LVX VERITAS VIRTVS

Institute for the Wireless Internet of Things
at Northeastern University

Colosseum Architecture and Emulation System

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

NSF

DARPA

Platforms for Advanced Wireless Research

MASSACHUSETTS TECHNOLOGY COLLABORATIVE

MITRE

COLOSSEUM
at Northeastern University

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

Institute for the Wireless Internet of Things at Northeastern

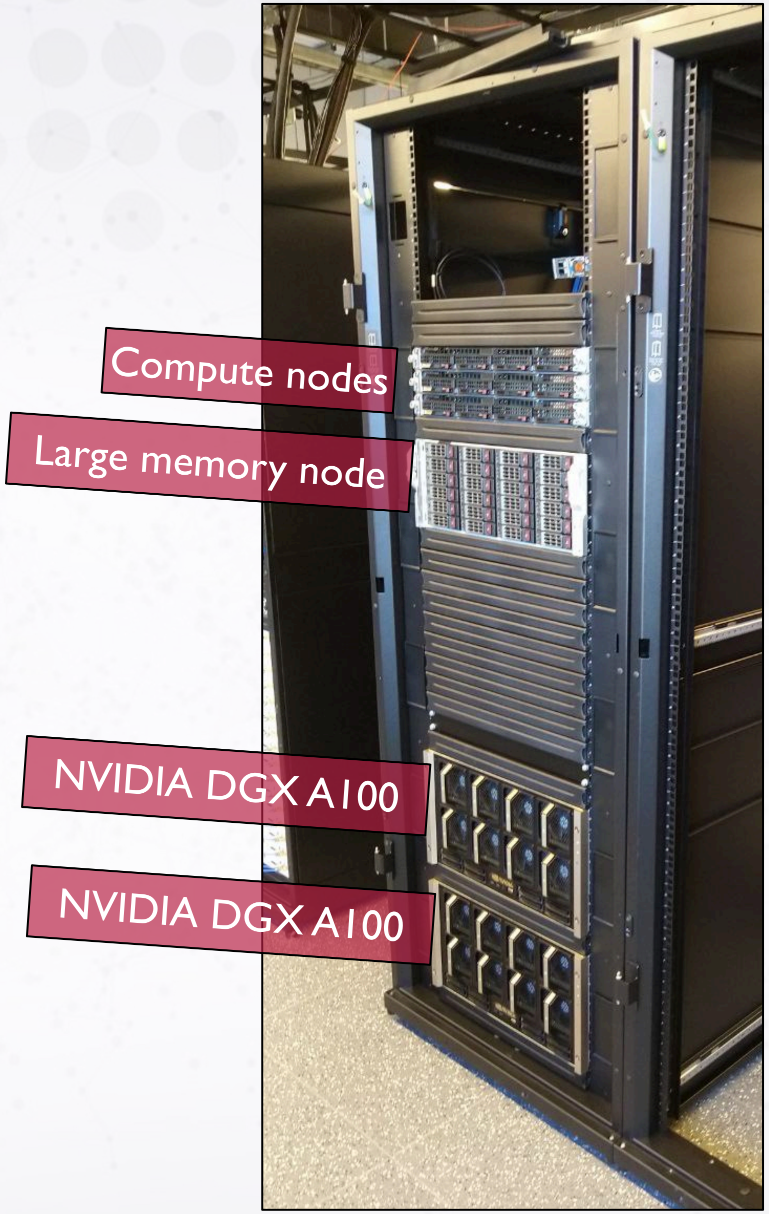
Colosseum as Enabler for AI/ML

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

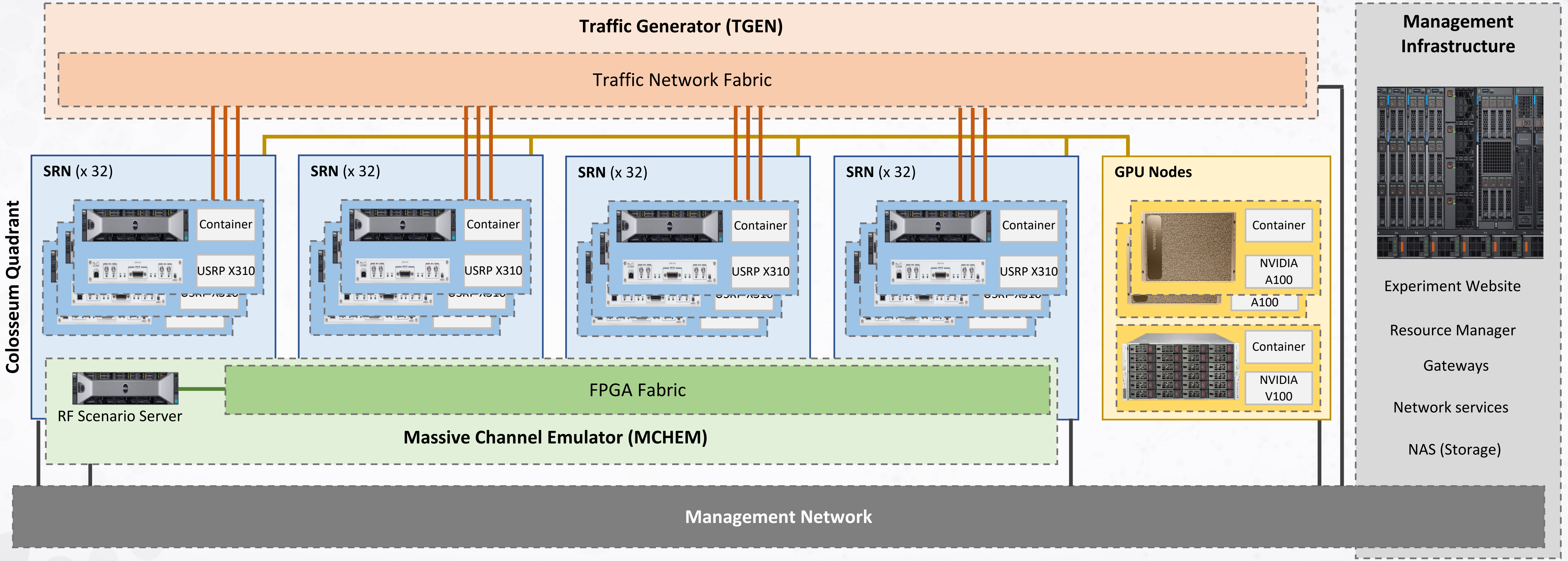
8 NVIDIA A100 GPU 40 GB

Mellanox Infiniband switch

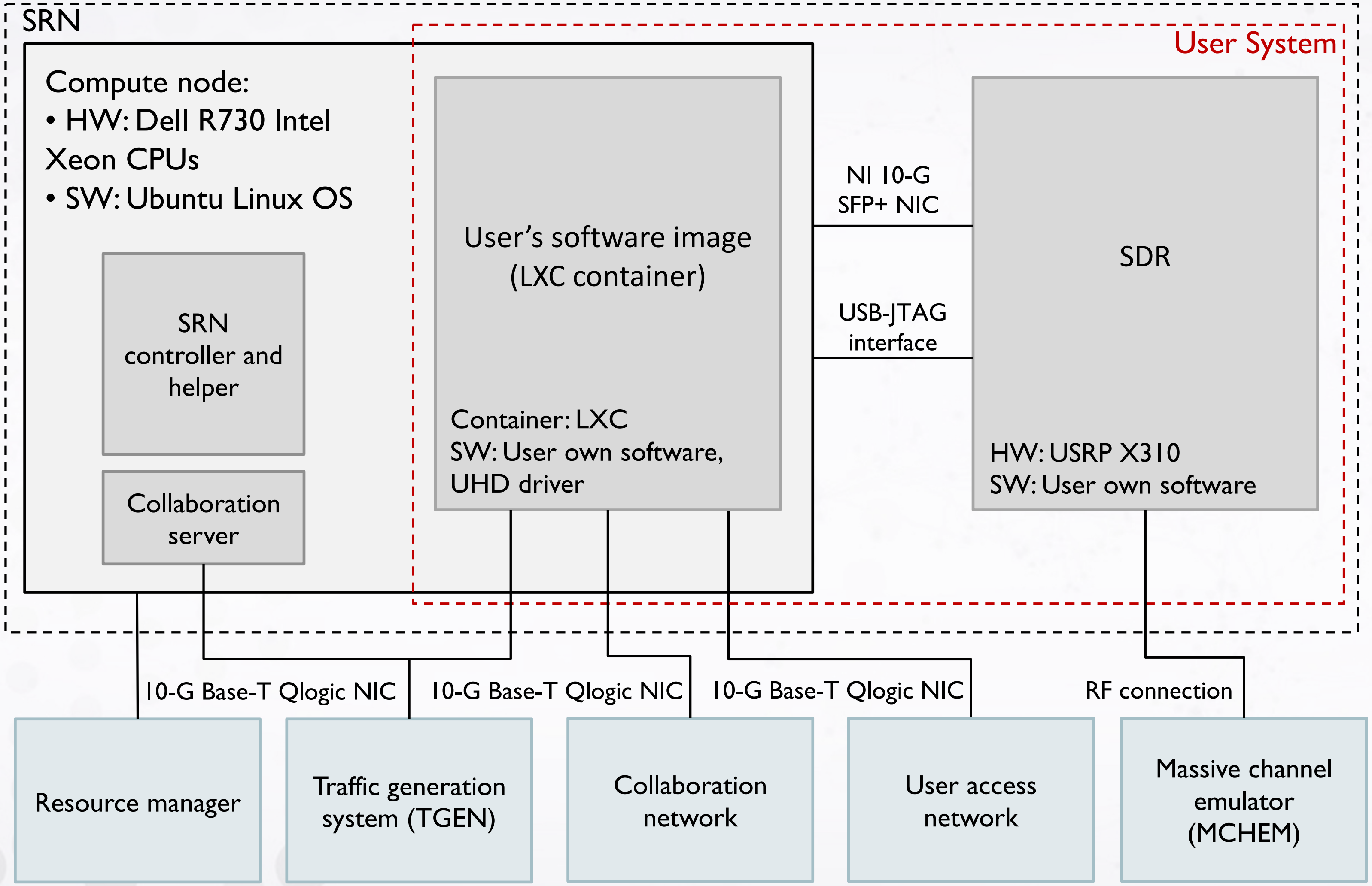


Institute for the Wireless Internet of Things at Northeastern

Colosseum Architecture



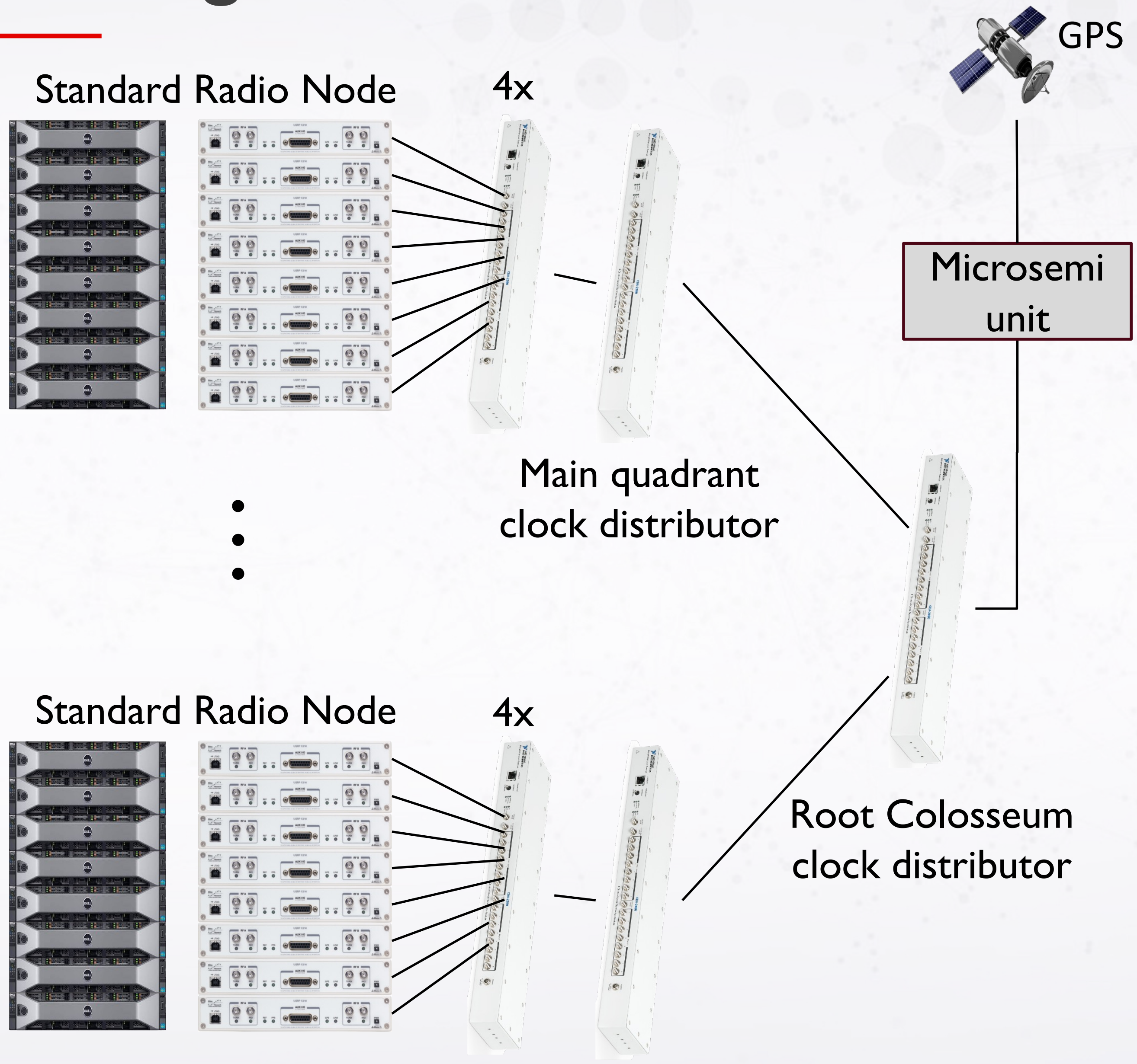
Standard Radio Node (SRN)



Institute for the Wireless Internet of Things at Northeastern

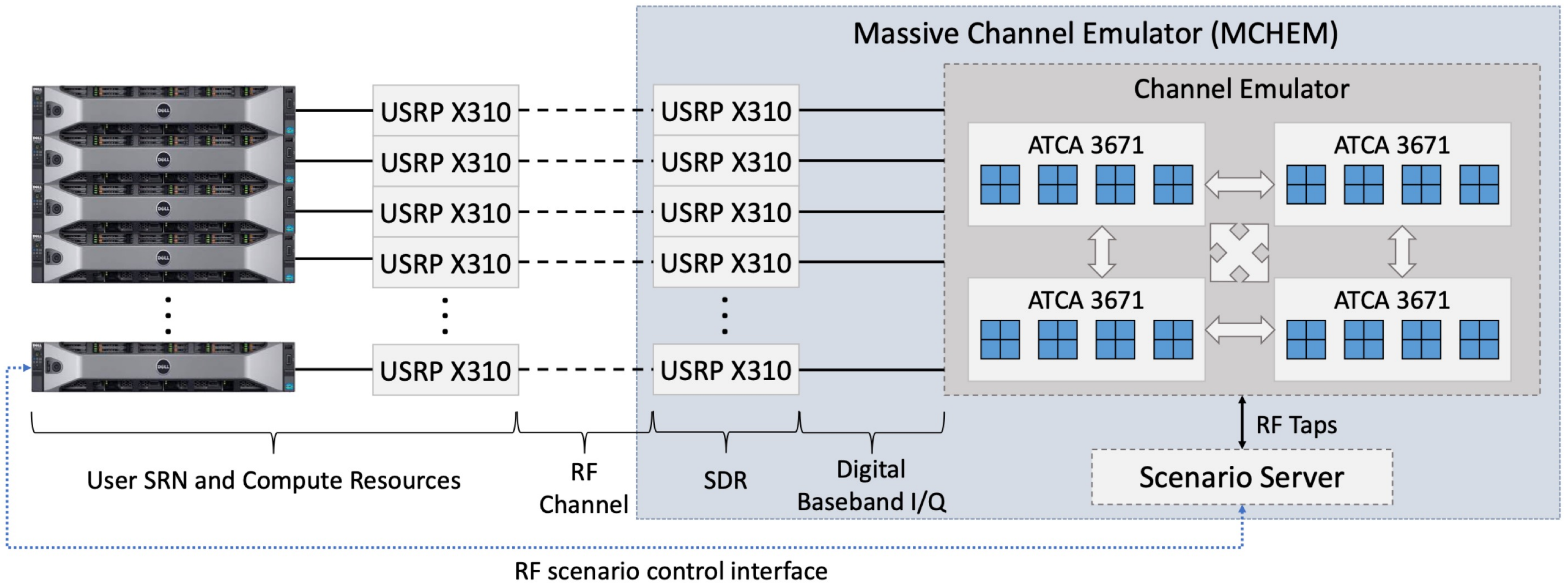
Enabling Distributed Beamforming on Colosseum

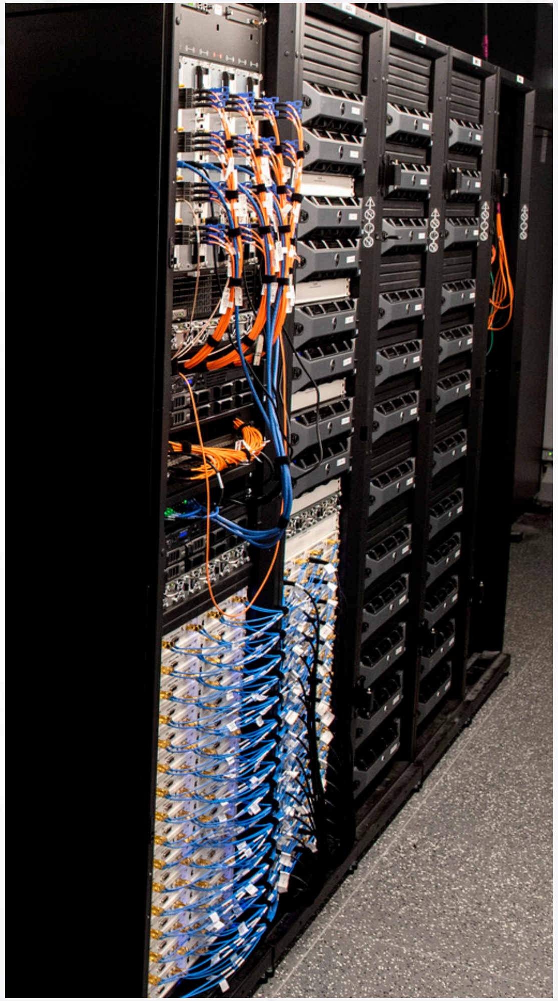
- Each quadrant is synchronized with 5 Octoclocks clock distributors
- The main Octoclock of the quadrant connects to the ”root” clock distributor of Colosseum
- A Microsemi unit connects the root Octoclock to a GPS antenna



Massive Channel Emulator (MCHEM)

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





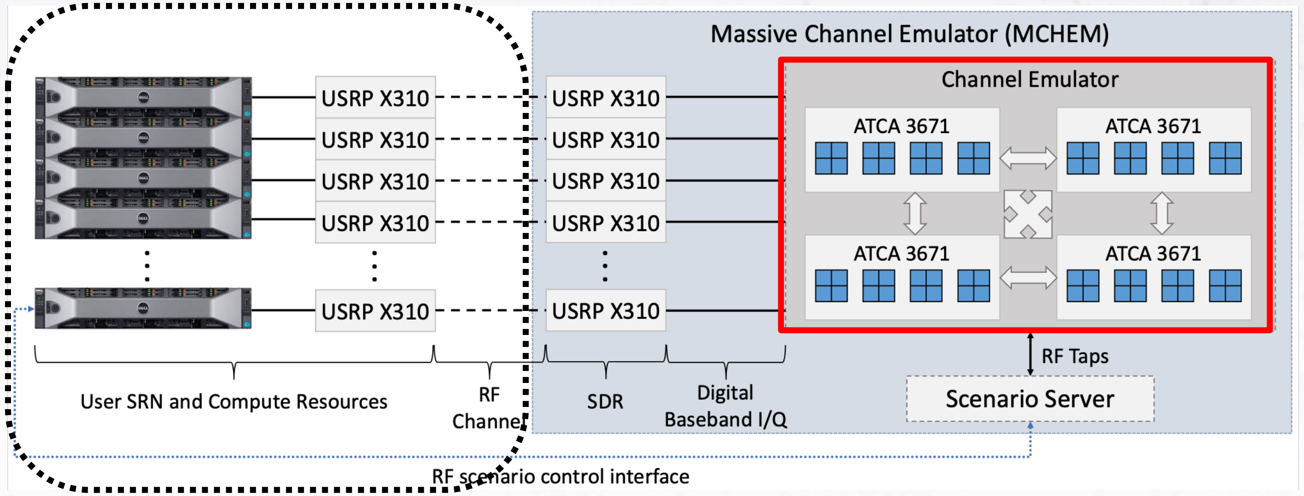
Scenarios ≠ protocol stack

Institute for the Wireless Internet of Things at Northeastern

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

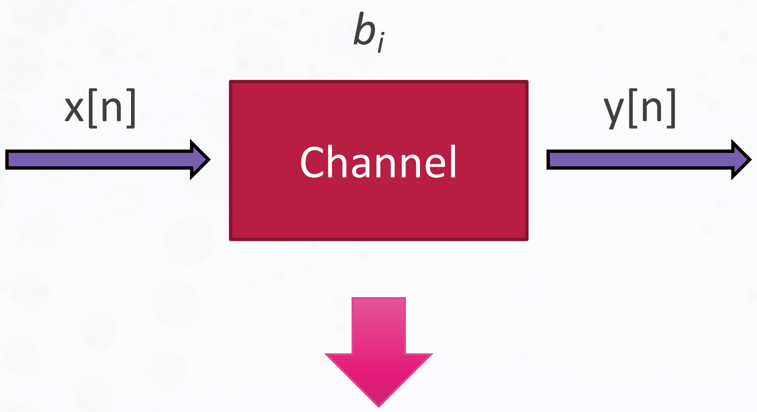


SRNs

MCHEM FPGAs

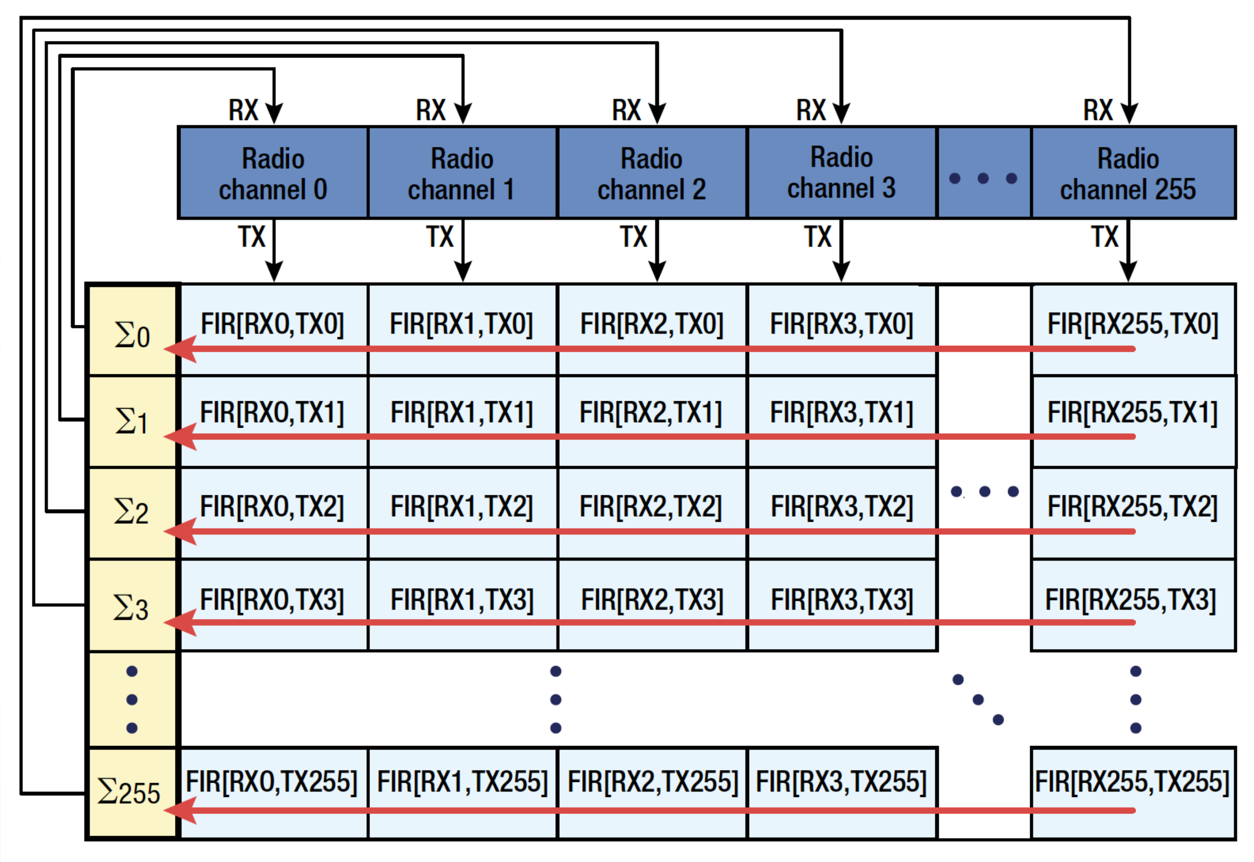
FPGA-based FIR Filters

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



$$y[n] = b_0 x[n] + b_1 x[n-1] + \cdots + b_N x[n-N]$$
$$= \sum_{i=0}^{N} b_i \cdot x[n-i],$$

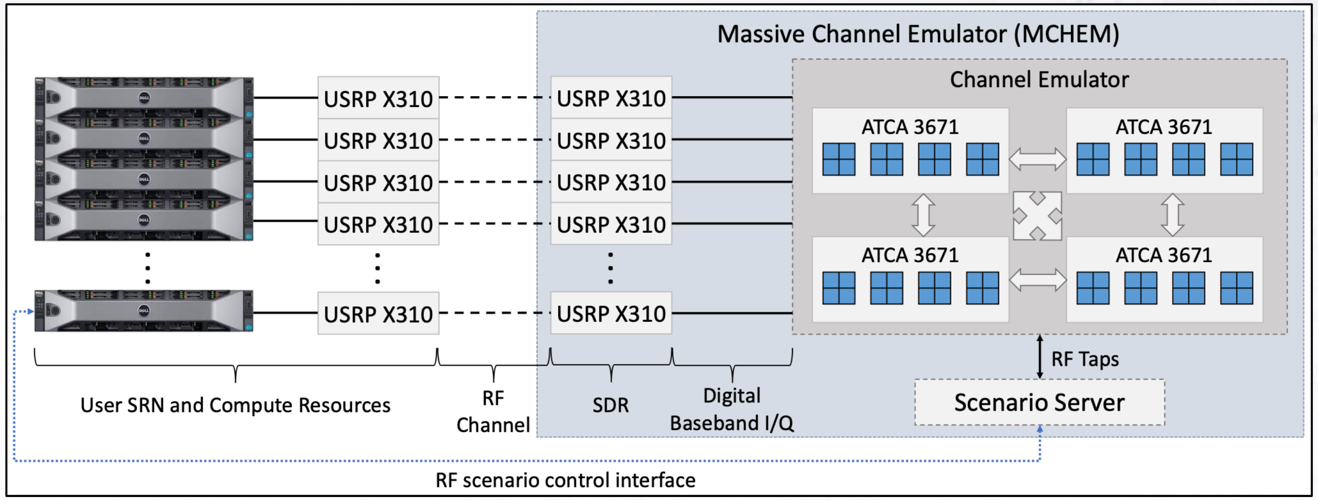
FIR taps



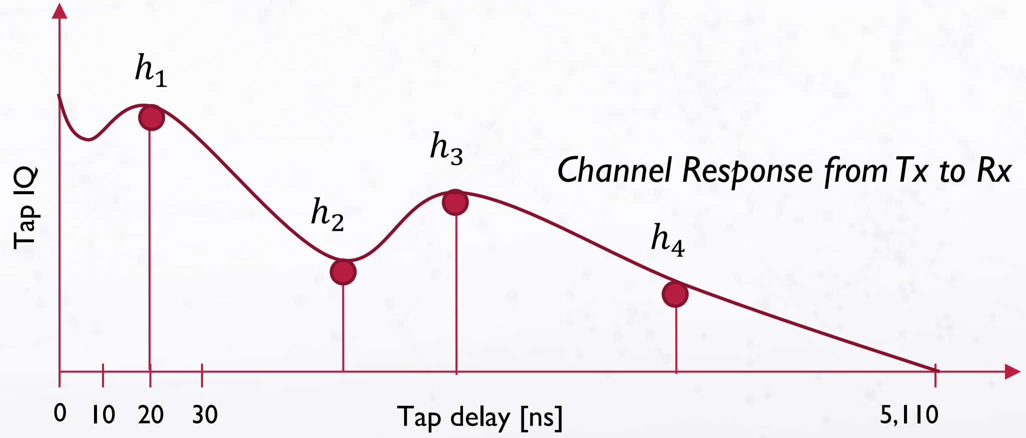
Institute for the Wireless Internet of Things at Northeastern

Complexity vs. Accuracy

- 512 complex-valued FIR taps for 65k RF Channels
- **Sparse filter: only 4 are non-zero**
- **Why?**
  - Colosseum has 1 ms channel coherence time and 10 ns channel tap resolution
  - Scenarios are **VERY** complex:
    - single-tap, 50 nodes, 10 minutes duration
    - > 100 GB storage needed
    - > 2 hours (**15 hours in the case of 4-tap**) to generate taps on servers w/ 24 CPUs & 96 GB RAM
- 4-taps are a good **trade-off** between **complexity** and **accuracy**



MCHEM block diagram



Institute for the Wireless Internet of Things at Northeastern

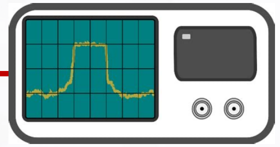
Ways to Generate Filter Taps

- **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



Taps Approximation

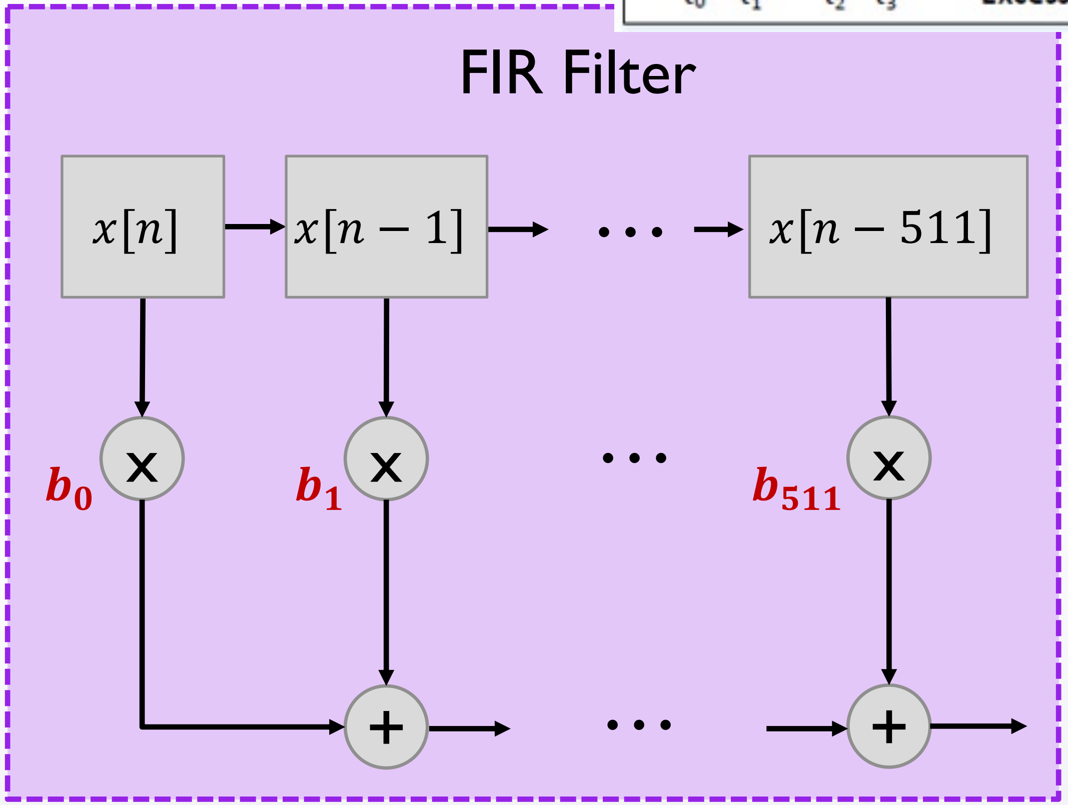
b_i

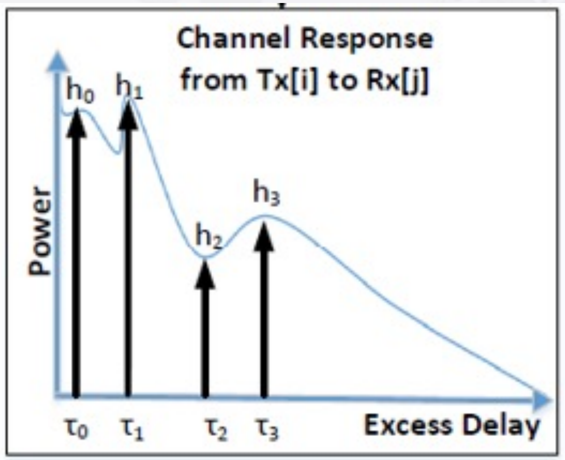
- **Software-based (ray tracer)**
  - Accurate but complex

Calibrate w/ measurements

Taps Approximation

b_i





MCHEM Imposes Some Constraints

Chanel Emulator Constraint	Source	Scenario Definition Impact
128 USRP X310s each with 2 UBX-160-LP RF Daughter Cards	Channel Emulator Design	Maximum of 128 2x2 MIMO Nodes
100 MSps Sampling Rate	FPGA Processing Bandwidth	3 meters distance resolution
10 ns Tap Delay Resolution		
80 MHz Usable Channel Bandwidth	RF Daughter Card Bandwidth	
4 non-zero complex taps per RF channel from -1.0 to +1.0 [Q15 fixed-point for each I and Q value]	FPGA Constraint	
5.12 us max tap delay	FPGA Delay Line Length (512 element buffer)	Delay Spread limited to 5.12 us Propagation Delay + Excess Delay <= 5.12 us Maximum distance between TX/RX nodes is 1.5km
1kHz Channel Update Rate (1ms coherence time)	FPGA Constraint	Constrains Maximum Doppler Spread and limits node velocity to e.g., ~11.6mph at 5.8 GHz

Colosseum RF and Traffic Scenarios

Institute for the Wireless Internet of Things at Northeastern University

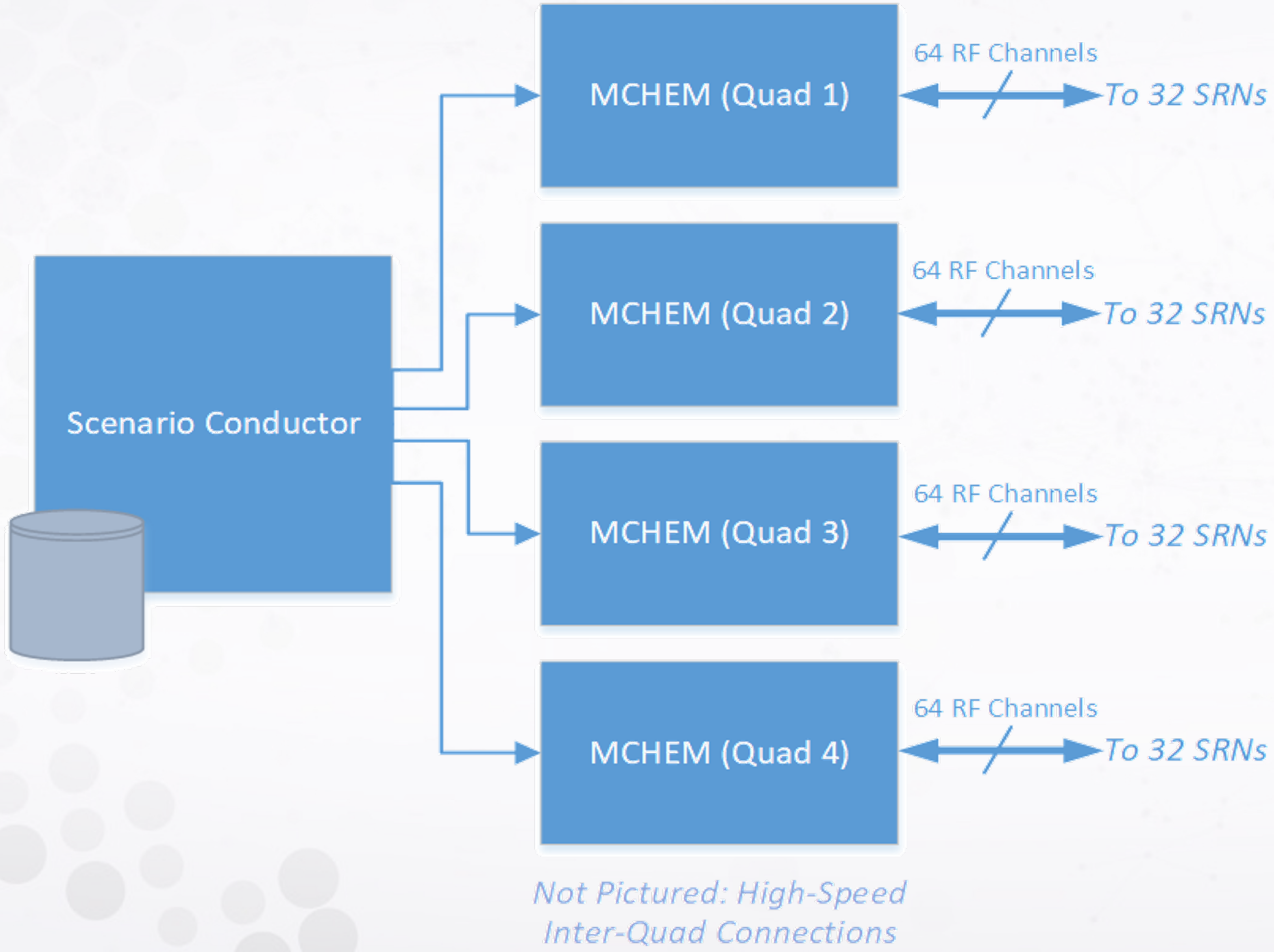
Scenario Capabilities

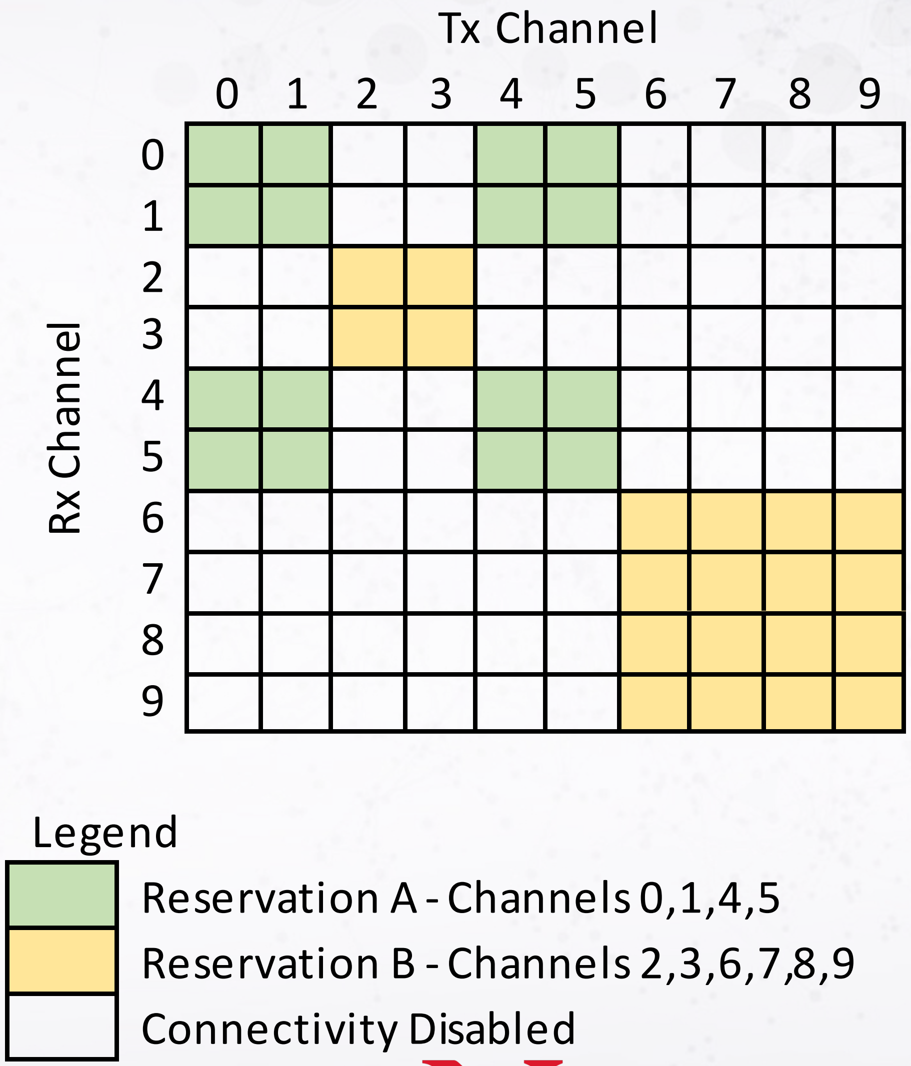
- Colosseum enables emulation at scale:
  - **256 RF transceivers**
    - >**65K** RF channels
  - Diverse **wireless conditions**
    - Fading
    - Mobility
    - Topologies
  - **Data traffic**
    - Downlink/Uplink
    - Bandwidth
    - Bitrate
    - UDP/TCP

RF Scenarios

Traffic Scenarios

Scenario Conductor

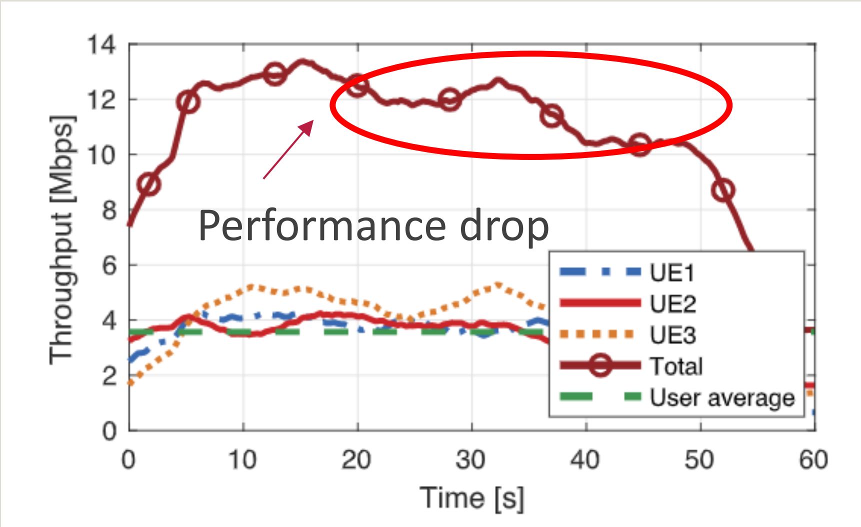




Functionalities and Limitations

Institute for the Wireless Internet of Things at Northeastern

- RF scenarios are **deterministic**: Experiments w/ same scenario execute the same way
- Will be extended w/ stochastic distributions in the filter taps
- Scenarios enable:
  - **Full control** over the wireless channel
    - non stationarity in the **distribution**
    - only keep **desired** channel effects
  - **Reproducibility** / **repeatability**
  - **Easy comparison** between algorithms

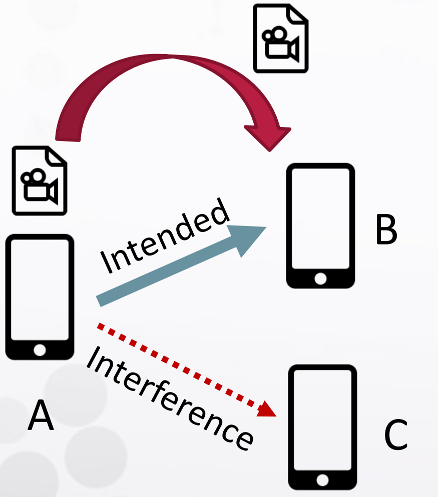


Is the performance drop due to the ***channel*** *or* ***bad algorithm design****?*

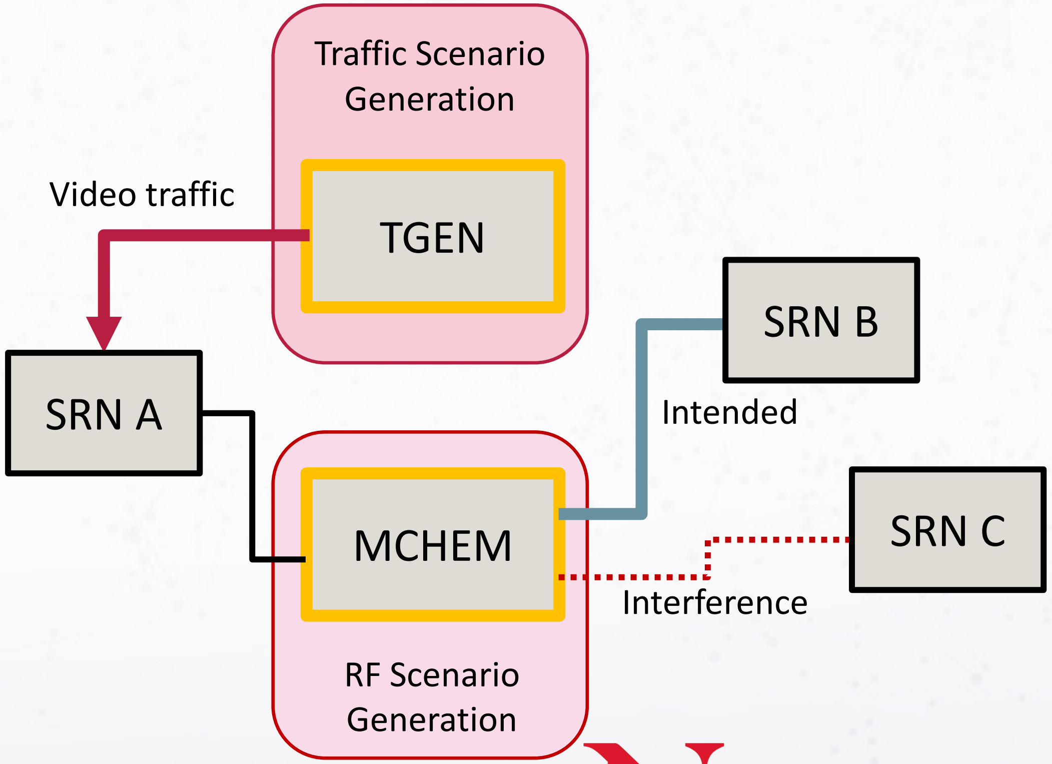
An example: performance drop

High-level Overview

- 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

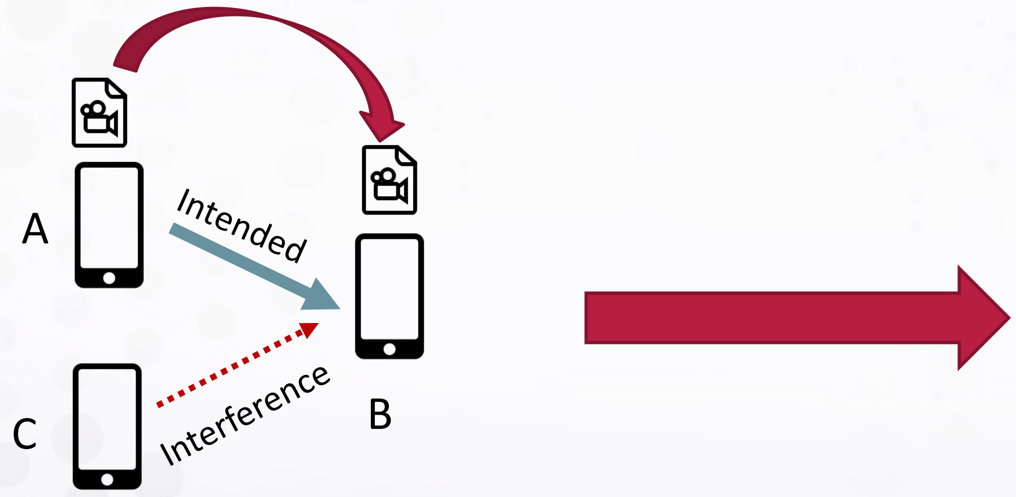


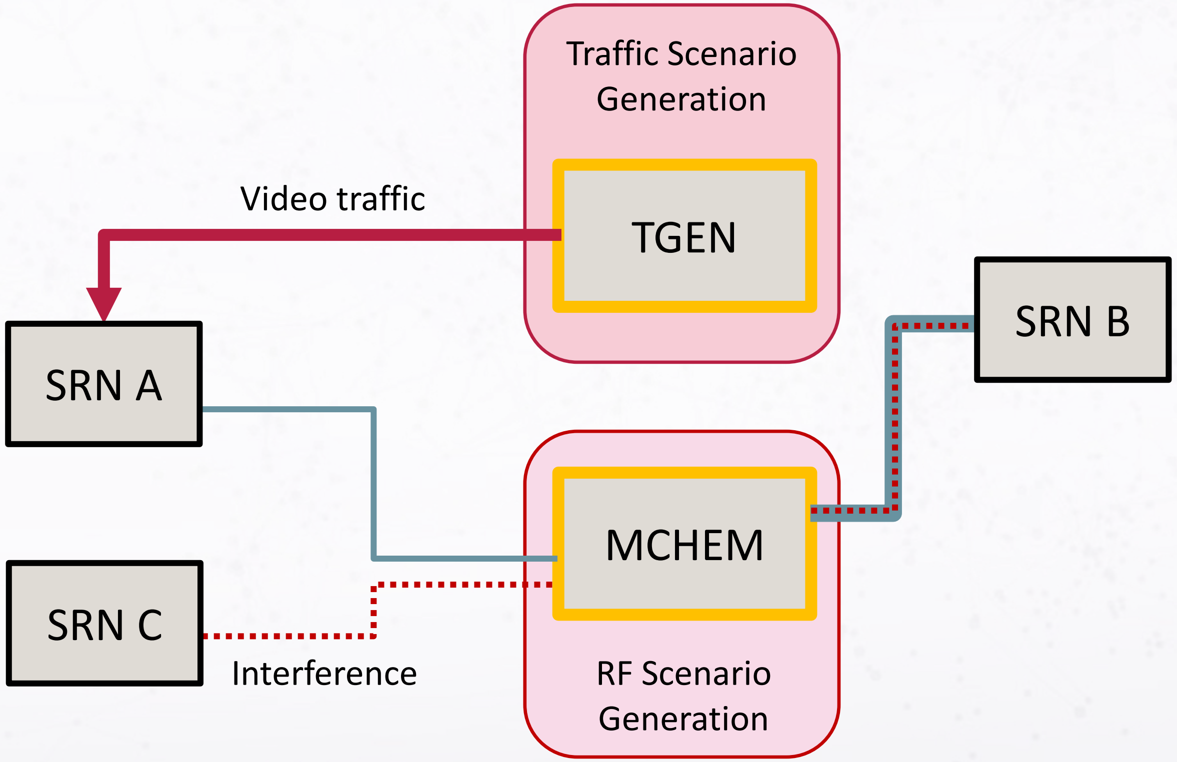
Institute for the Wireless Internet of Things at Northeastern

High-level Overview

- All signals are **summed** at the receiver

- **Each node can experience interference from all the other 255 transceivers**

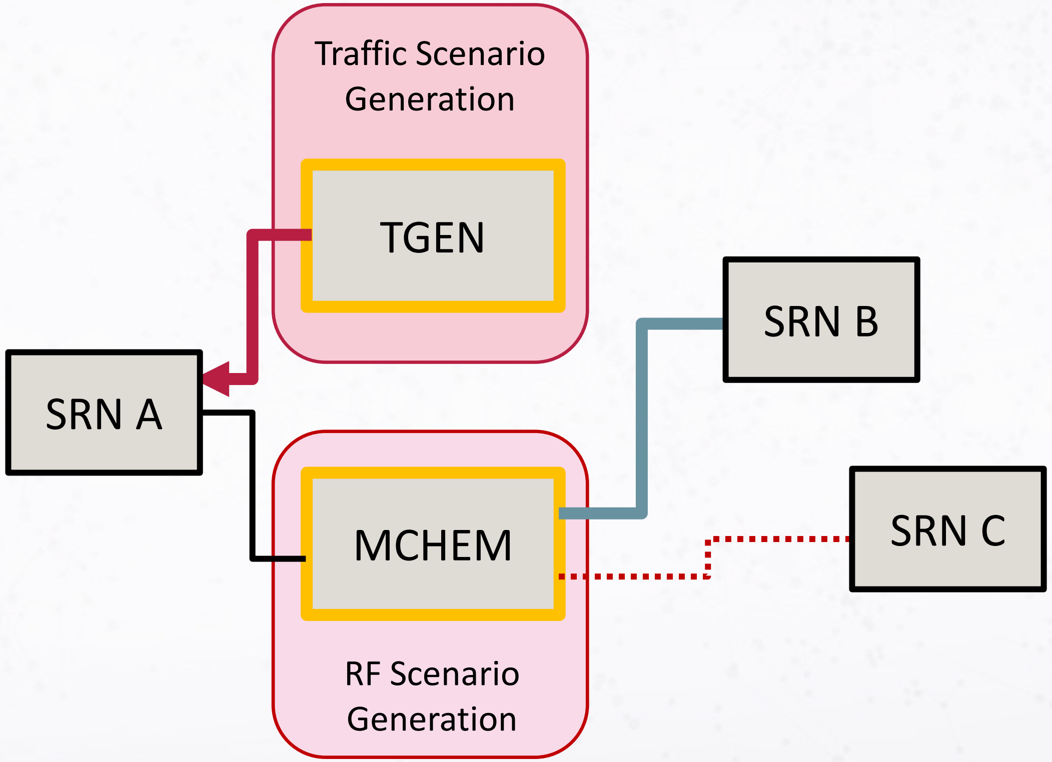




Institute for the Wireless Internet of Things at Northeastern

Traffic Generator

- Based on the Multi-Generator (MGEN) Network Test Tool
- Enables definition of traffic flows with different packet
  - Rate
  - Size
  - Distributions
  - etc.



MGEN repository: https://github.com/USNavalResearchLaboratory/mgen

MGEN Traffic Definition

- Definition of traffic in a single line of 7 columns

start-time (s), end-time (s), type (UDP), mode (Periodic, Regular, Fixed), [Throughput Size], TOS (for scoring), score

```
10,85,UDP,PERIODIC,[0.5 130],TOS,0x00
```

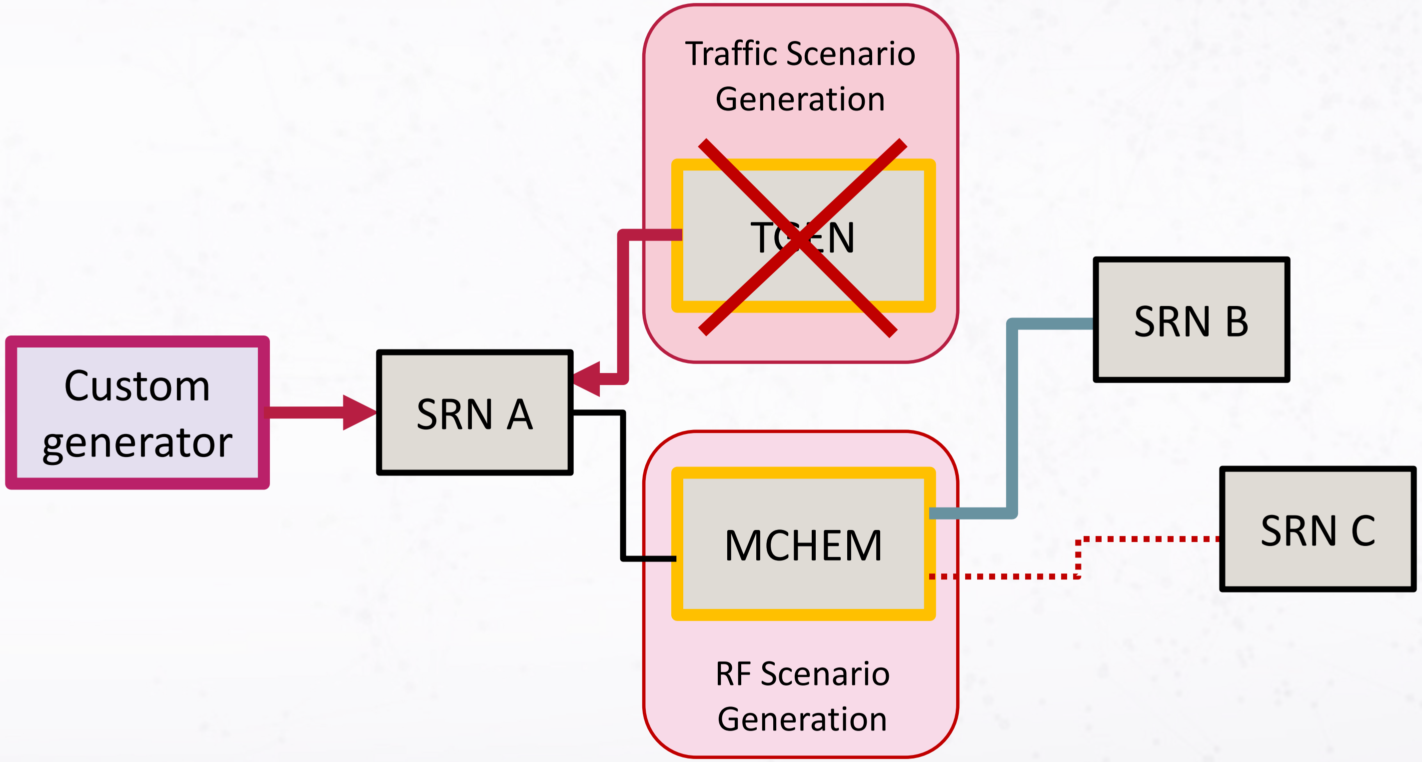
- Can be combined to create more advanced traffic profiles

```
617,915,UDP,TOS,0x40,BURST [REGULAR 20 PERIODIC [936 1400] FIXED 0.5]
```

Institute for the Wireless Internet of Things at Northeastern

Use Custom Traffic Generators

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



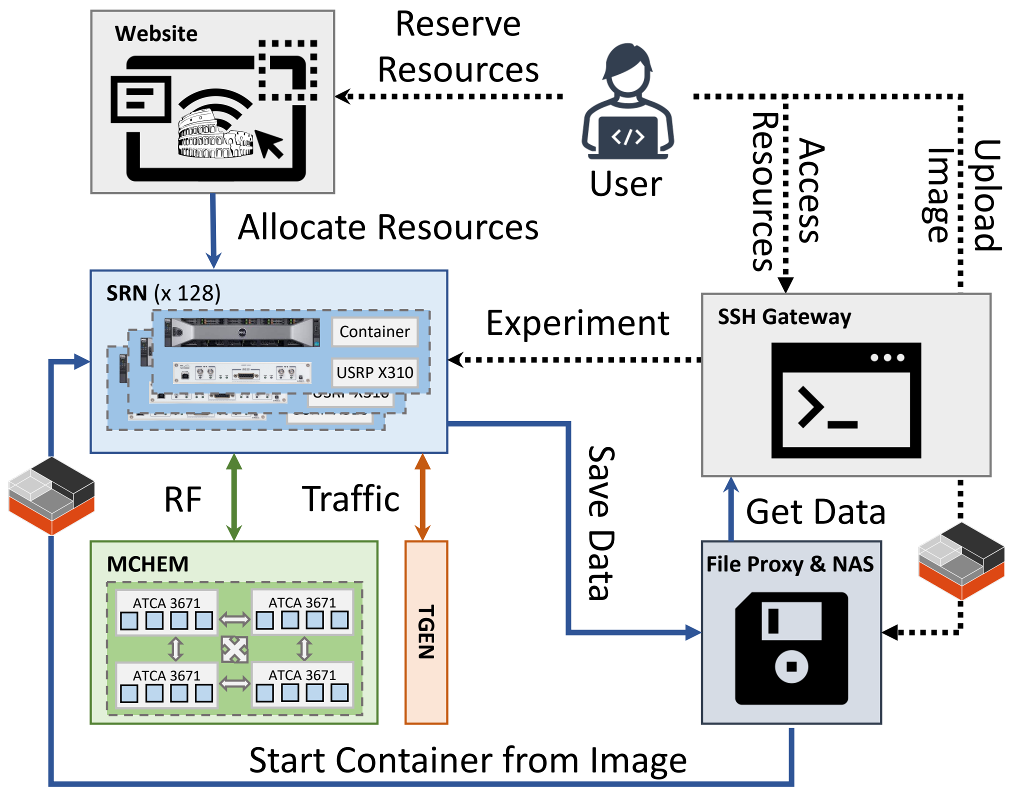
- TGEN gets bypassed

How to Get Access

Institute for the Wireless Internet of Things
at Northeastern University

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

Institute for the Wireless Internet of Things at Northeastern

How to Ask for Access

- Fill the form online to request for a team/account
- Requests are usually approved in a few days

Institute for the Wireless Internet of Things at Northeastern University

New Colosseum team request

This form is only for academic PIs, or researchers affiliated with US Department of Defense laboratories (e.g., Air Force Research Laboratory, Army Research Laboratory, Navy Research Laboratory, etc). If you are an industry, international (non-US), or US government (non-DoD) investigator interested in using Colosseum, please contact us at colosseum@northeastern.edu.

By submitting this form, you agree that upon the approval of your team request, the logo of your Institution/Research-Lab/Company will be added to the Colosseum website for statistics.

Sign in to Google to save your progress. Learn more

* Indicates required question

LVX VERITAS VIRTVS

Institute for the Wireless Internet of Things

at Northeastern University

Thank You! Q&A

NSF

DARPA

Platforms for Advanced Wireless Research

MASSACHUSETTS TECHNOLOGY COLLABORATIVE

MITRE

COLOSSEUM
at Northeastern University