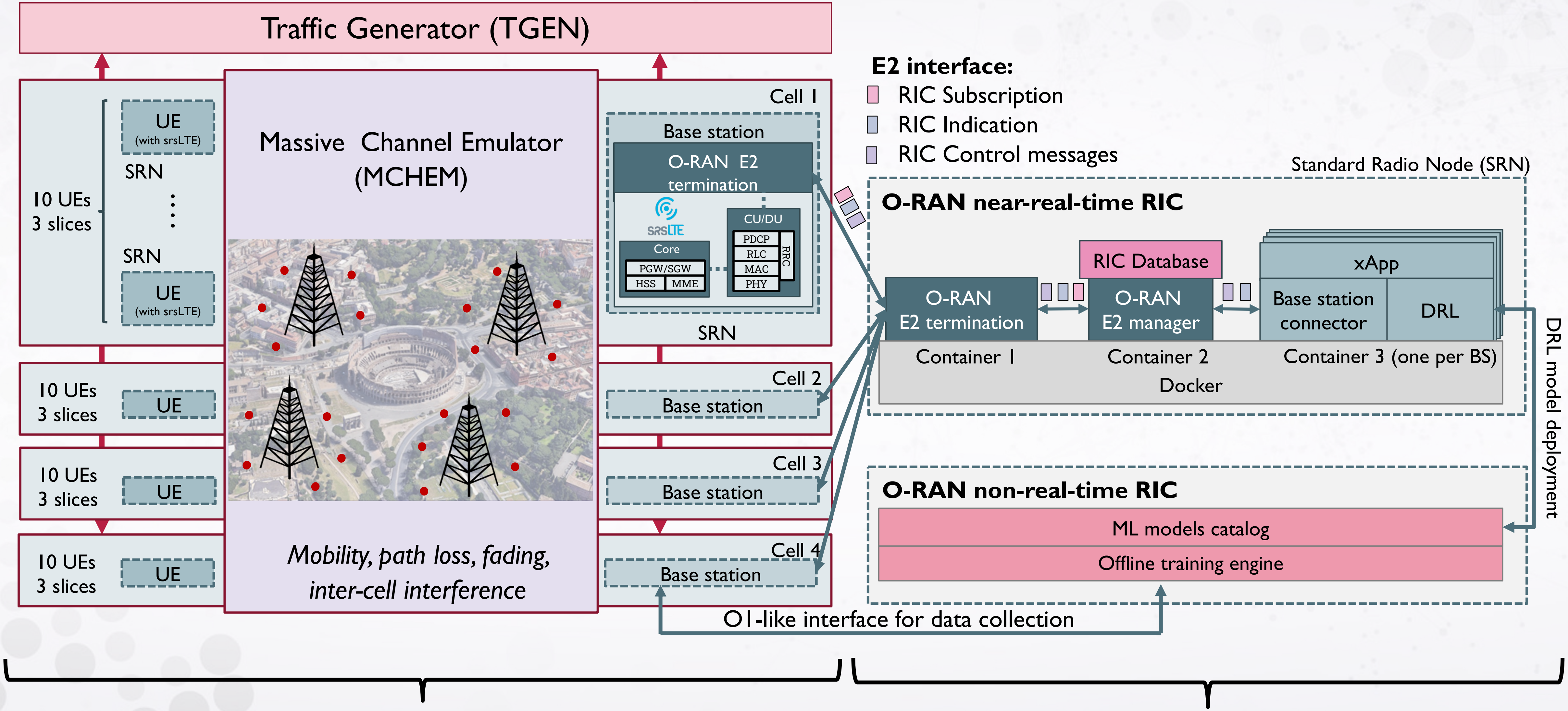

Downlink throughput




Base station locations

# Example of Programmable RAN Study

L. Bonati, S. D'Oro, M. Polese, S. Basagni, and T. Melodia, "*Intelligence and Learning in O-RAN for Data-driven NextG Cellular Networks*", IEEE Communications Magazine, vol. 59, no. 10, pp. 21–27, October 2021




**Fully virtualized RAN on white-box hardware**

**O-RAN open-source infrastructure**

# 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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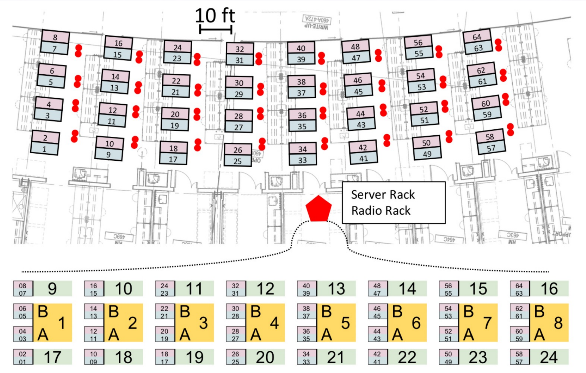
at Northeastern University

Validate in real wireless environment



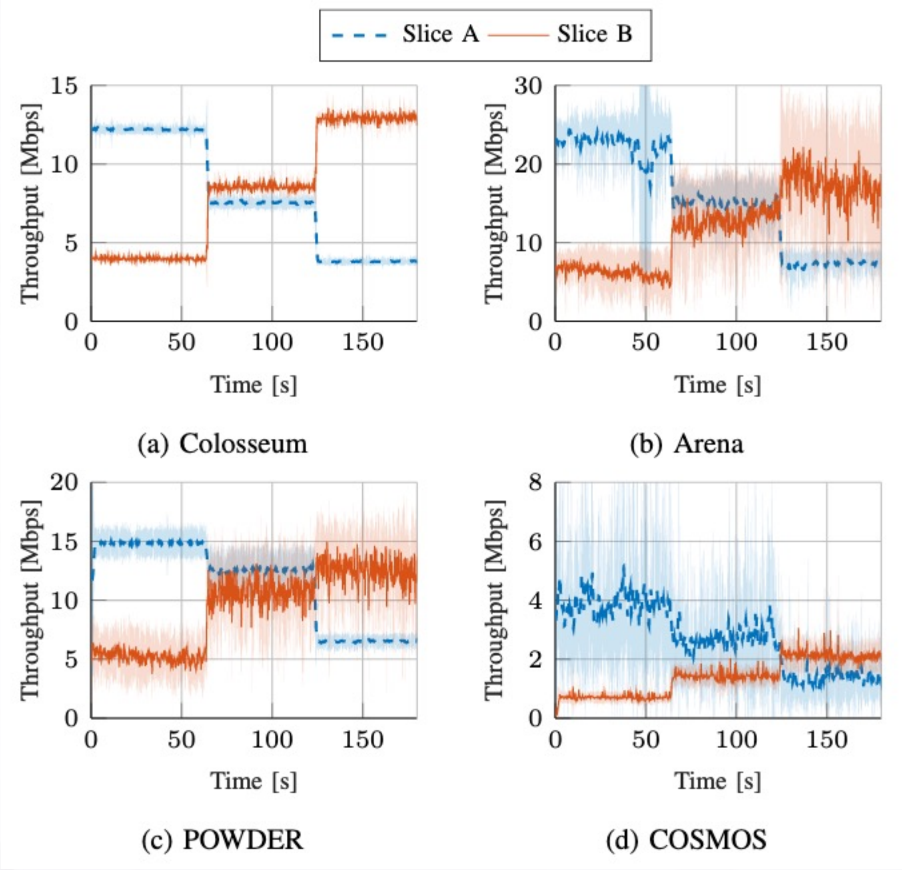

Arena

Test large-scale capabilities

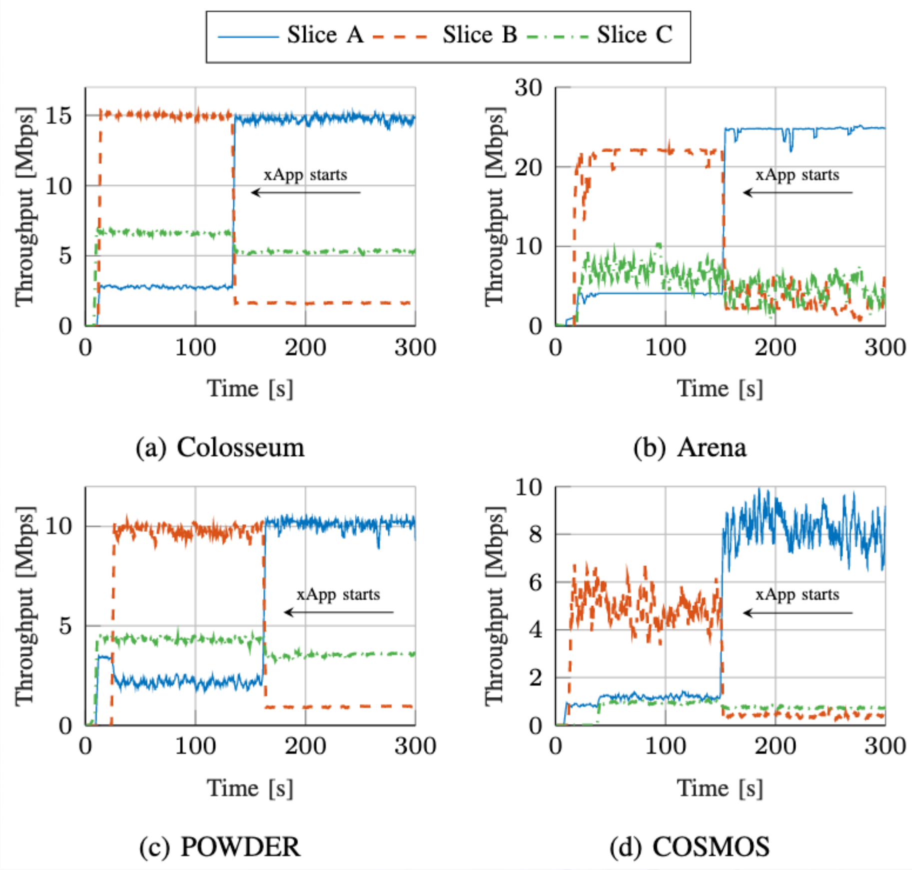
Platforms for Advanced Wireless Research

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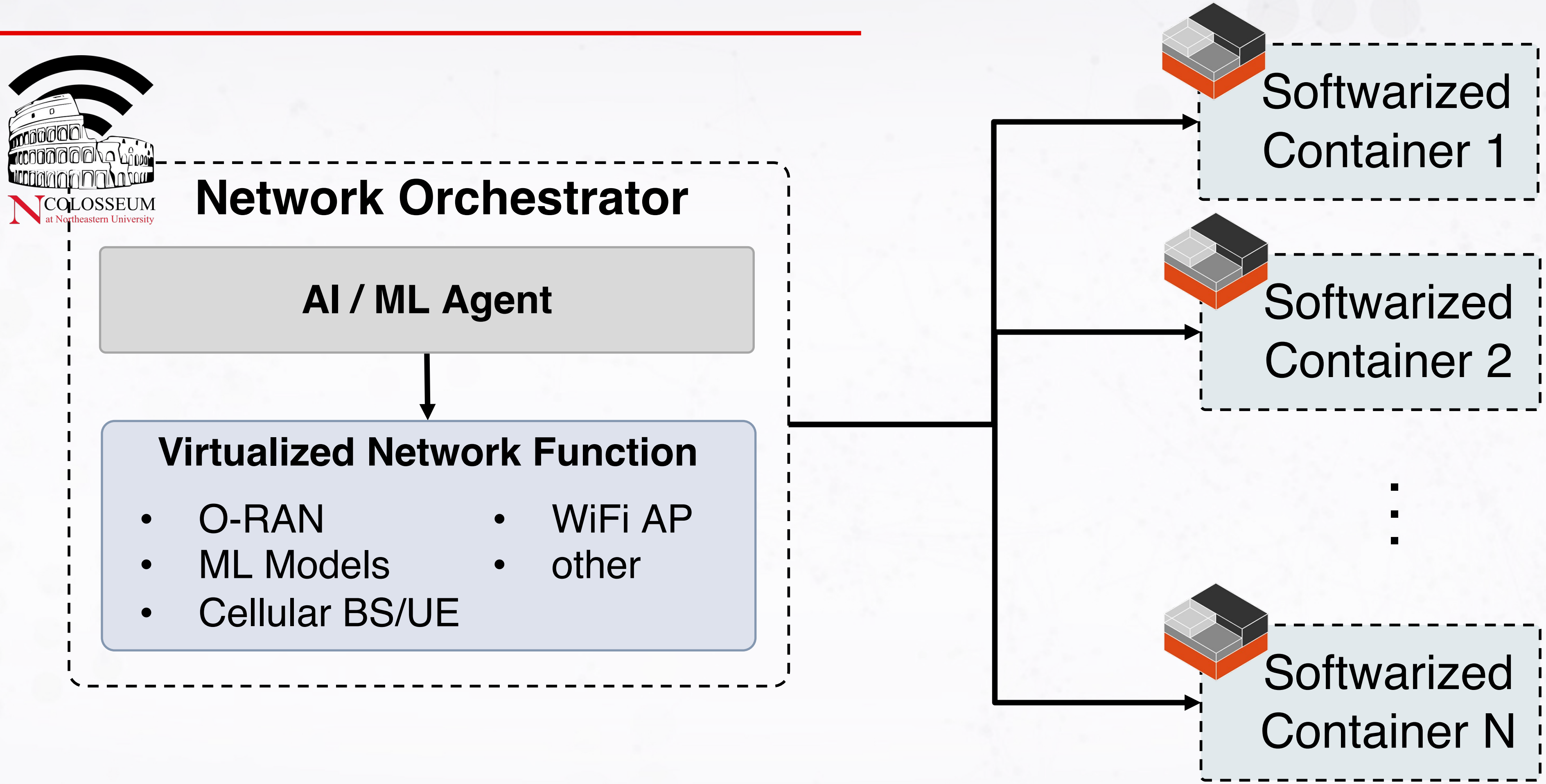
L. Bonati, M. Polese, S. D'Oro, S. Basagni, T. Melodia, "*OpenRAN Gym: AI/ML Development, Data Collection, and Testing for O-RAN on PAWR Platforms,*" Computer Networks, vol. 220, pp. 1-11, January 2023

# 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

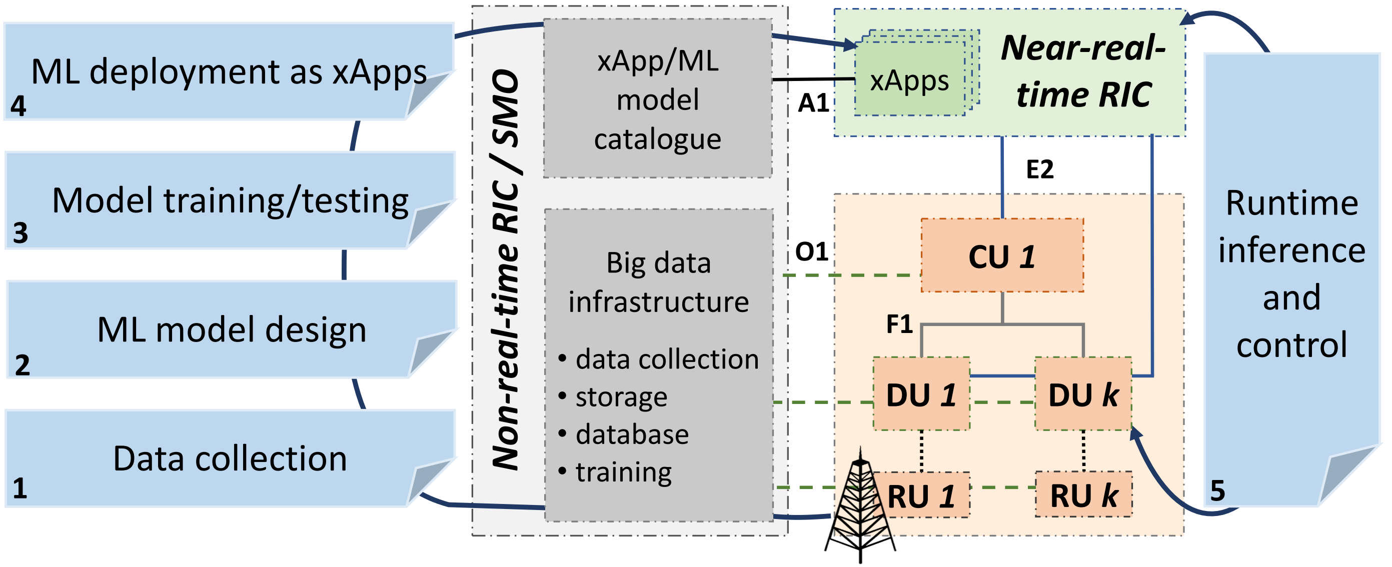
# OpenRAN Gym

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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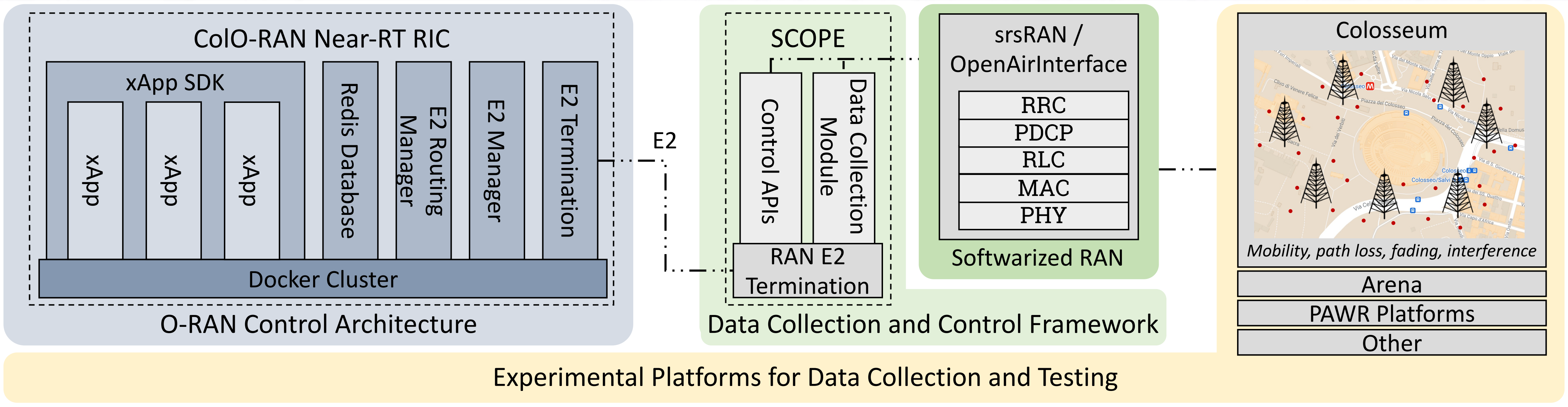
# OpenRAN Gym Components

More info at [openrangym.com](openrangym.com)

- 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)



## Part II

# Colosseum Scenarios and Massive Channel Emulator

# Scenarios

- Colosseum allows emulation at scale:
  - **256 RF transceivers**
    - >**65K** RF channels
  - Diverse **wireless conditions**
    - Fading
    - Mobility
    - Topologies
  - **Data traffic**
    - Downlink/Uplink
    - Bandwidth
    - Bitrate
    - UDP/TCP

**RF Scenarios**

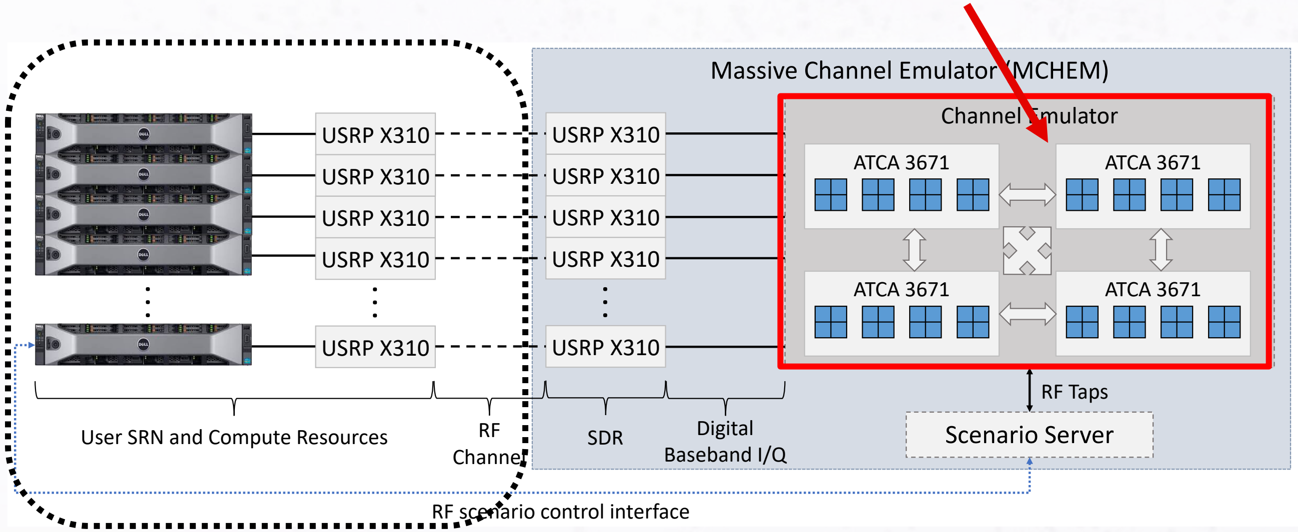
**Traffic Scenarios**

# RF Scenarios – Wireless Channel Modeling

- **Wireless channel:**
  - Modeled as a Finite Impulse response (FIR)
  - 512 complex-valued FIR taps
    - 512 delays (or paths) for the same signal
  - Stored in the Scenario Server

SRNs

MCHEM FPGAs




- The channel is **emulated** by **MCHEM**
  1. SRNs generate signals
  2. MCHEM applies the taps to SRNs' signals
     - FPGA-based FIR filtering
  3. Signals are forwarded to SRNs

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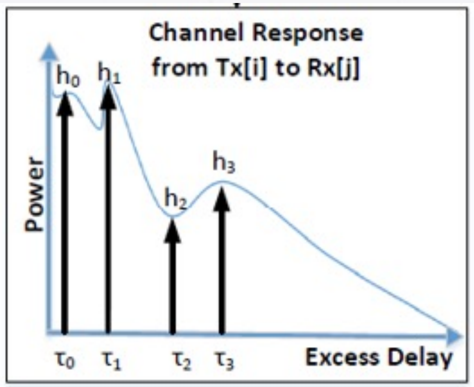
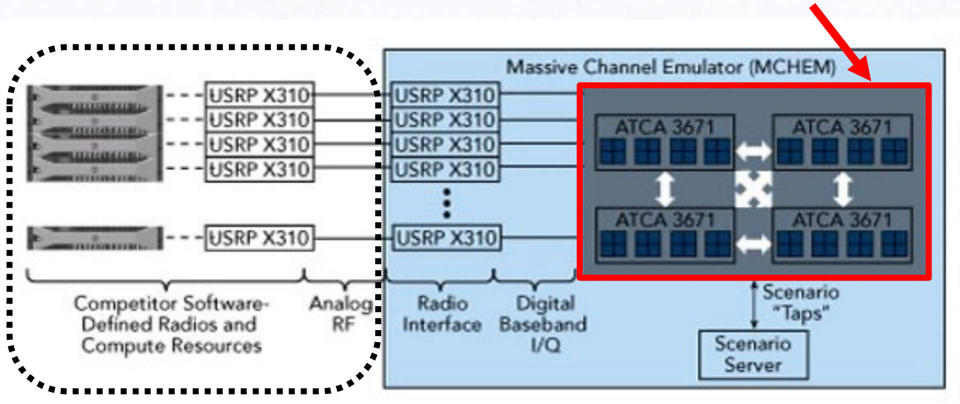
# Complexity vs. Accuracy

- **FIR taps:**
  - 512 complex-valued FIR taps for 65K RF Channels
  - **Sparse filter: only 4 are non-zero**




- **Why?**
  - Colosseum has 1 ms channel resolution
  - Scenarios are **VERY** complex
  - **Example:**
    - single-tap / 4-tap
    - 50 nodes
    - 10 minutes duration
    - > 100 GB storage needed (FIR taps only!!)
    - > 2 hours (**15 hours in the case of 4-tap**) to generate taps on servers w/ 24 CPUs and 96 GB of RAM → don't try this at home!

SRNs MCHEM FPGAs

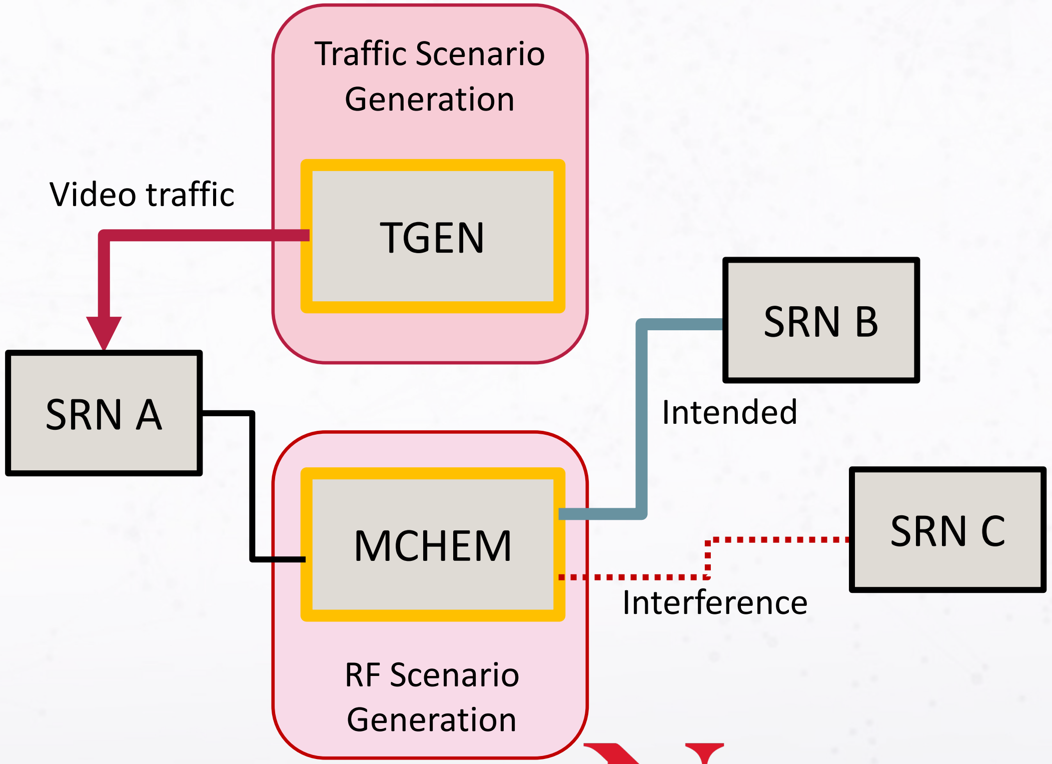


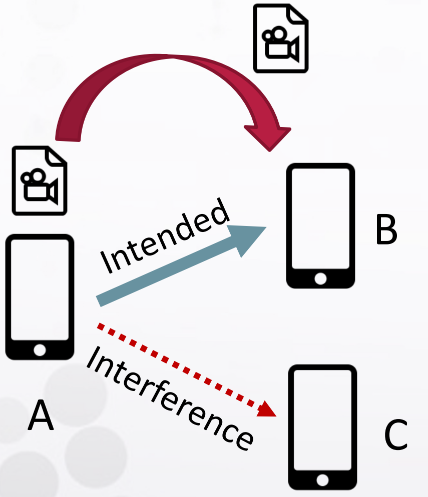

- 4-taps are a good **trade-off** between **complexity** and **accuracy**

# High-level Overview of Scenario Emulation

- Three main components:
  - **Standard Radio Nodes (SRN)**
    - Operates as a radio front-end
  - **Massive Channel EMulator (MCHEM)**
    - Emulates channel conditions
  - **Traffic GENerator (TGEN)**
    - Generate traffic for each node

*Colosseum implementation*




*Logic representation*

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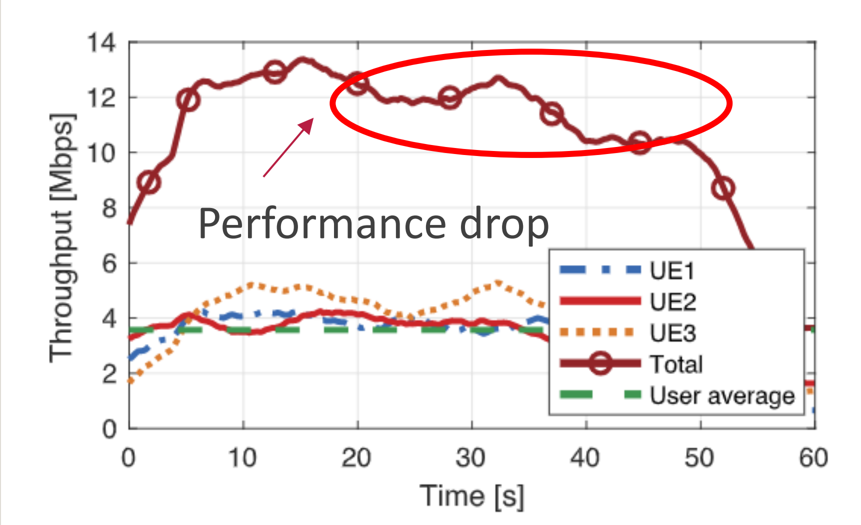
# Scenarios – The Colosseum Way

- RF 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

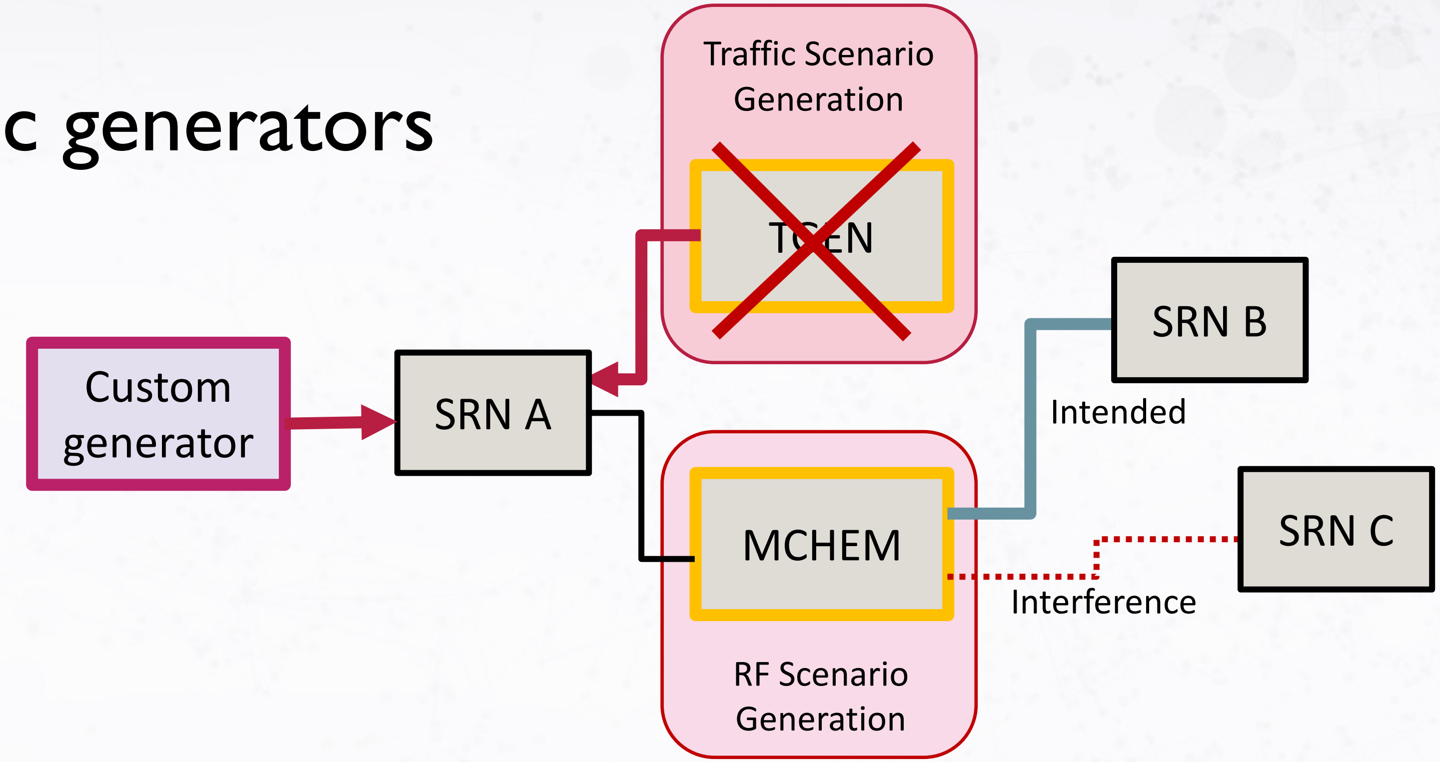



*Is the performance drop due to the* ***channel*** *or* ***bad algorithm design****?*

***An example: performance drop***

# Traffic Scenarios - Customization

- Users can use custom traffic generators
- Examples:
  - iPerf2
  - iPerf3
  - Netperf
  - MTR
- TGEN gets bypassed

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## Thank You! Q&A

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