



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:

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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

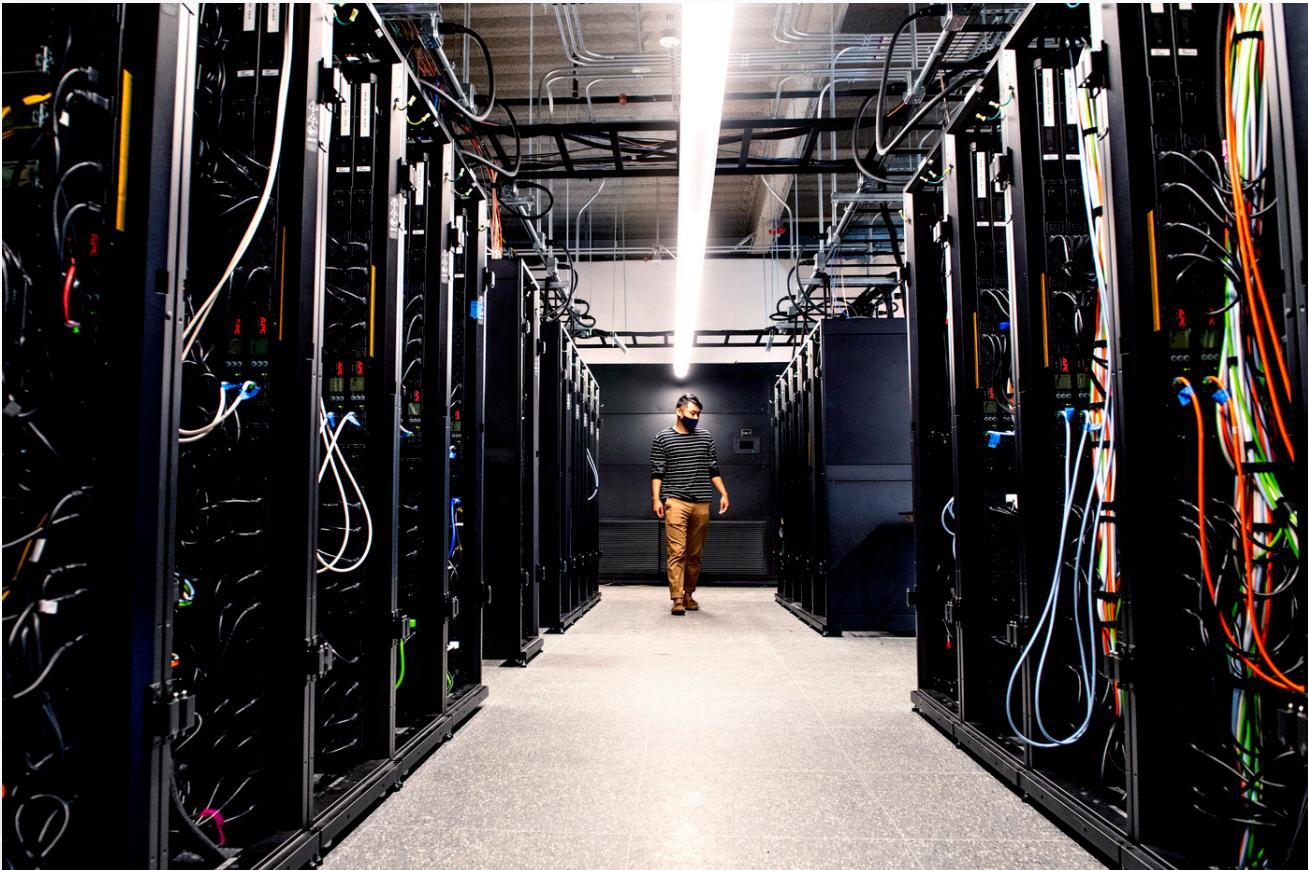


Part I

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**

Colosseum as Enabler for AI/ML

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

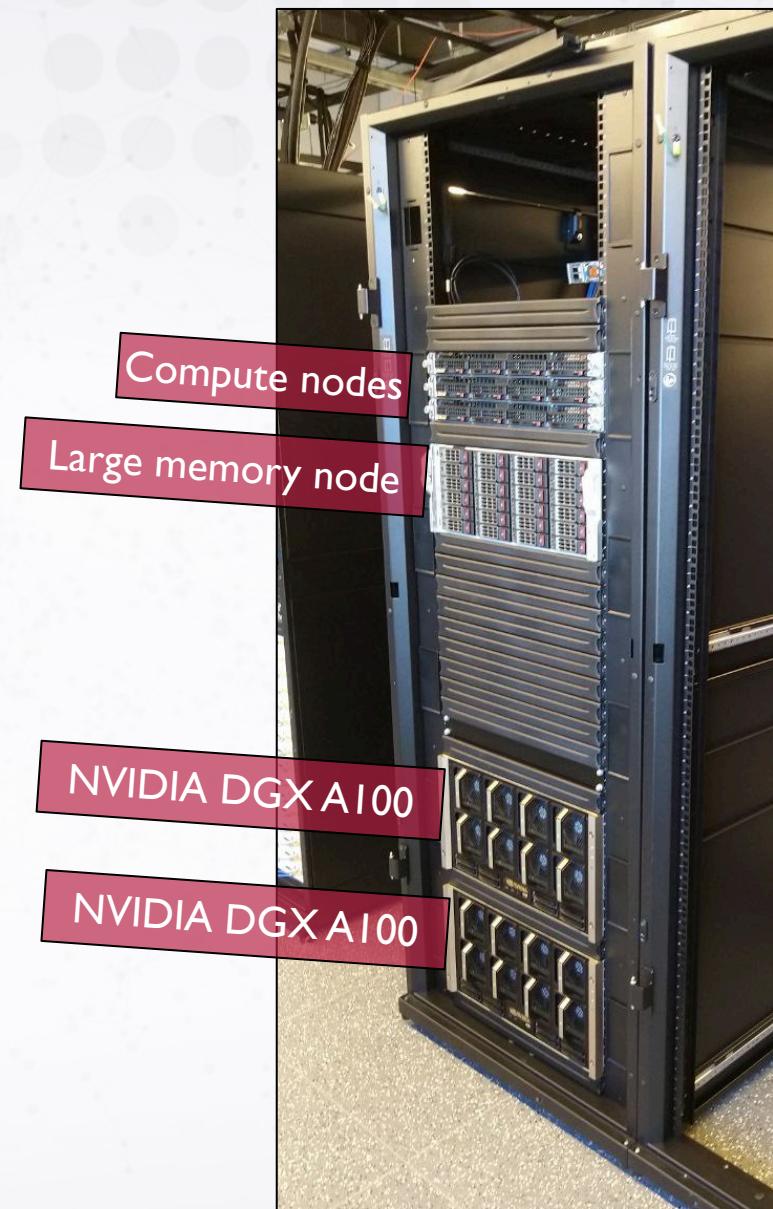
- 2x NVIDIA DGX A100: 8 GPUs each, 10 petaFLOPS compute power
- 1x large memory node (Supermicro Superserver 8049U-E1CR4T): 6 GPUs, 3TB of RAM
- 3x compute nodes
- 1x Mellanox Infiniband switch: Tbps dedicated



8 NVIDIA A100 GPU 40 GB



Mellanox Infiniband switch



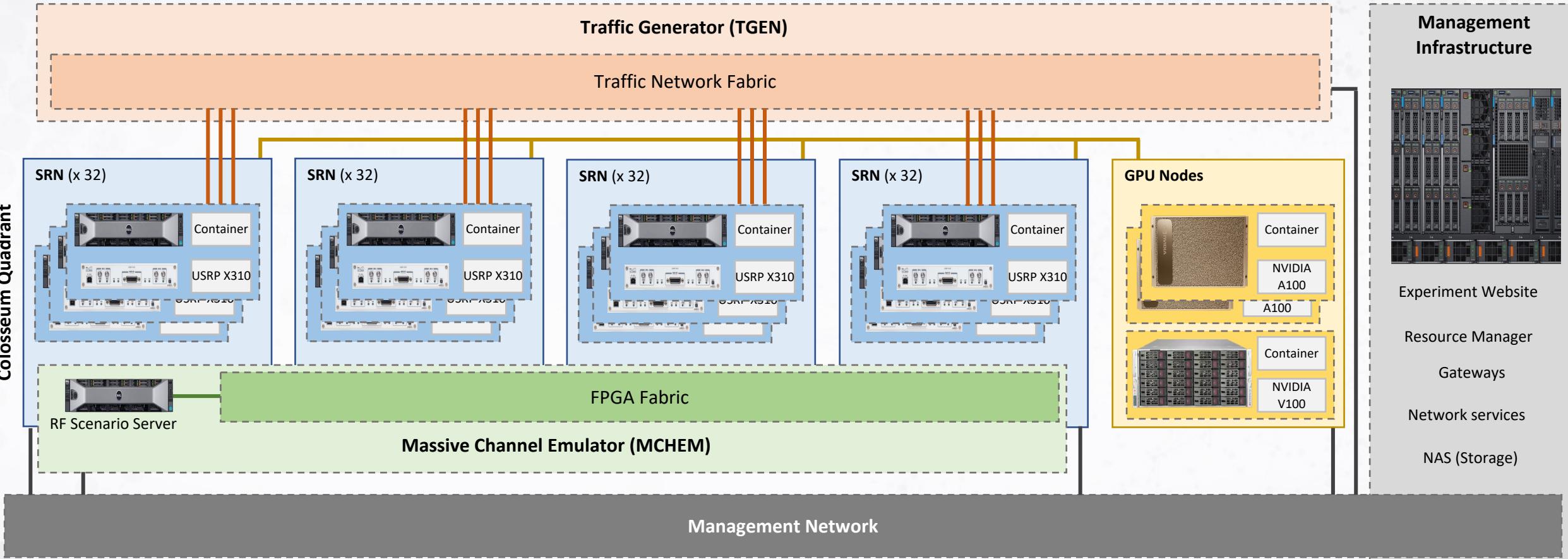
Colosseum: Much More Than a Supercomputer

- 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

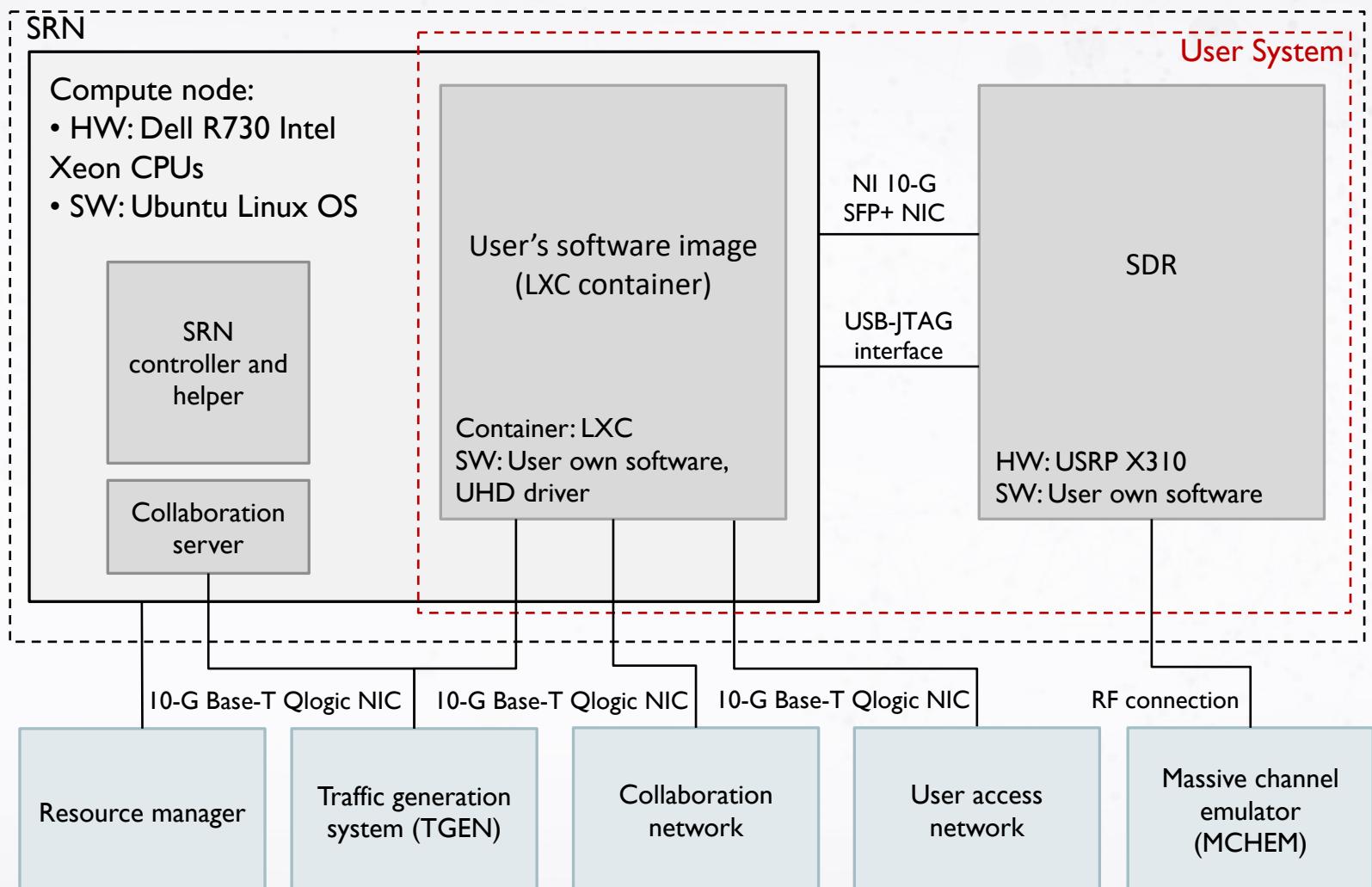


Colosseum Architecture

Colosseum Quadrant

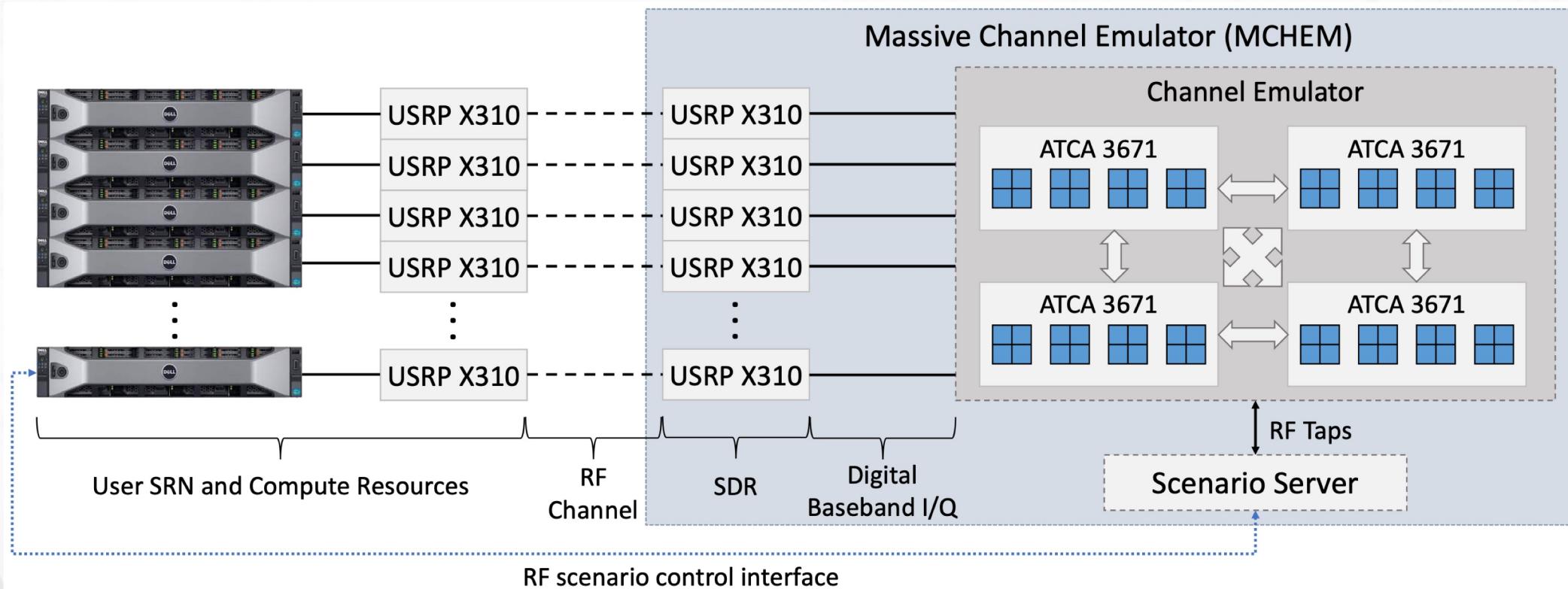


Standard Radio Node (SRN)



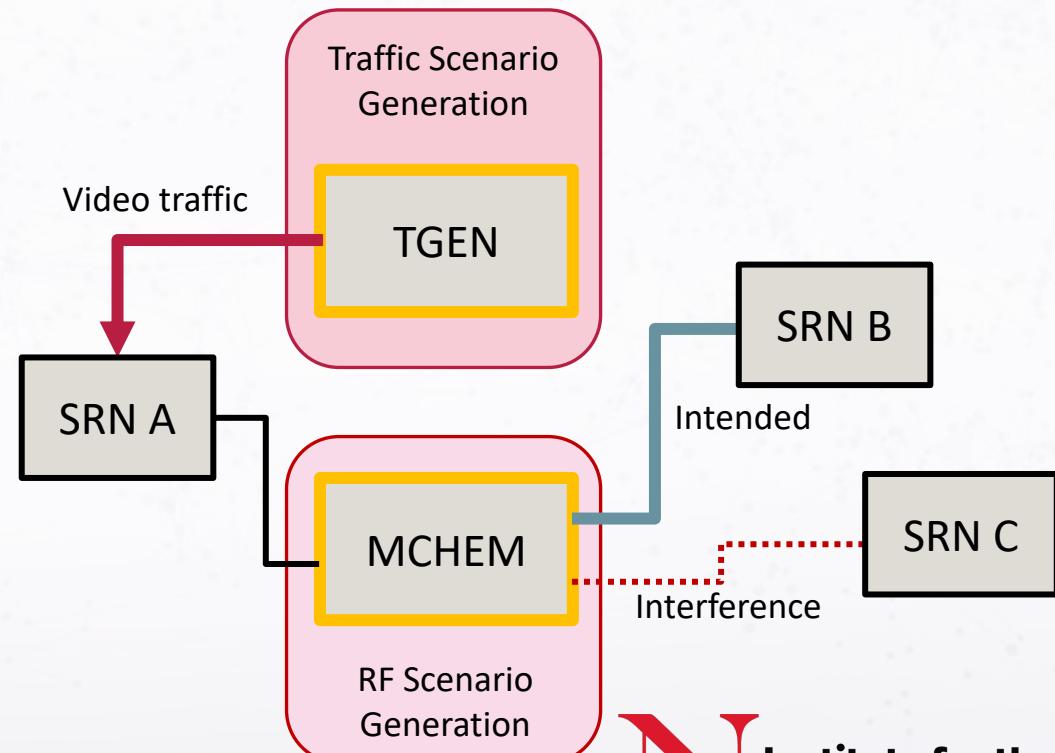
Massive Channel Emulator (MCHEM)

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



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

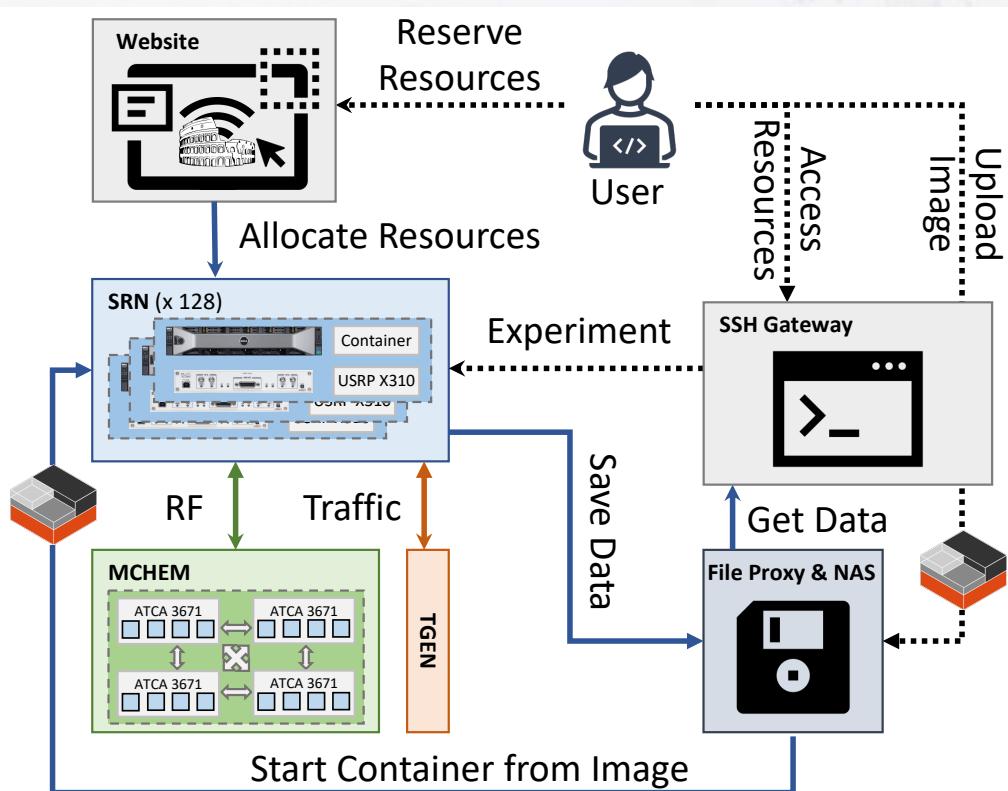


Open to the Research Community

- 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

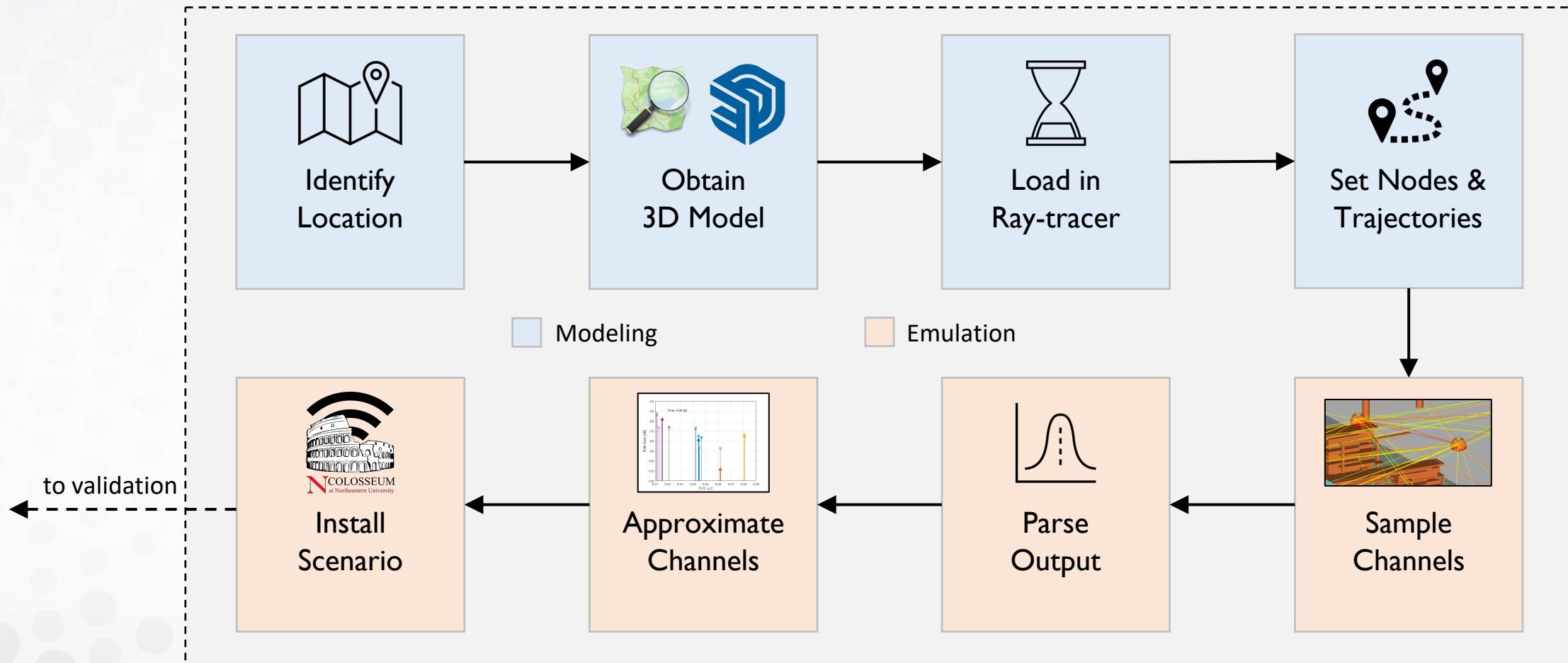
How to get access:

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



Scenario Creation Overview

Scenario Creation Overview



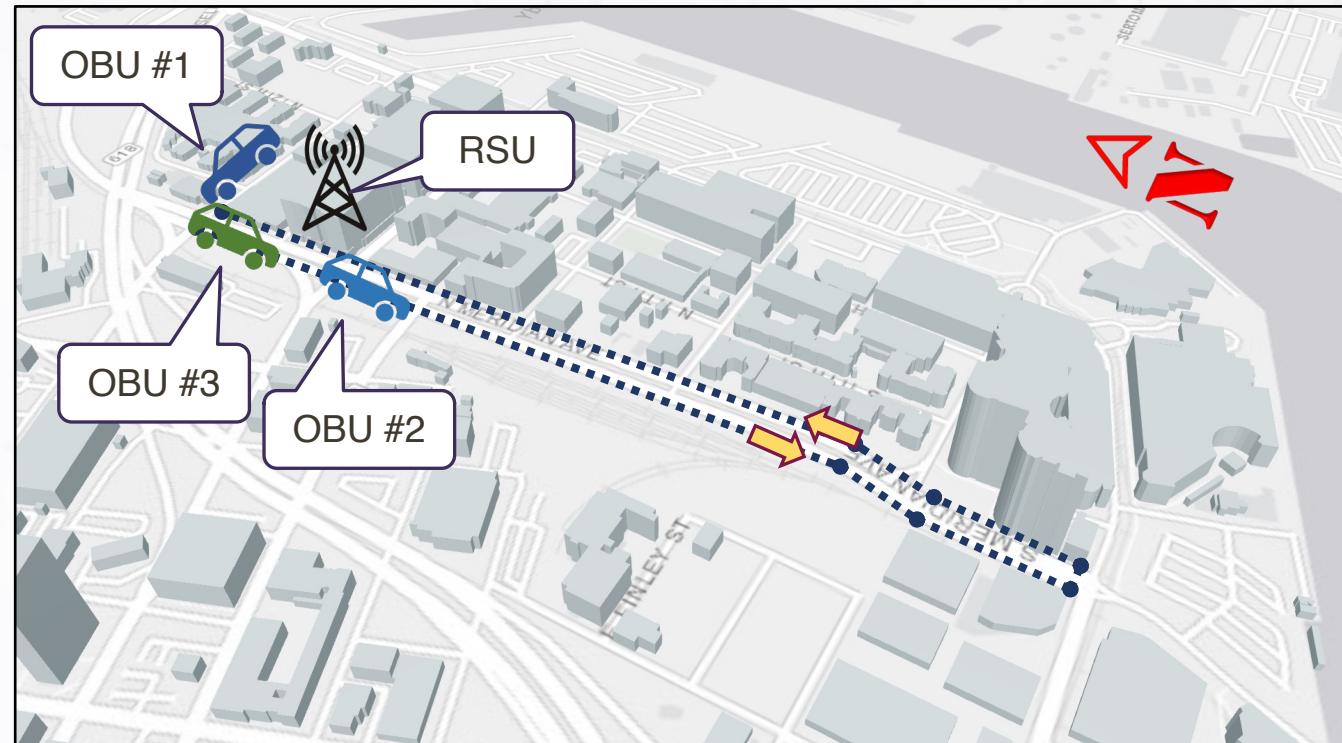
D. Villa, M. Tehrani-Moayyed, P. Johari, S. Basagni, T. Melodia, "CaST: A Toolchain for Creating and Characterizing Realistic Wireless Network Emulation Scenarios", Proceedings of ACM WiNTECH 2022, Sydney, Australia, October 2022

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

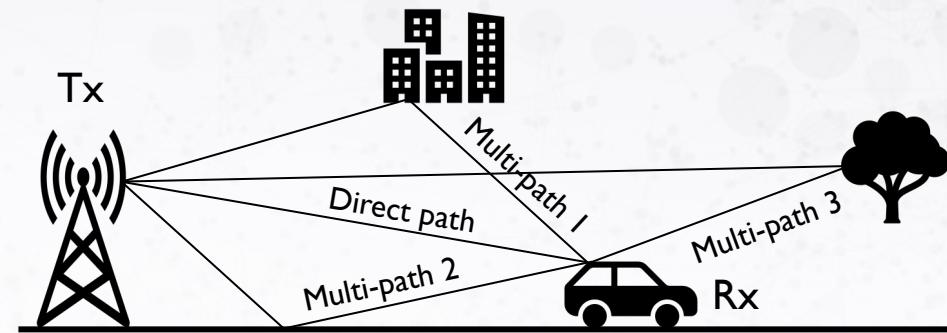
1. **Identify** scenario location
2. **Obtain** 3D model from OSM
3. **Convert** model in STL to feed Wireless InSite
4. **Define** nodes and trajectory
5. **Sample** the channel using the ray-tracer
6. **Parse** the output to extract channels at each time instant
7. **Approximate** channels
8. **Install**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



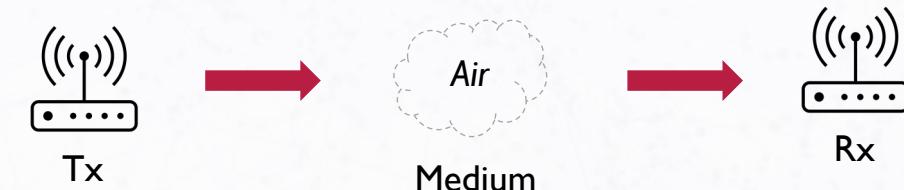
Tampa, FL mobile scenario

Scenario Validation

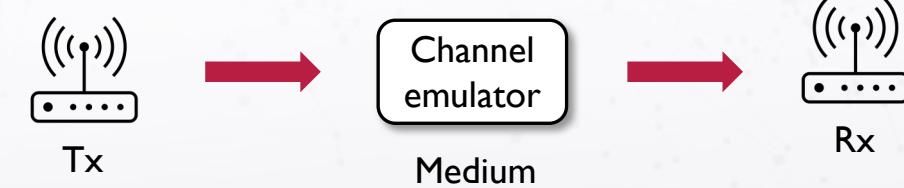
- Channel sounding goals:
 - **Evaluate** an RF channel characteristics
 - **Analyze** the environment
 - **Optimize** the design
- **No over-the-air** communication
- **Emulated** medium
- Sounding goals in emulators:
 - **Validate** original traces:
 - Channel Impulse Response (**CIR**) for Time of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



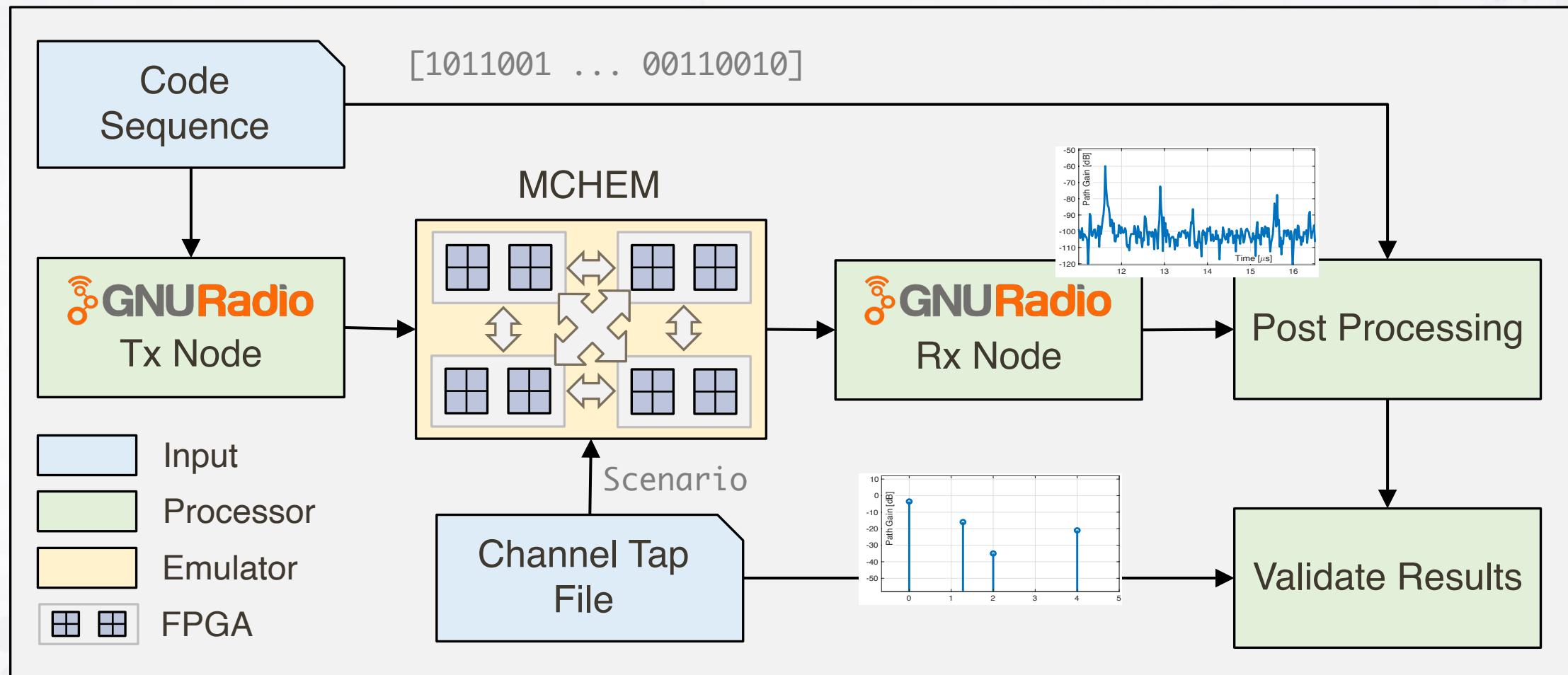
Communication over-the-air



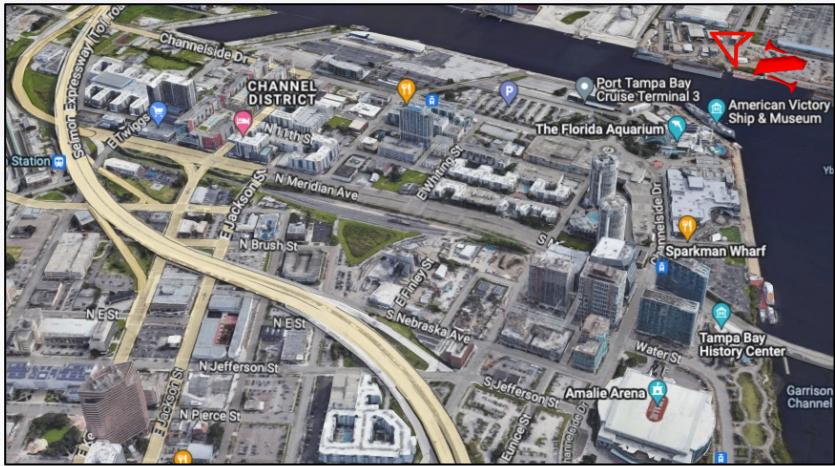
Communication in emulators



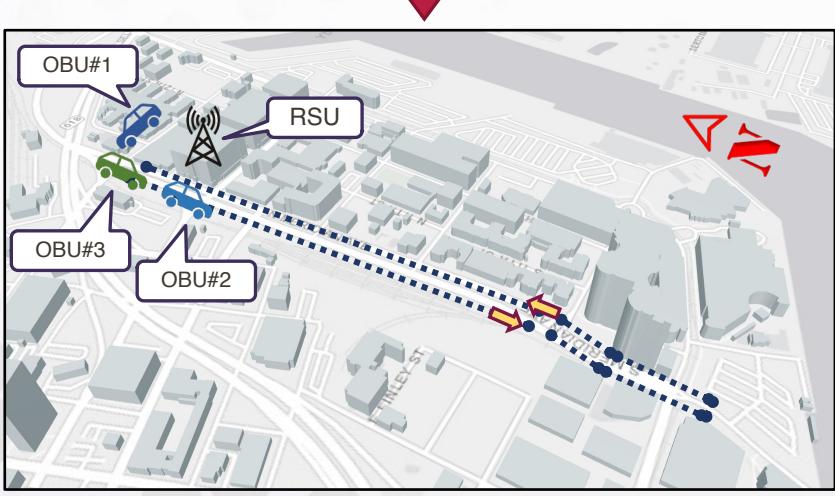
CaST Channel Sounding Workflow



Some Results: Use Case V2X Tampa, FL

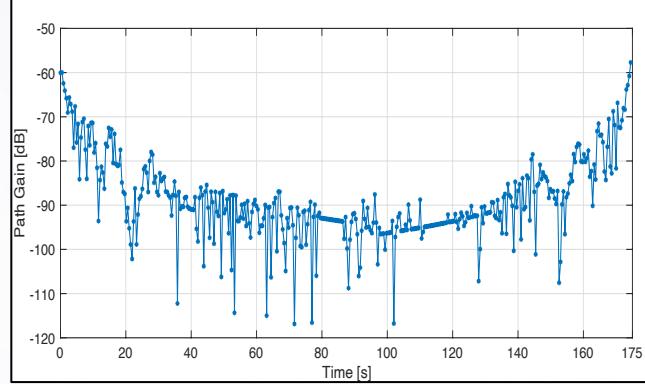


Real Environment

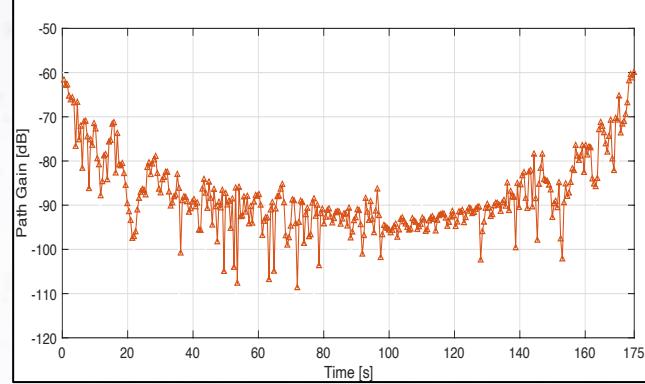


Digital Environment

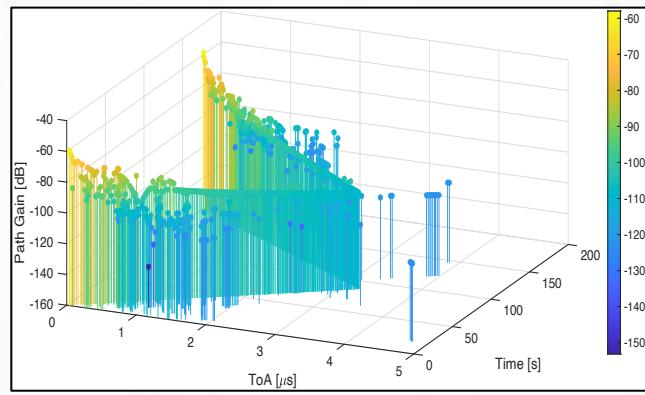
**CaST
Sounder**



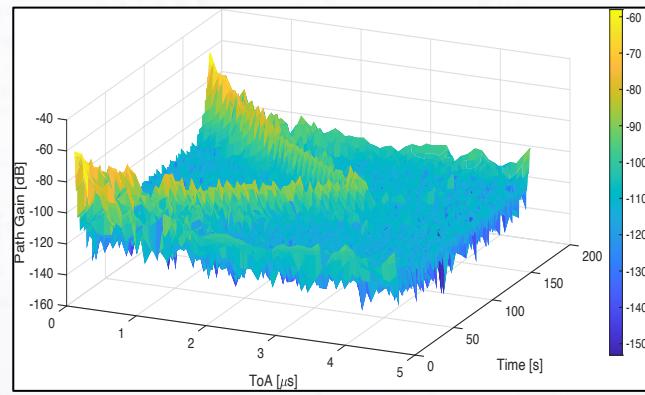
Theoretical path gains RSU-OBU#2



Emulated path gains RSU-OBU#2



Theoretical channel taps RSU-OBU#2

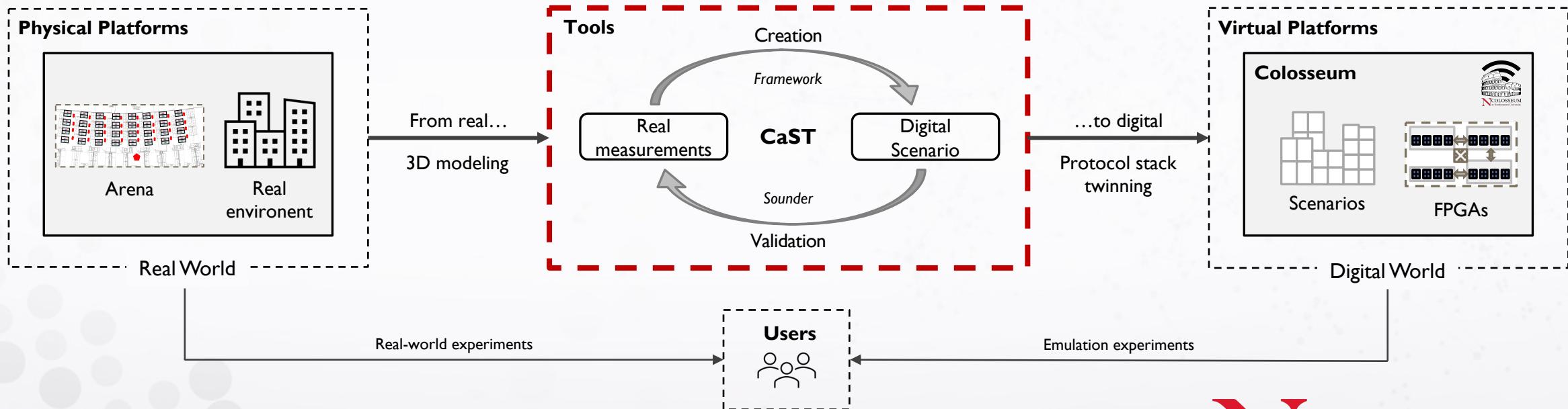


Emulated channel taps RSU-OBU#2

**Good match between real
and emulated environment**

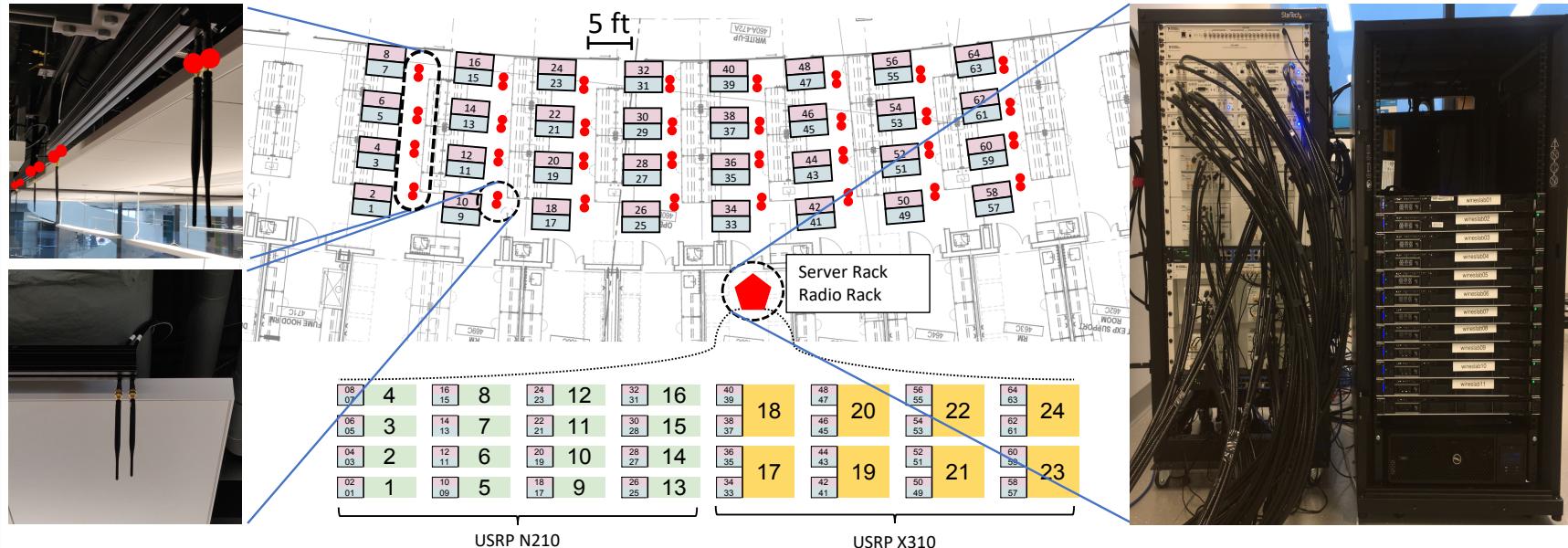
Colosseum as a Digital Twin

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



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.



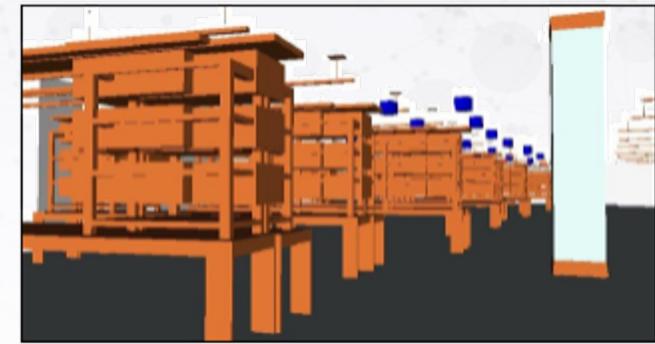
- **Real-time real-channel** evaluation platform
- **Fully-synchronized** testbed
- Repeatable, flexible, and scalable **high-fi** indoor experiments

From Real to Digital

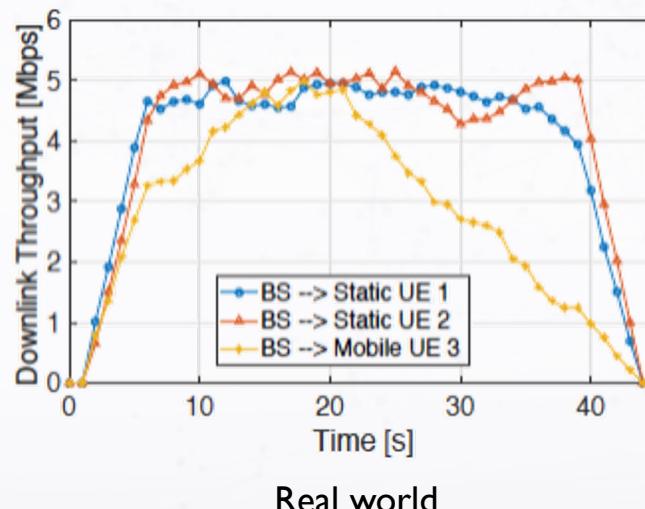
- Create **3D representation** of **real-world location** (e.g., w/ Sketchup, OpenStreetMap)
- **Model channels** through ray-tracing (e.g., w/ Wireless InSite, CaST)
- **Validate** through experiments in digital and real world



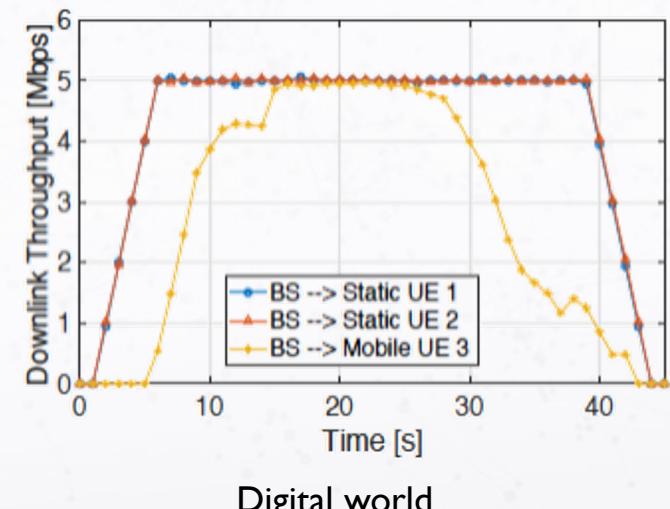
Real world



Digital world



Real world



Digital world

Good match between real and digital environment

Colosseum as Enabler for AI/ML

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

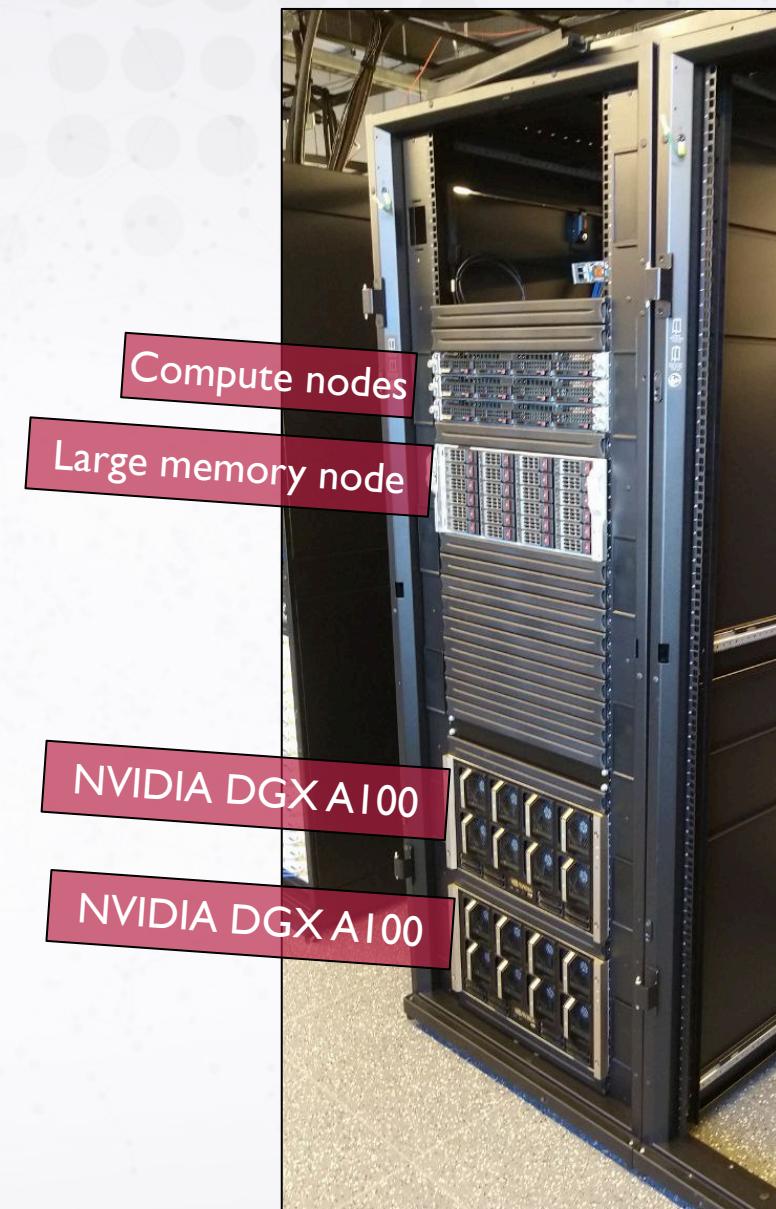
- 2x NVIDIA DGX A100: 8 GPUs each, 10 petaFLOPS compute power
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- 3x compute nodes
- 1x Mellanox Infiniband switch: Tbps dedicated



8 NVIDIA A100 GPU 40 GB



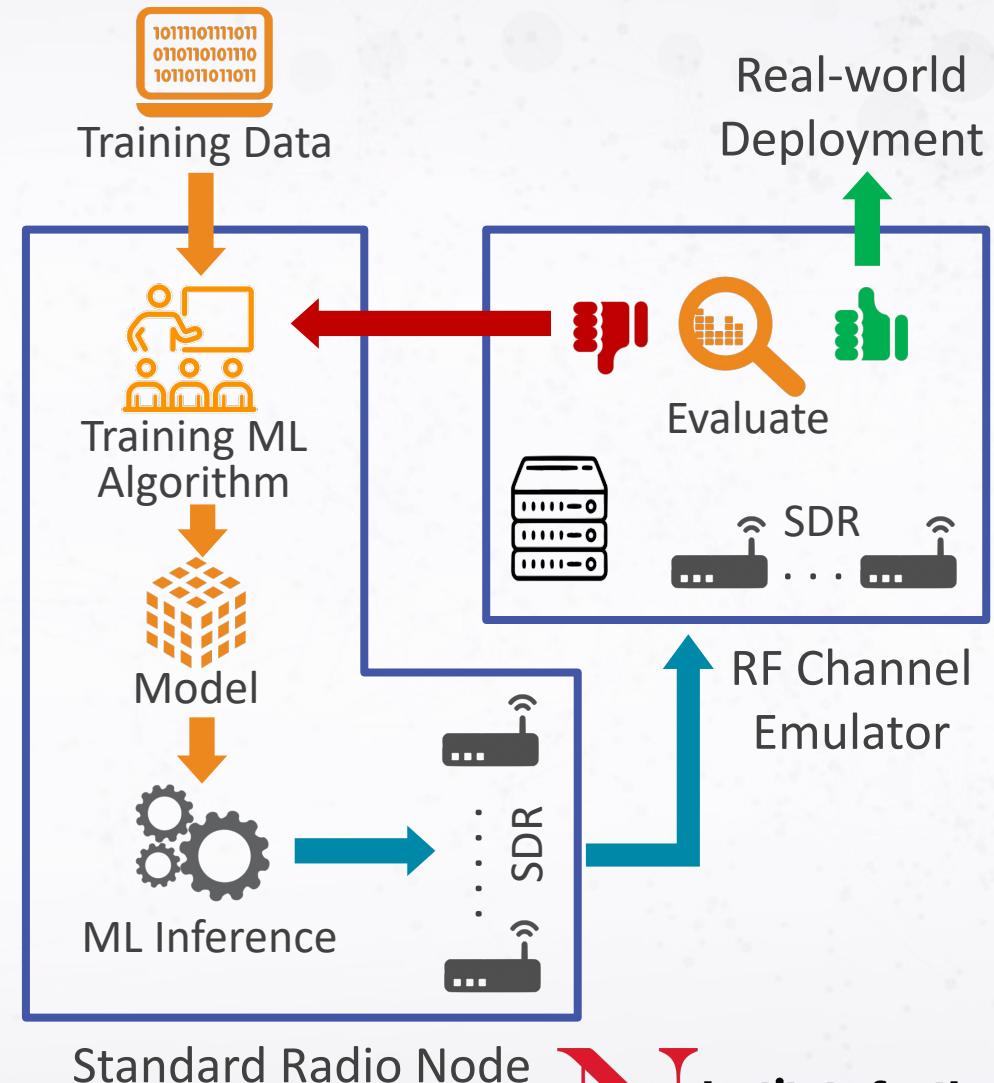
Mellanox Infiniband switch



Colosseum Use Cases

Fusion of Artificial Intelligence and Wireless

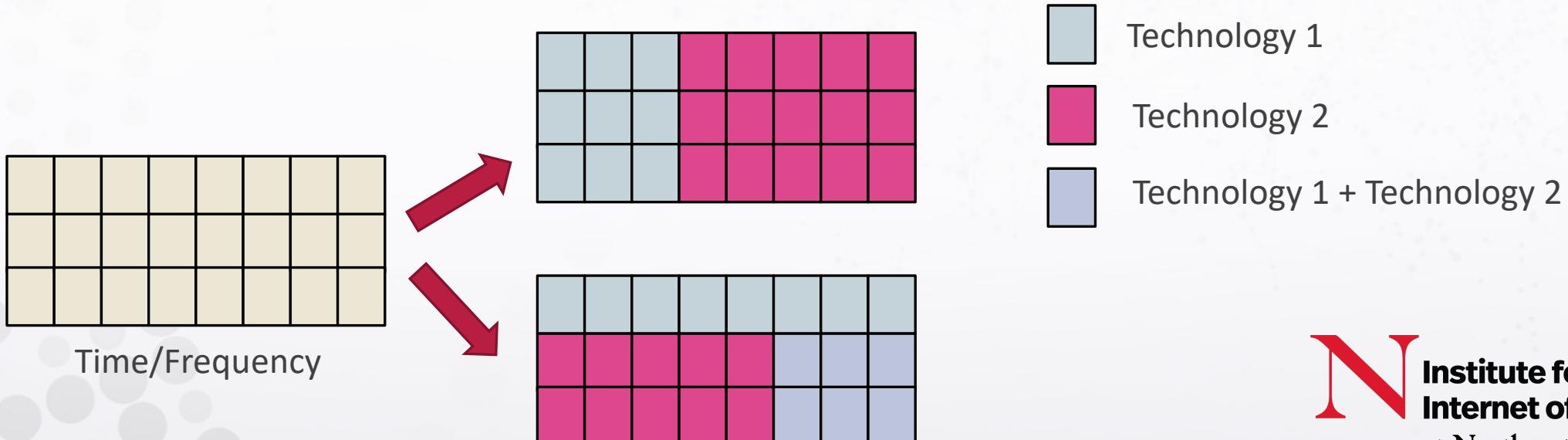
- **Trend:** IoT applications are getting **smarter** by incorporating Artificial Intelligence
- **Challenge:** Large-scale in-field deployment of IoT devices to train and test with AI algorithms is challenging, time consuming and often expensive
- **Opportunity:** Colosseum provides a unique platform 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



Standard Radio Node

Spectrum Sharing

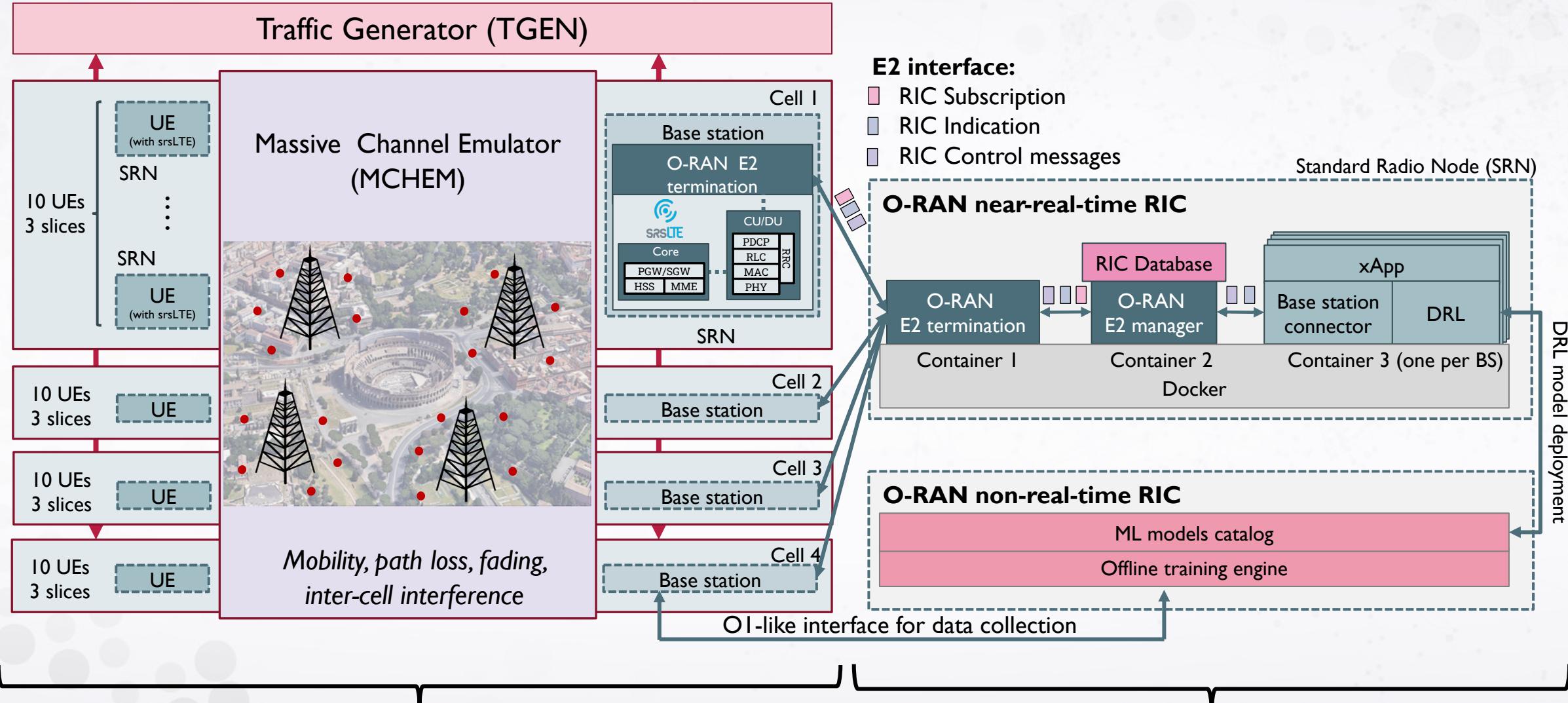
- **Trend:** With the **ever-increasing number of connected devices** and new technologies, **coexistence** is essential to overcome spectrum scarcity
- **Challenge:** Can several transmissions **coexist** on the same spectrum band **reliably?**
- **Opportunity:** With Colosseum AI capabilities, **adaptive 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



Open RAN on Colosseum

Example of Programmable RAN Study

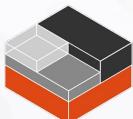
L. Bonati, S. D'Oro, M. Polese, S. Basagni, and T. Melodia, "Intelligence and Learning in O-RAN for Data-driven NextG Cellular Networks", IEEE Communications Magazine, vol. 59, no. 10, pp. 21–27, October 2021



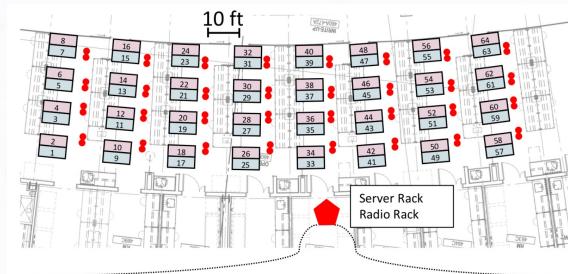
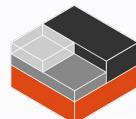
Prototype At-scale, Test in the Wild

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

Test at-scale
on emulated
scenarios

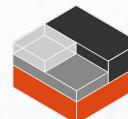


Validate in
real wireless
environment



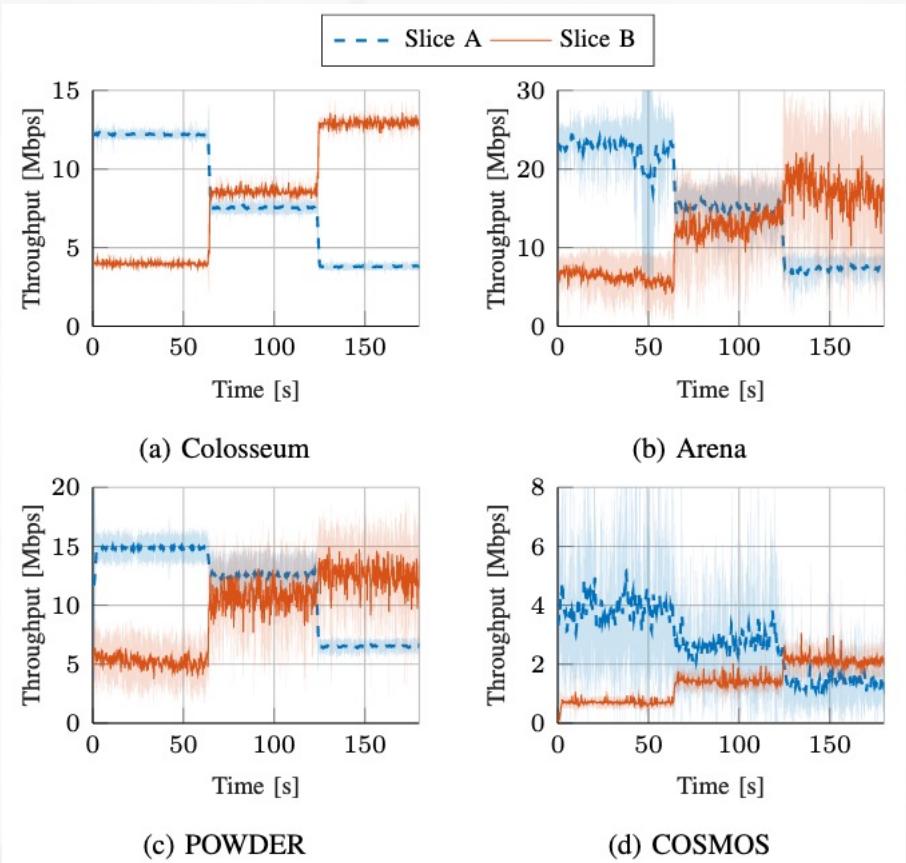
Arena

Test large-
scale
capabilities

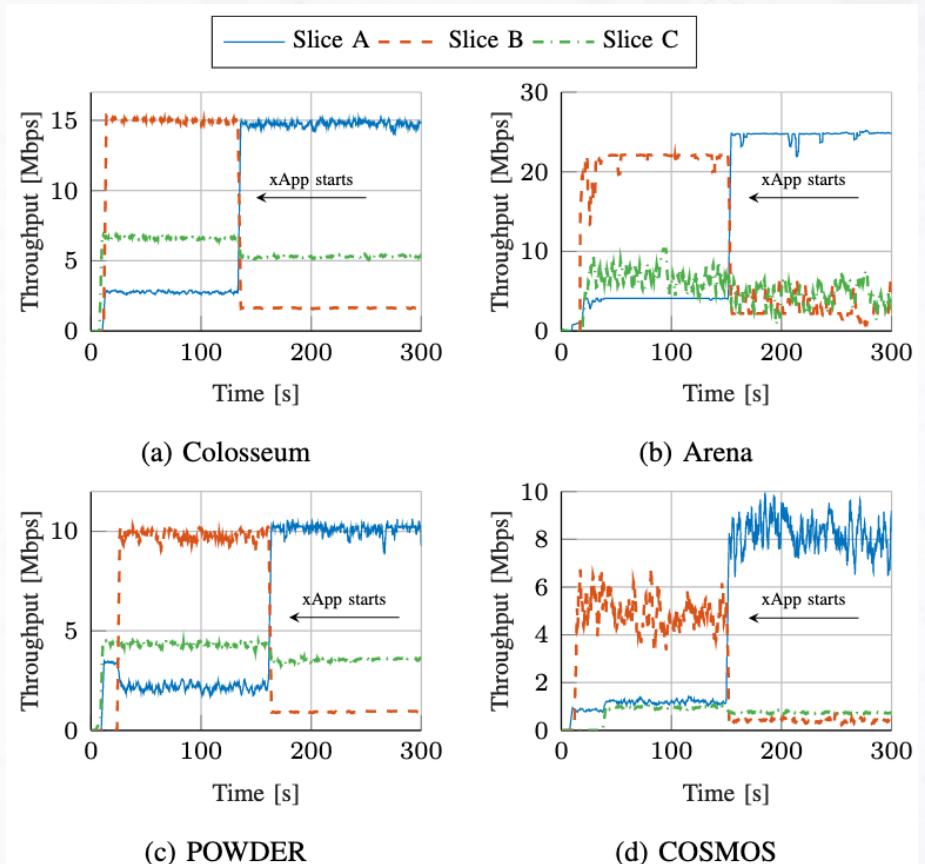


From Colosseum to PAWR

Periodic change of slicing resources



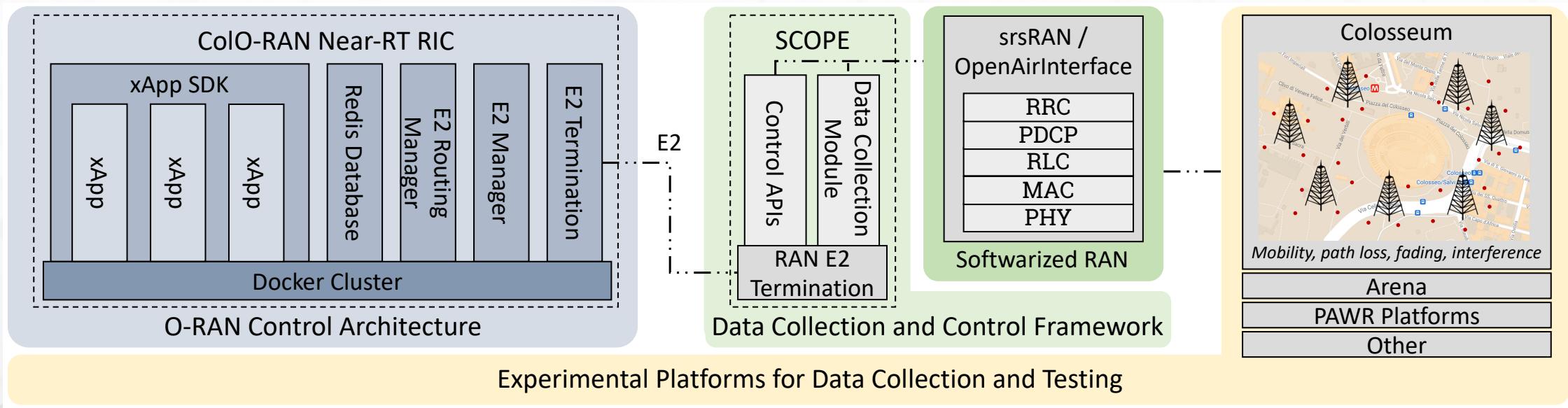
xApp closed-control loop



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

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)



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

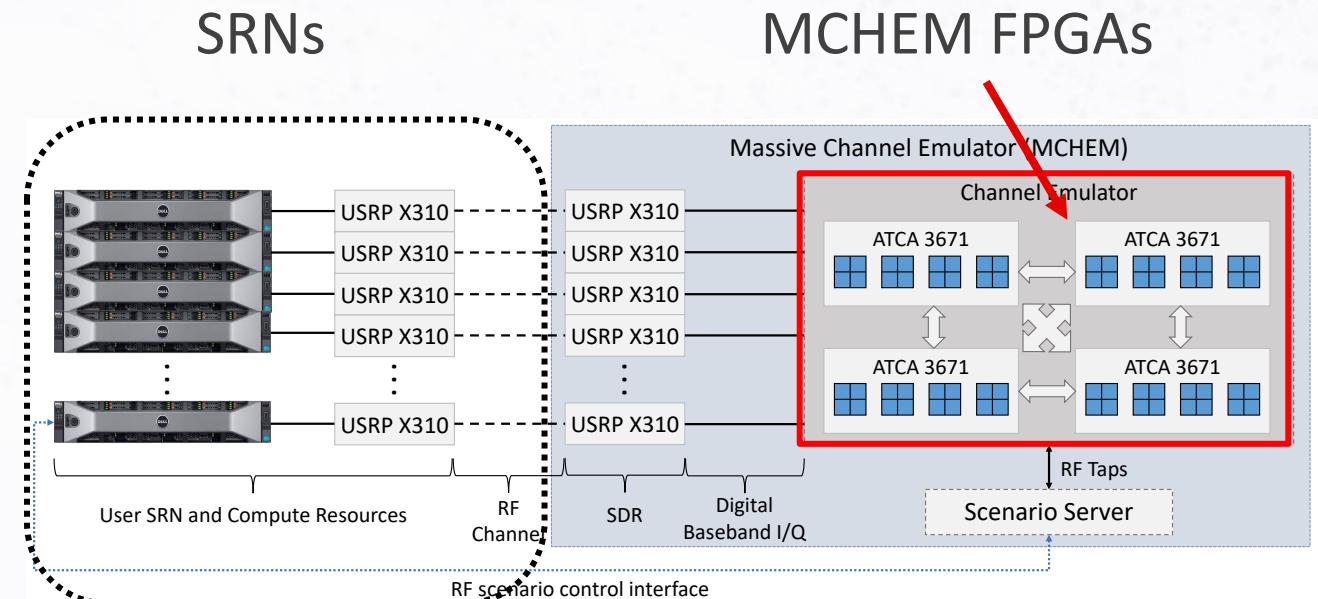
RF Scenarios – Wireless Channel Modeling

- **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

- 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



RF Channel Emulation with FIR Filters

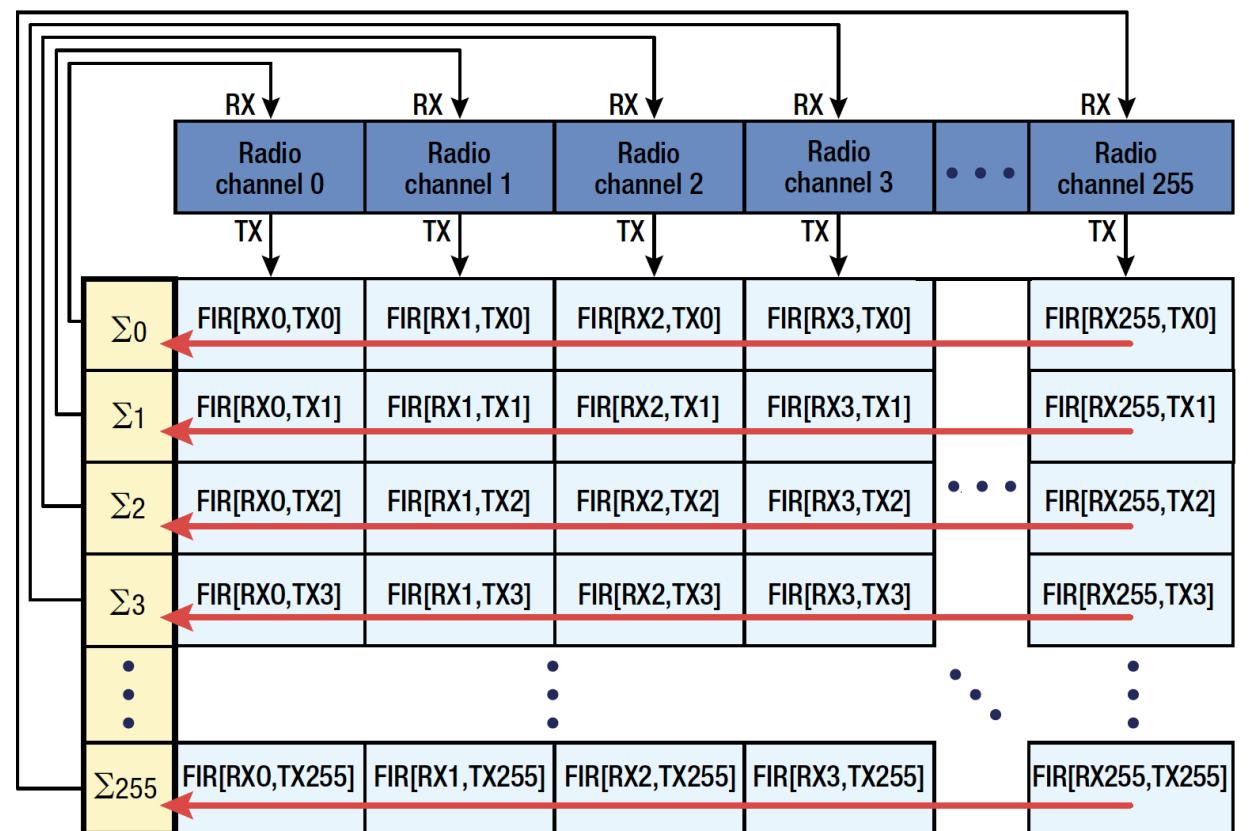
The received signal is the **convolution** in time of the transmitted signal and the channel impulse response



$$y[n] = b_0x[n] + b_1x[n - 1] + \dots + b_Nx[n - N]$$

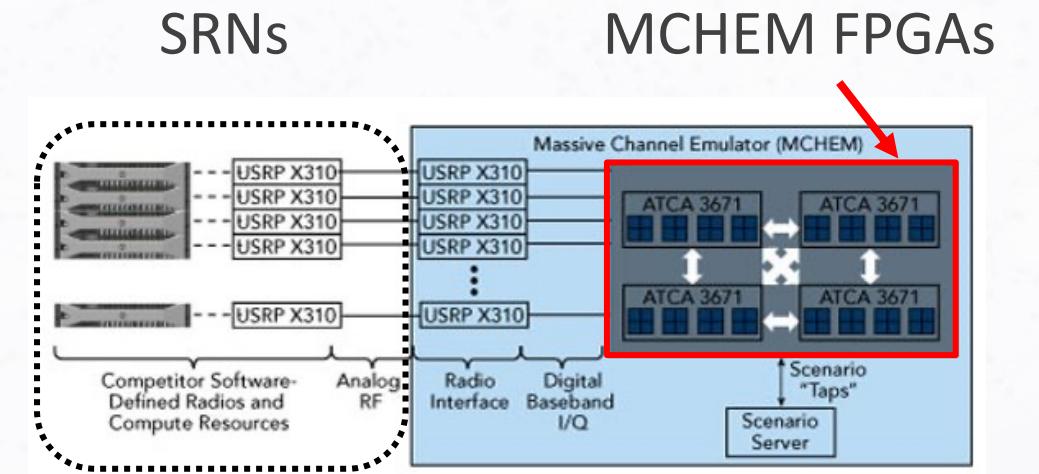
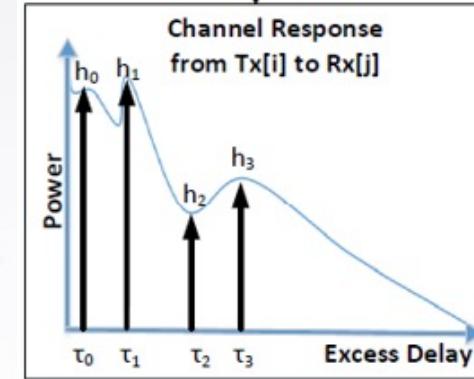
$$= \sum_{i=0}^N b_i \cdot x[n - i],$$

FIR taps



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

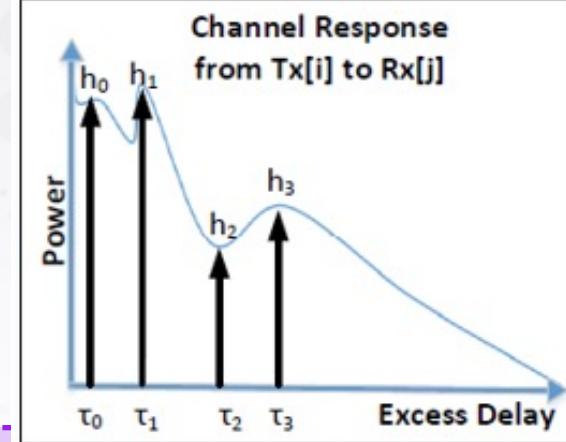


Ways to Generate Filter Taps

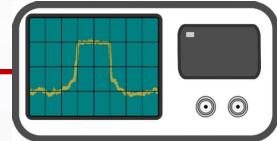
- **Mathematical model**
 - Deterministic/added randomness, no ground truth



$$20 \log_{10}(d) + 20 \log_{10}(f) + 92.45$$

 b_i 

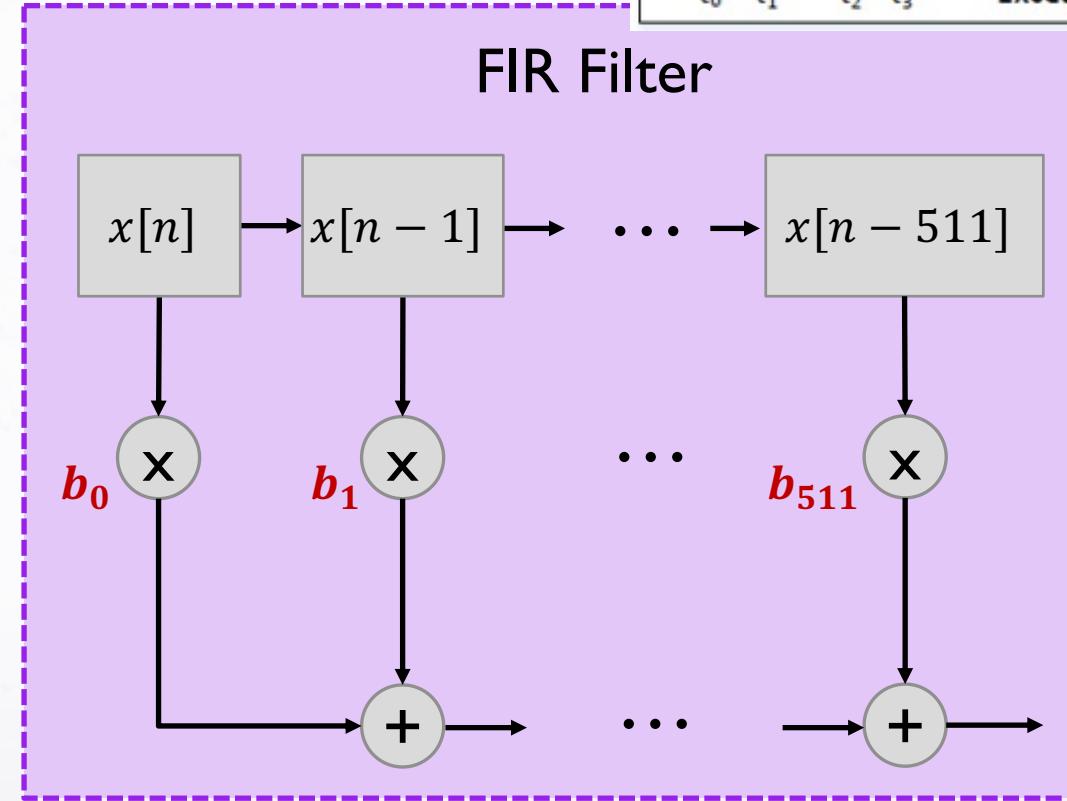
- **On-site measurements**
 - Realistic but site/time specific

 b_i

- **Software-based (ray tracer)**
 - Accurate but complex



Calibrate
w/ measurements

 b_i 

High-level Overview of Scenario Emulation

- Three main components:

- Standard Radio Nodes (SRN)**

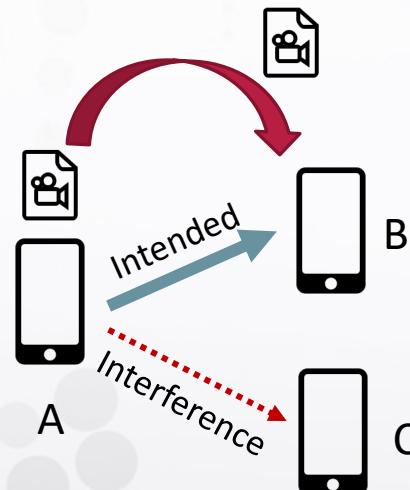
- Operates as a radio front-end

- Massive Channel EMulator (MCHEM)**

- Emulates channel conditions

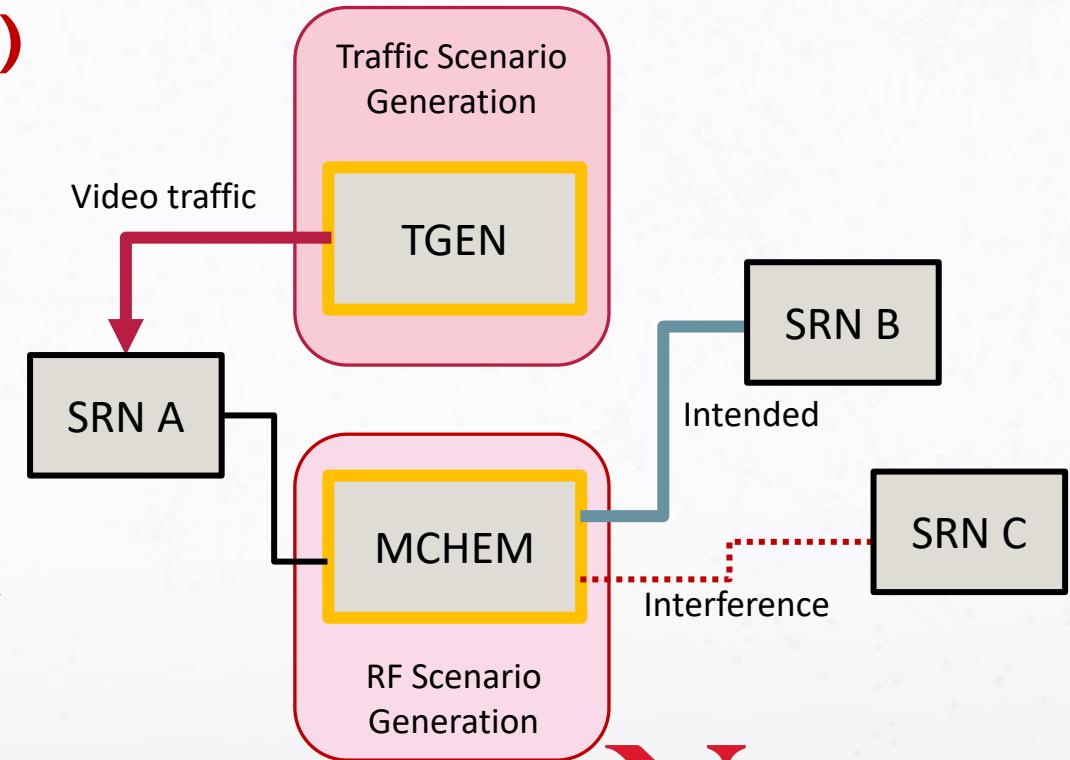
- Traffic GENerator (TGEN)**

- Generate traffic for each node



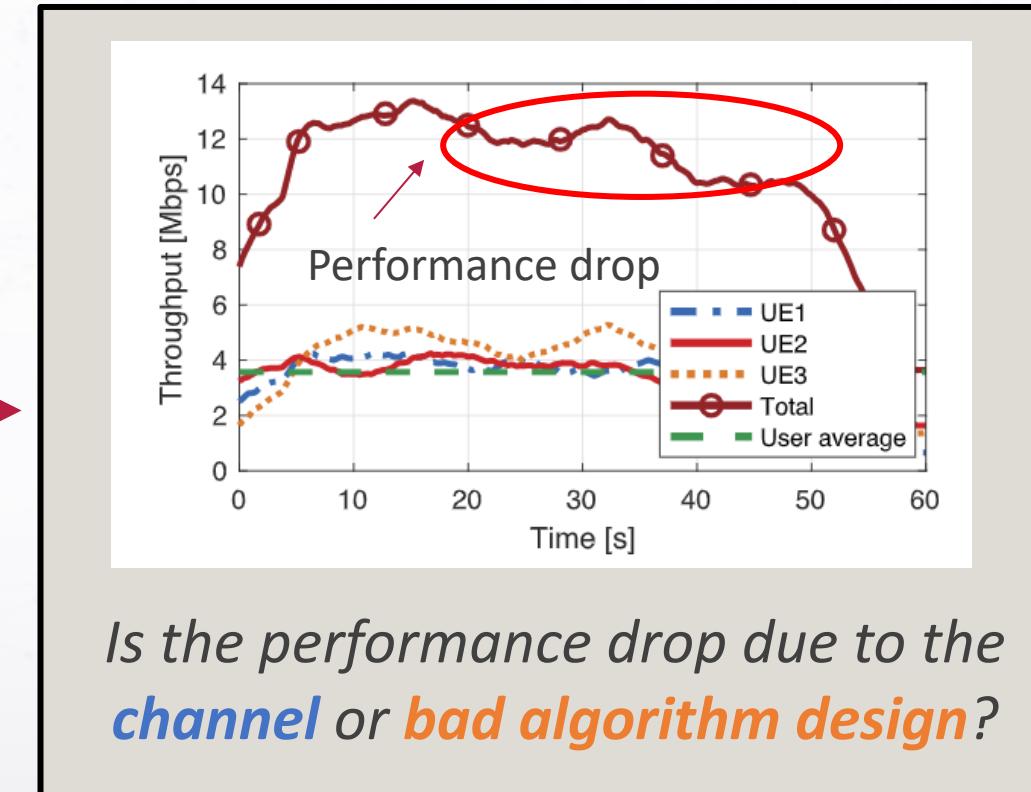
Logic representation

Colosseum implementation



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



An example: performance drop

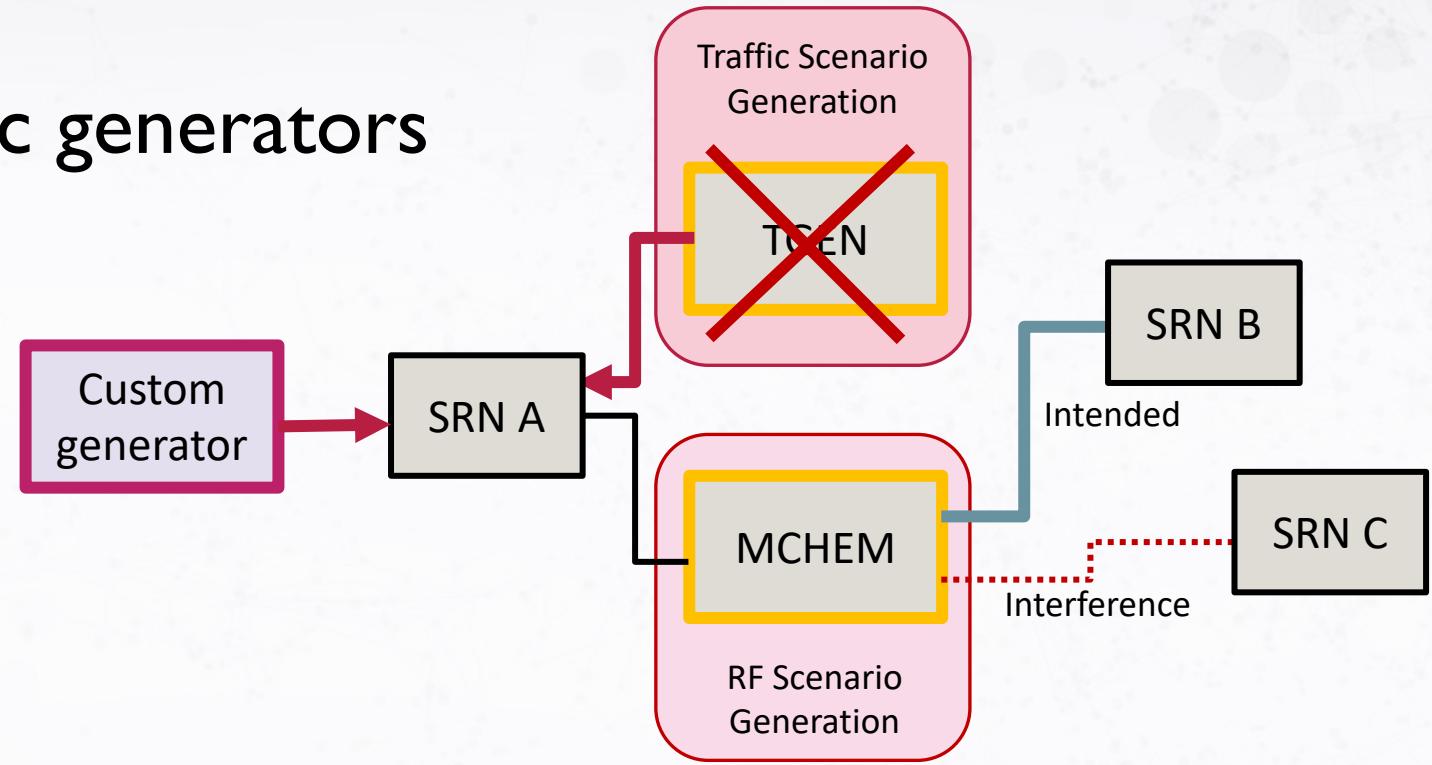
Traffic Scenarios - Customization

- Users can use custom traffic generators

- Examples:

- iPerf2
- iPerf3
- Netperf
- MTR

- TGEN gets bypassed



Interactive Reservation Demo and Q&A