



Institute for the Wireless Internet of Things at Northeastern University

Colosseum Architecture and Emulation System

Colosseum Team:

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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.

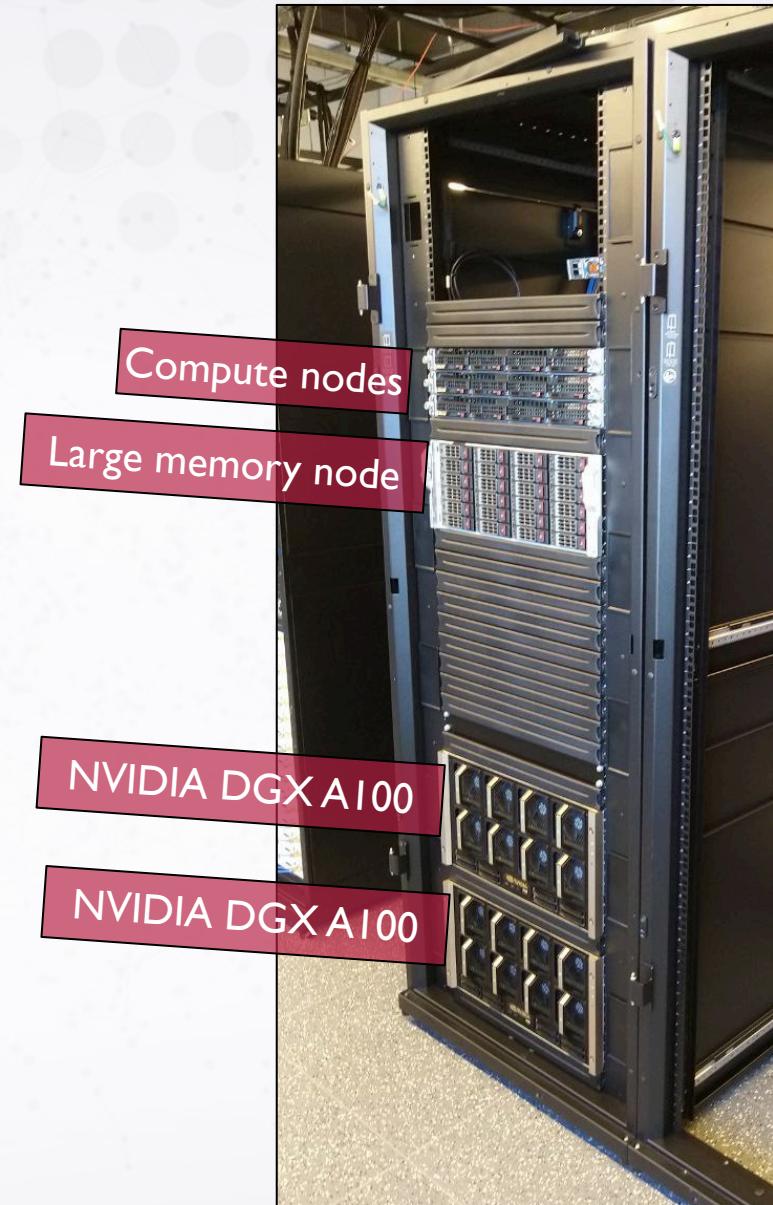
- 2x NVIDIA DGX A100: 8 GPUs each, 10 petaFLOPS compute power
- 1x large memory node (Supermicro Superserver 8049U-E1CR4T): 6 GPUs, 3TB of RAM
- 3x compute nodes
- 1x Mellanox Infiniband switch: Tbps dedicated



8 NVIDIA A100 GPU 40 GB

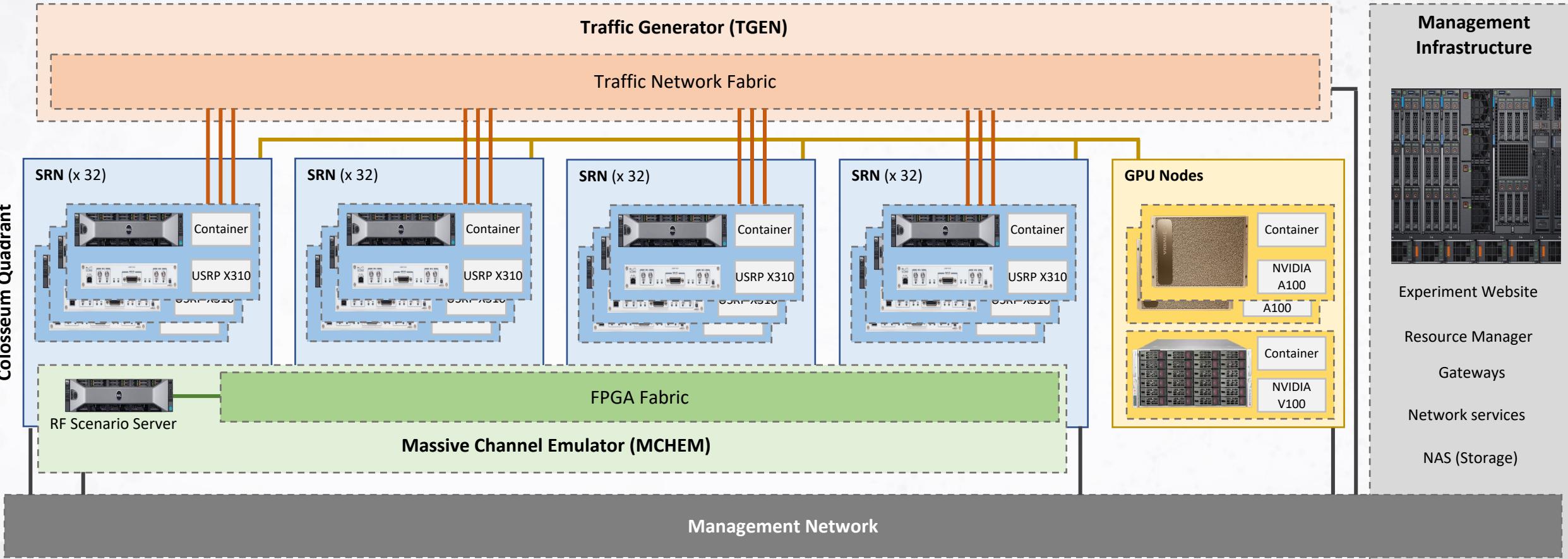


Mellanox Infiniband switch

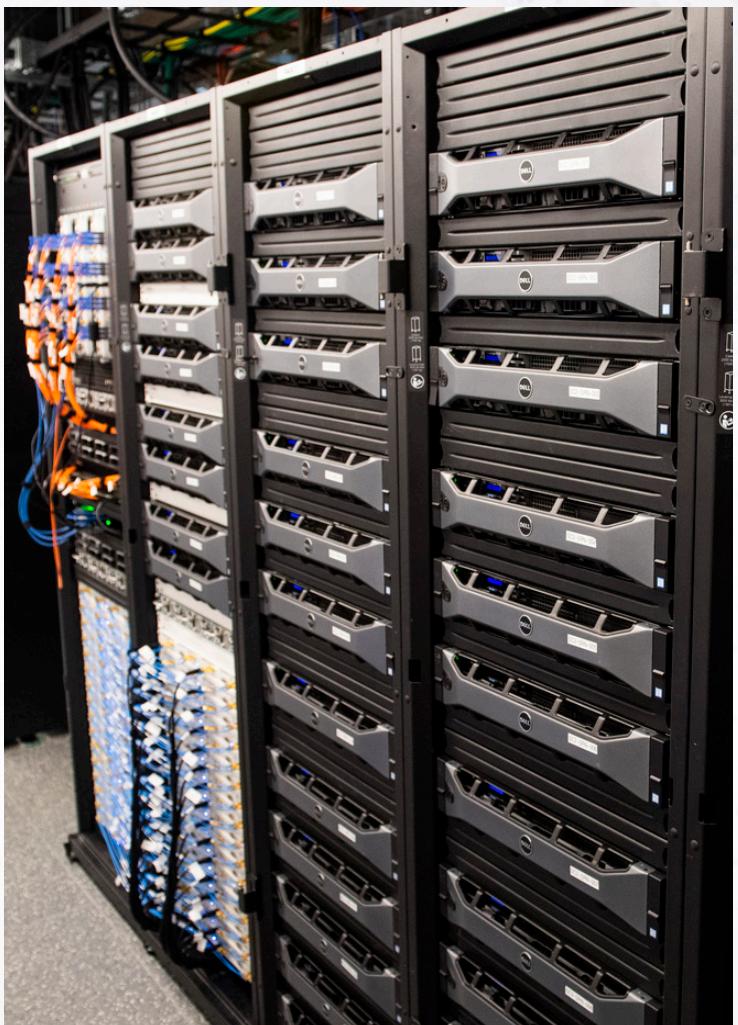
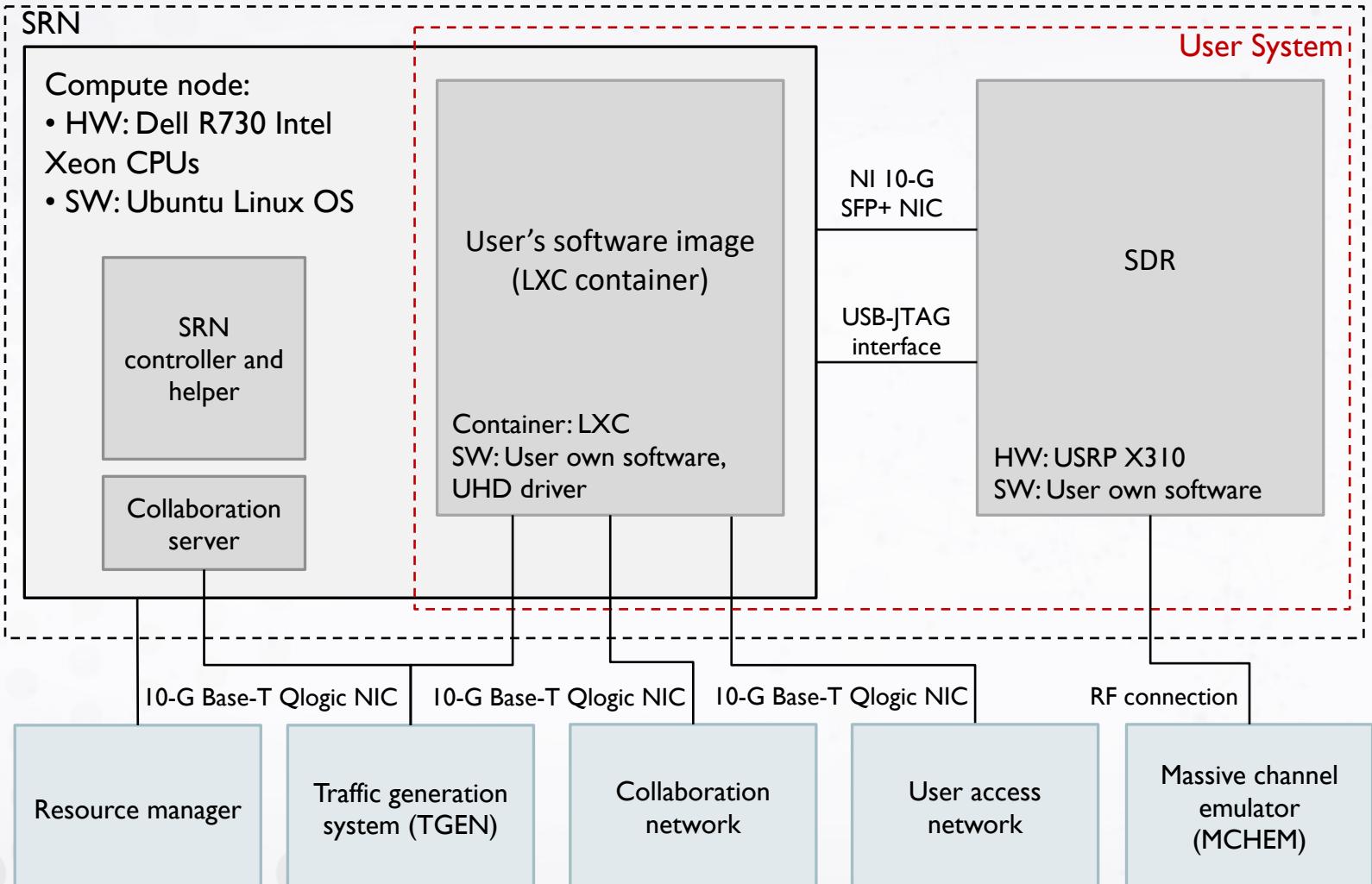


Colosseum Architecture

Colosseum Quadrant

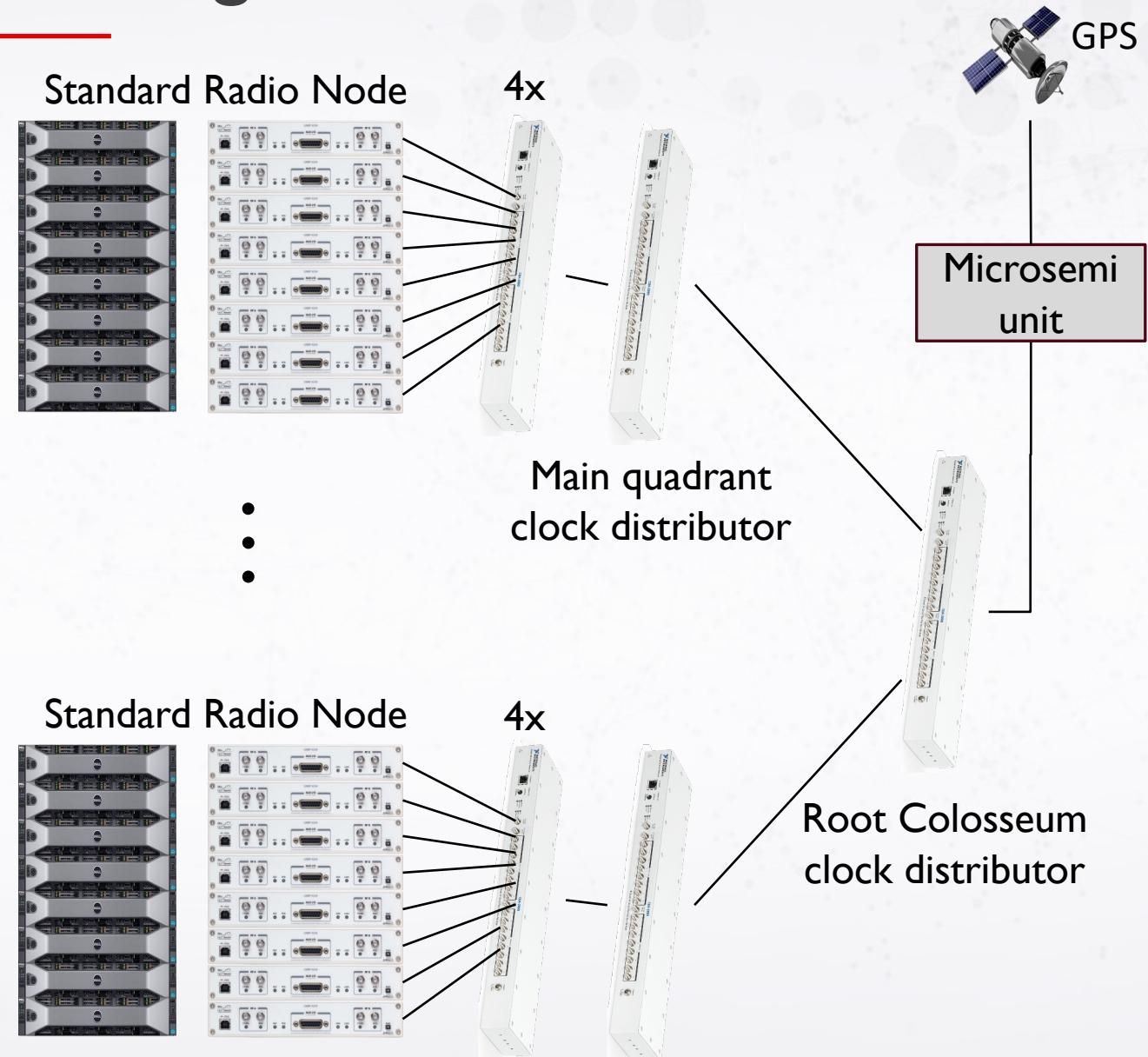


Standard Radio Node (SRN)



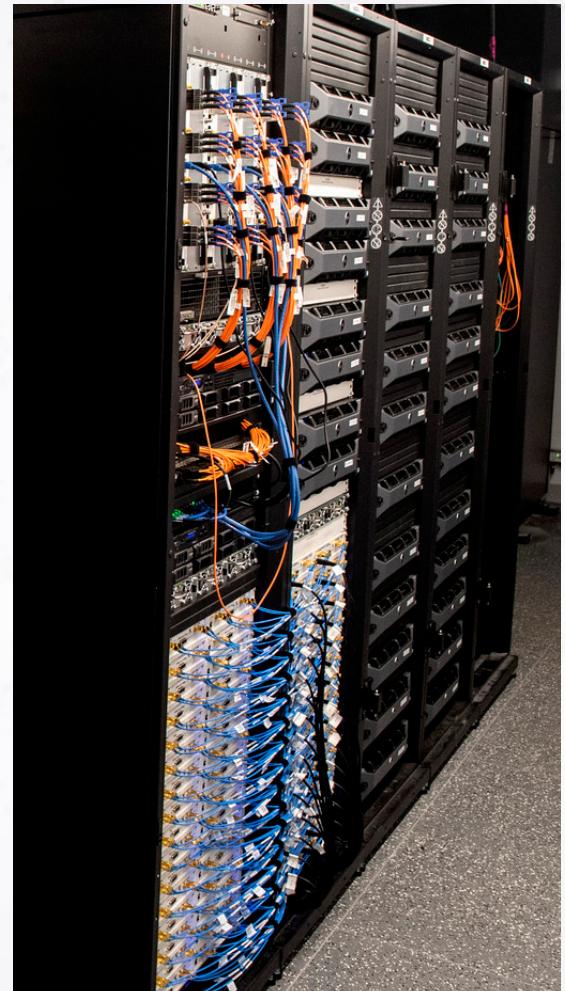
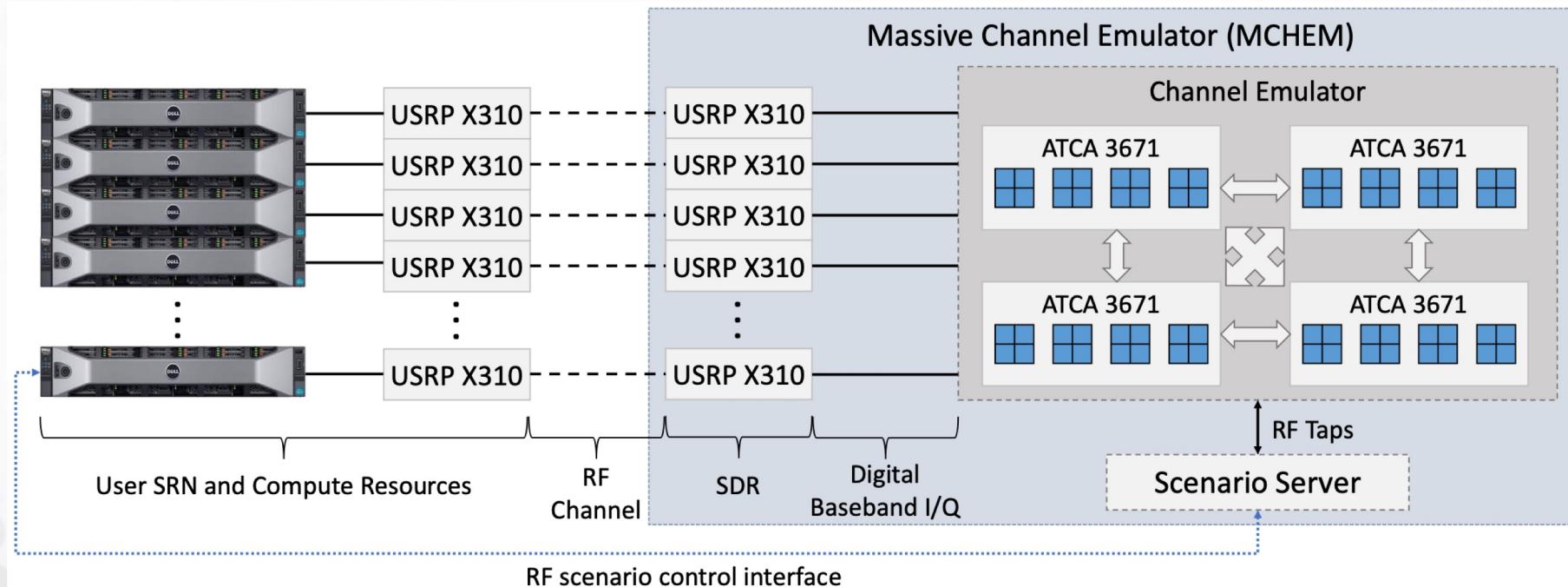
Enabling Distributed Beamforming on Colosseum

- 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

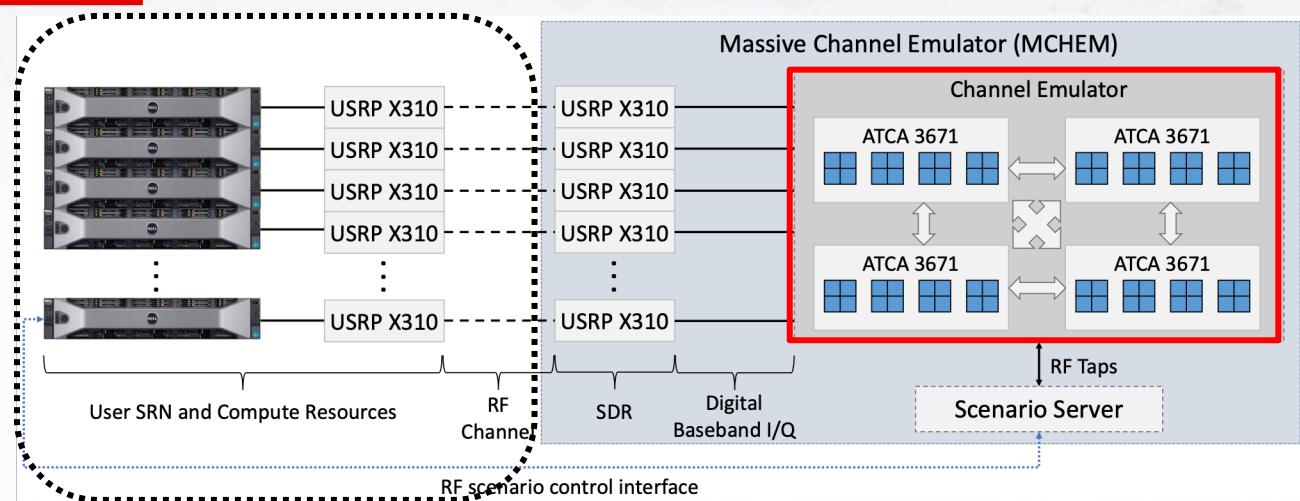
Wireless Channel Modeling

- **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



FPGA-based FIR Filters

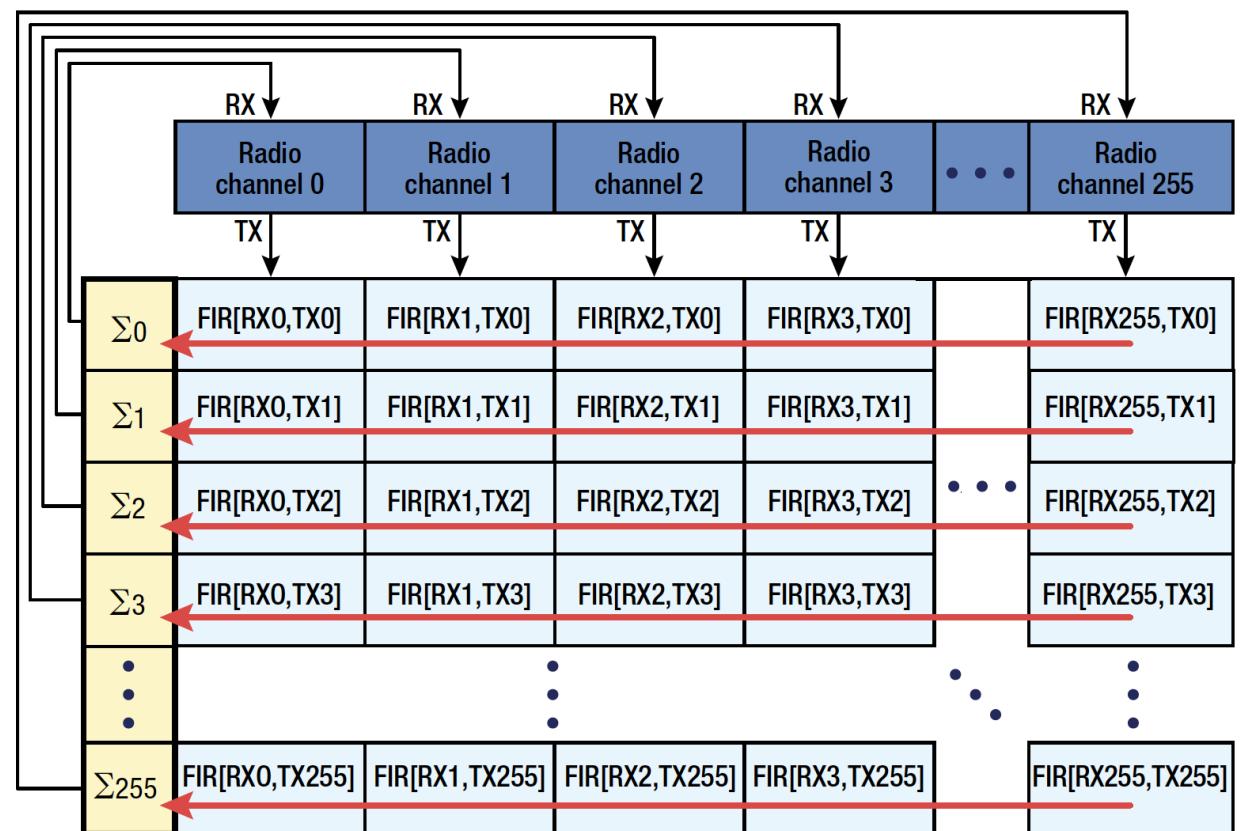
The received signal is the **convolution** in time of the transmitted signal and the channel impulse response



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

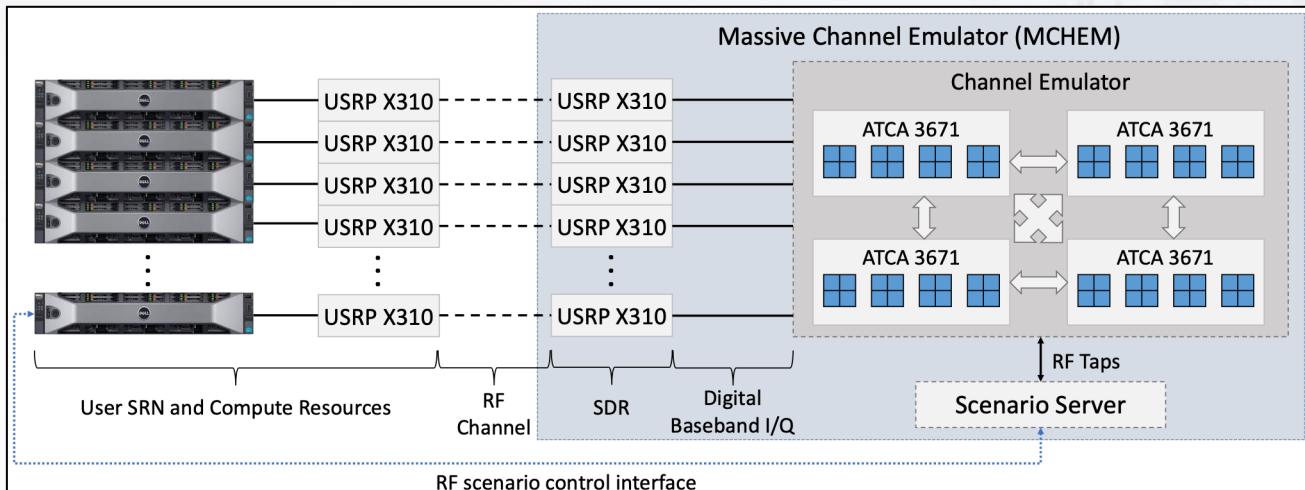
$$= \sum_{i=0}^N b_i \cdot x[n - i],$$

FIR taps

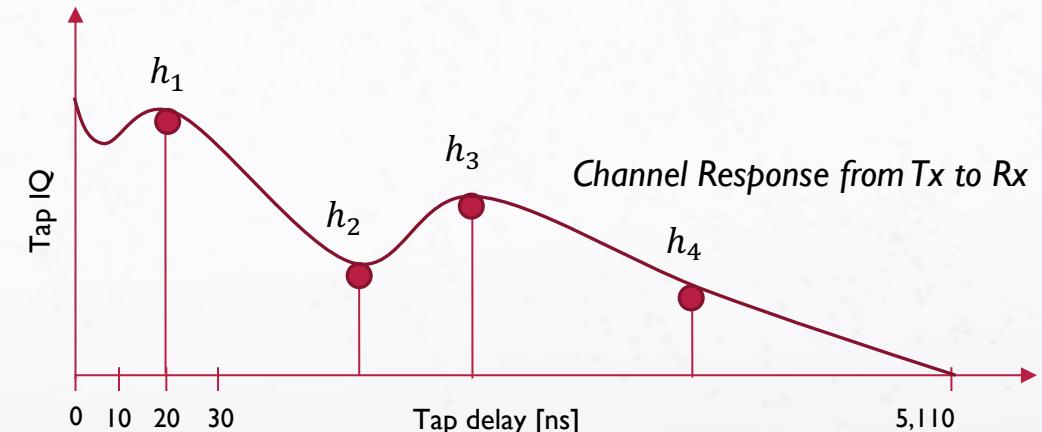


Complexity vs. Accuracy

- 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

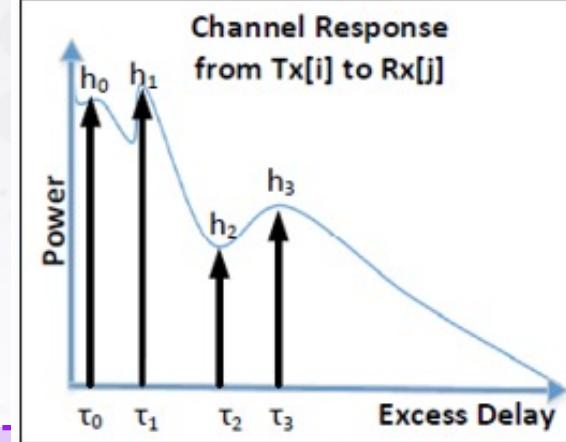


Ways to Generate Filter Taps

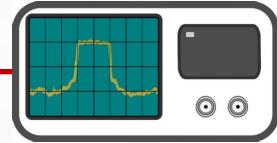
- **Mathematical model**
 - Deterministic/added randomness, no ground truth



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

 b_i 

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



Taps Approximation

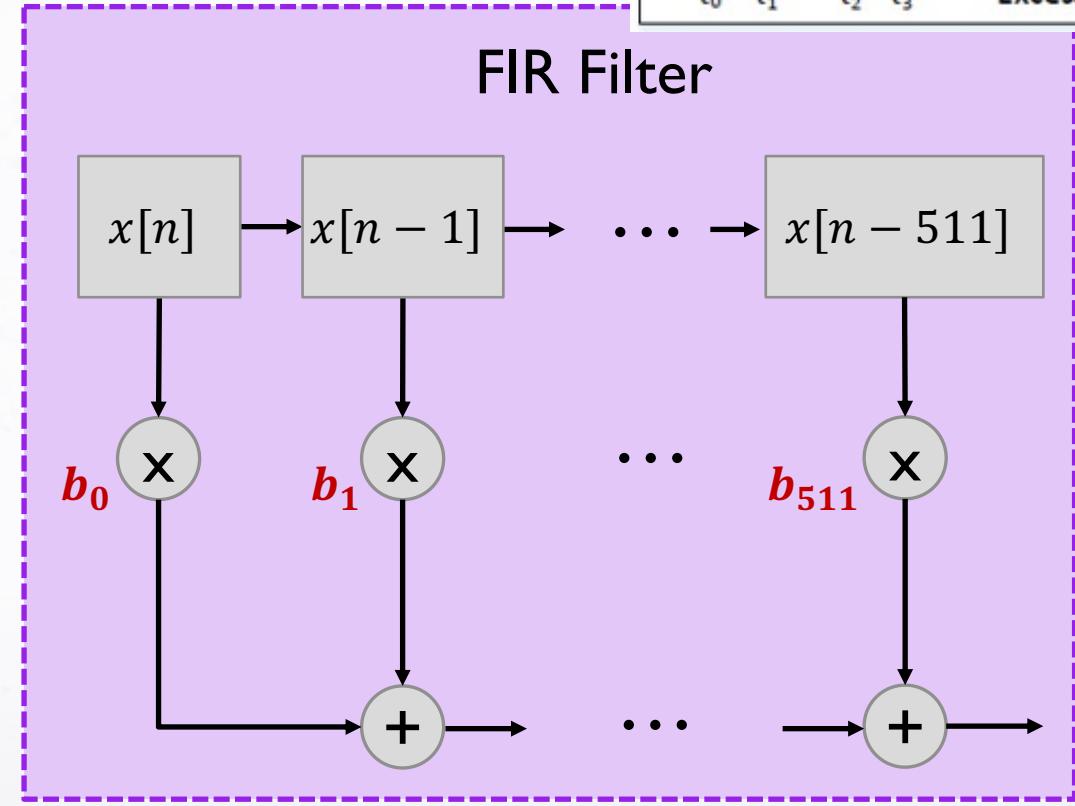
 b_i

- **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

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

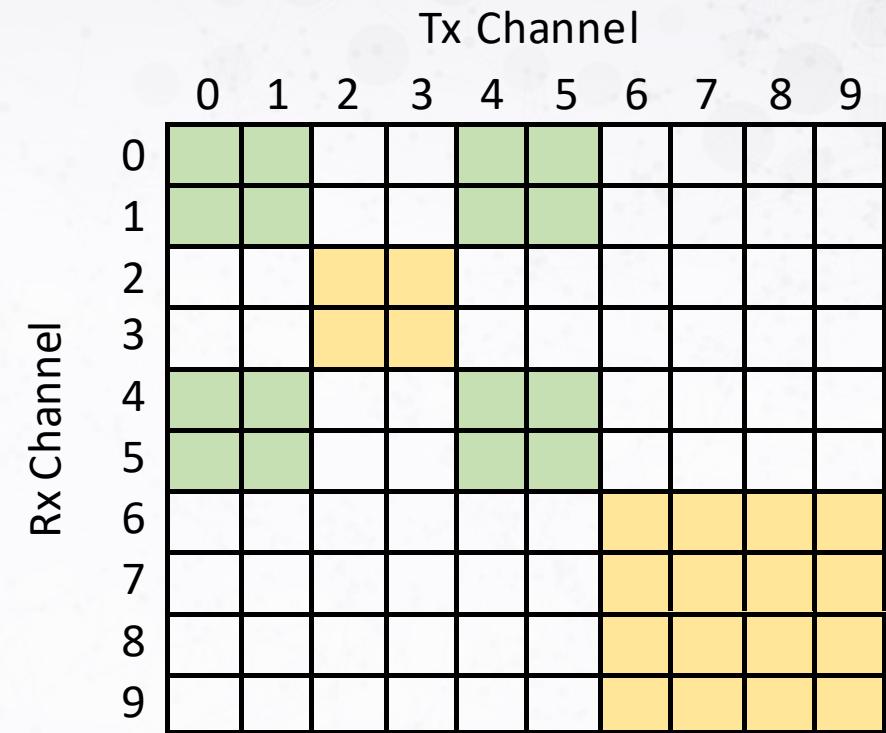
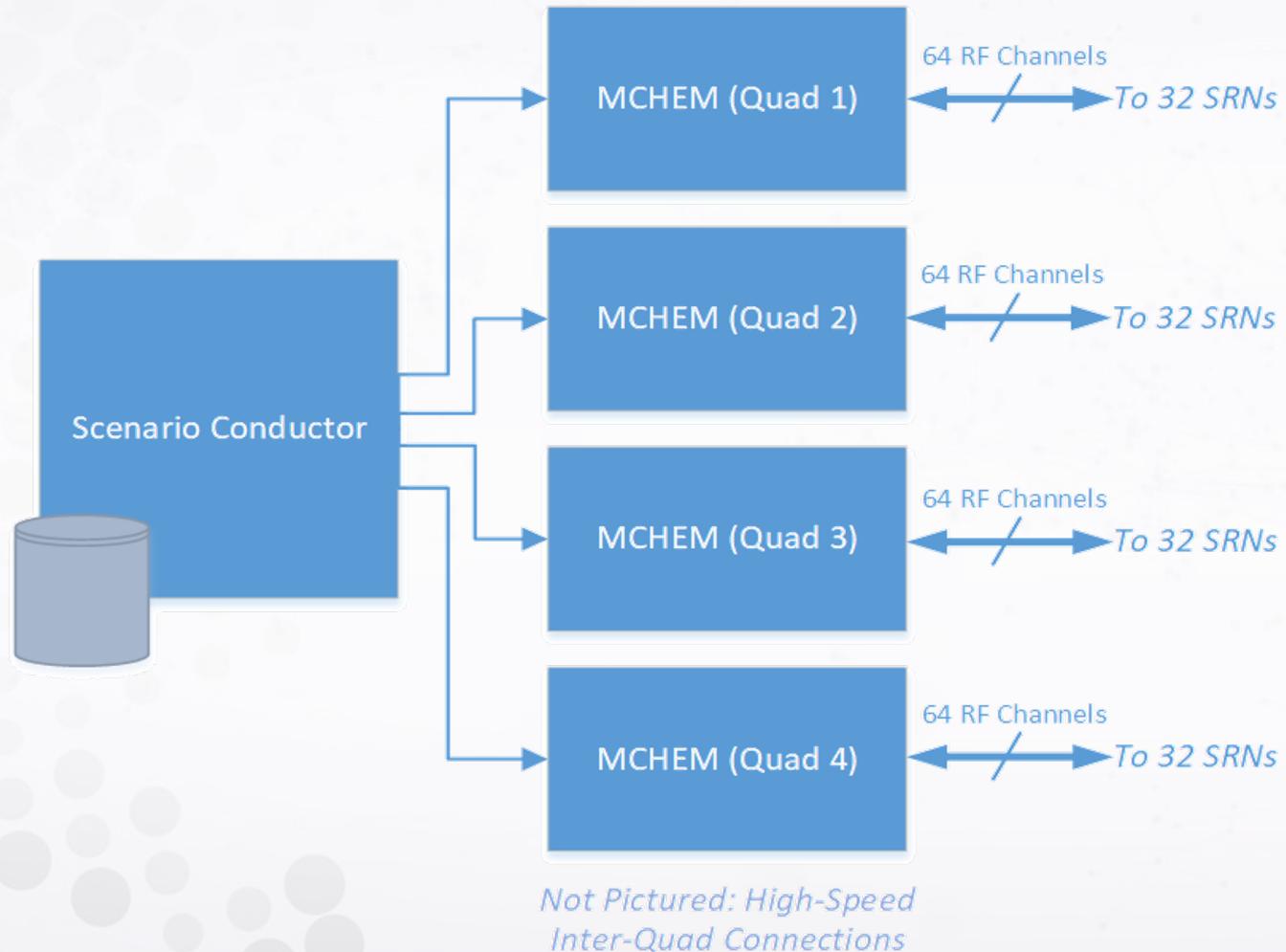


Traffic Scenarios



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Scenario Conductor

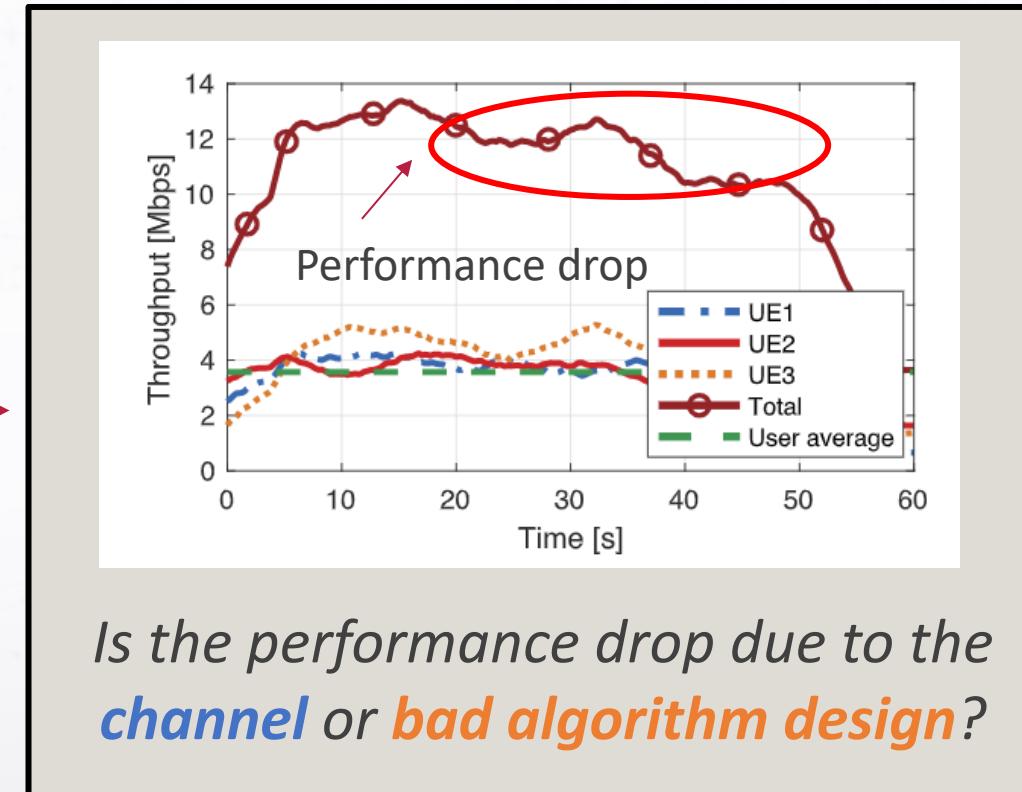


Legend

- Reservation A - Channels 0,1,4,5
- Reservation B - Channels 2,3,6,7,8,9
- Connectivity Disabled

Functionalities and Limitations

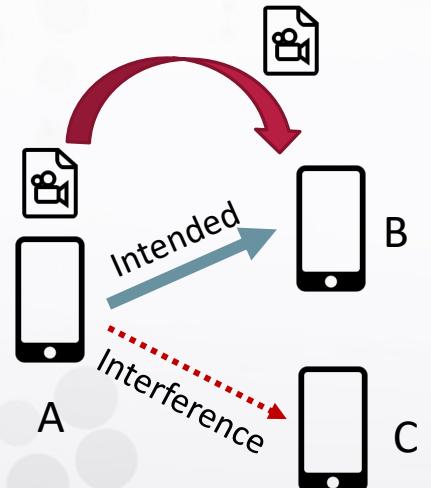
- RF scenarios are **deterministic**: Experiments w/ same scenario execute the same way
- Will be extended w/ stochastic distributions in the filter taps
- Scenarios enable:
 - **Full control** over the wireless channel
 - non stationarity in the **distribution**
 - only keep **desired** channel effects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



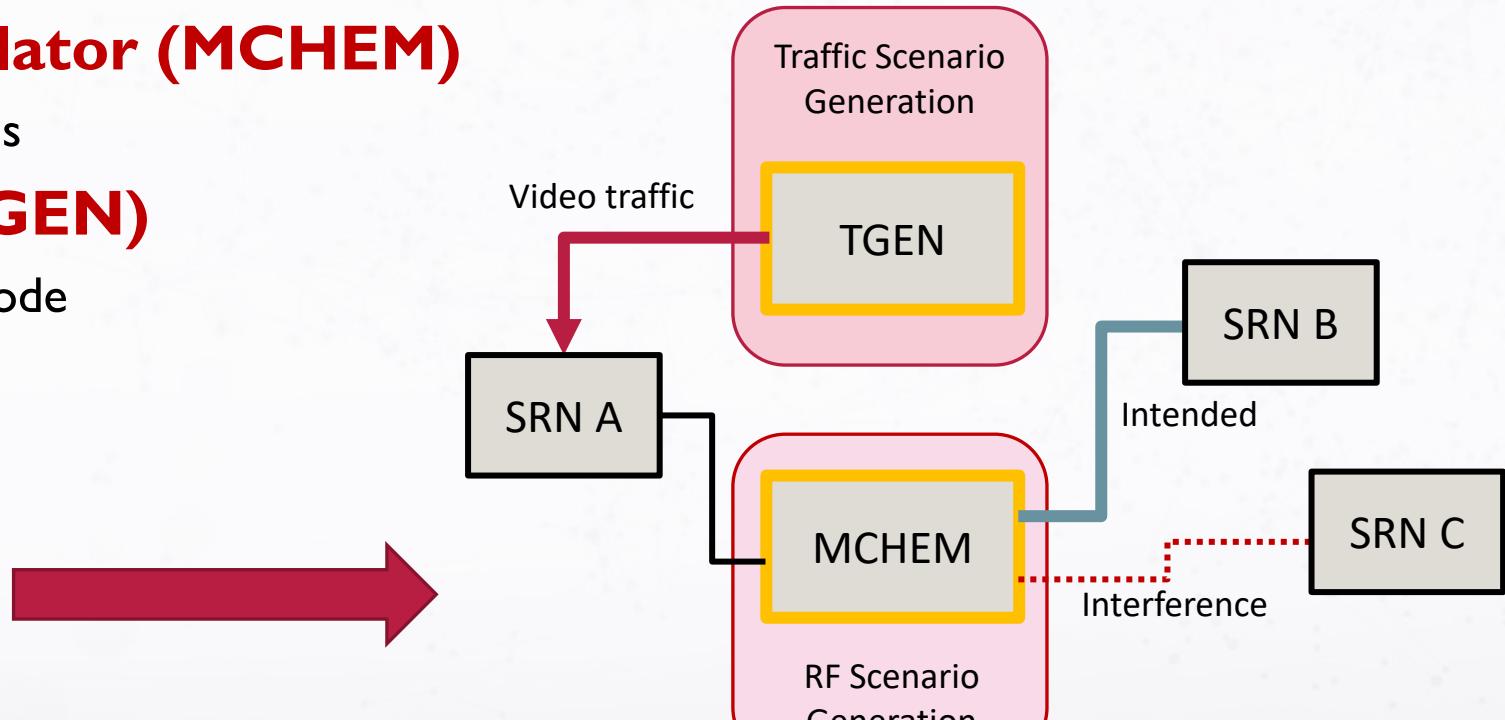
An example: performance drop

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

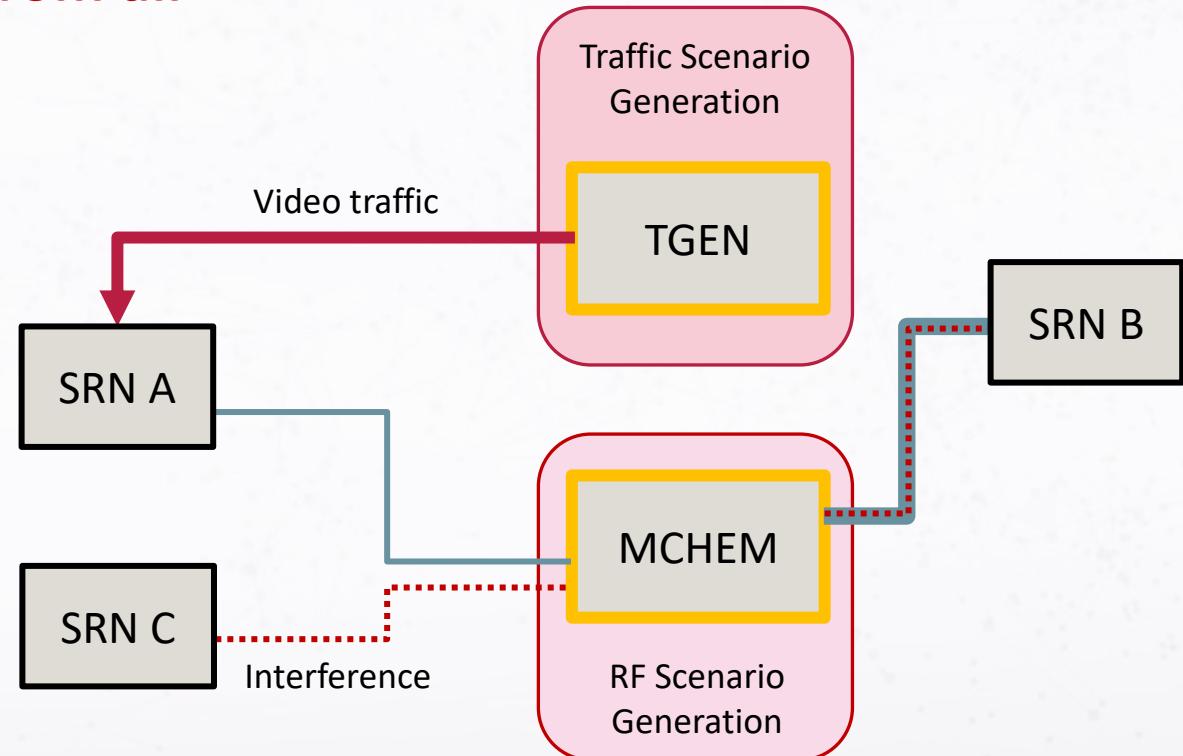
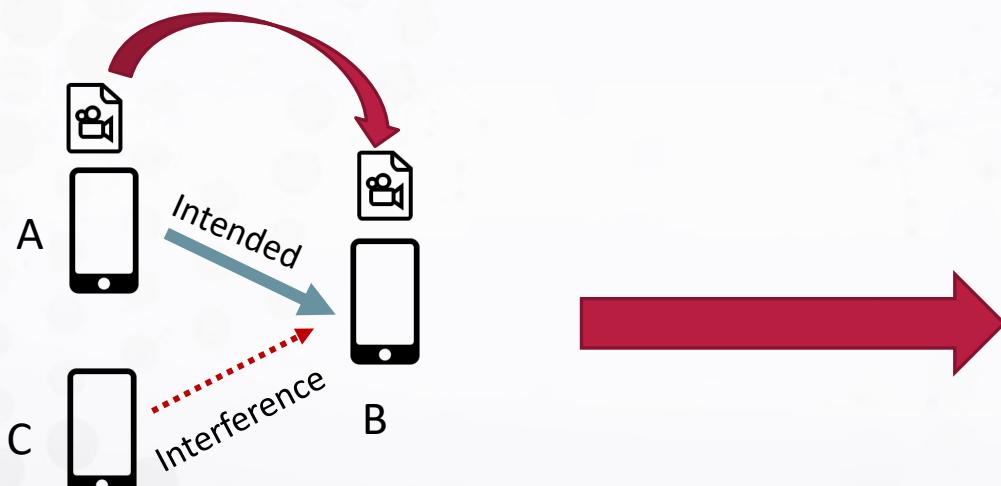


Logic representation



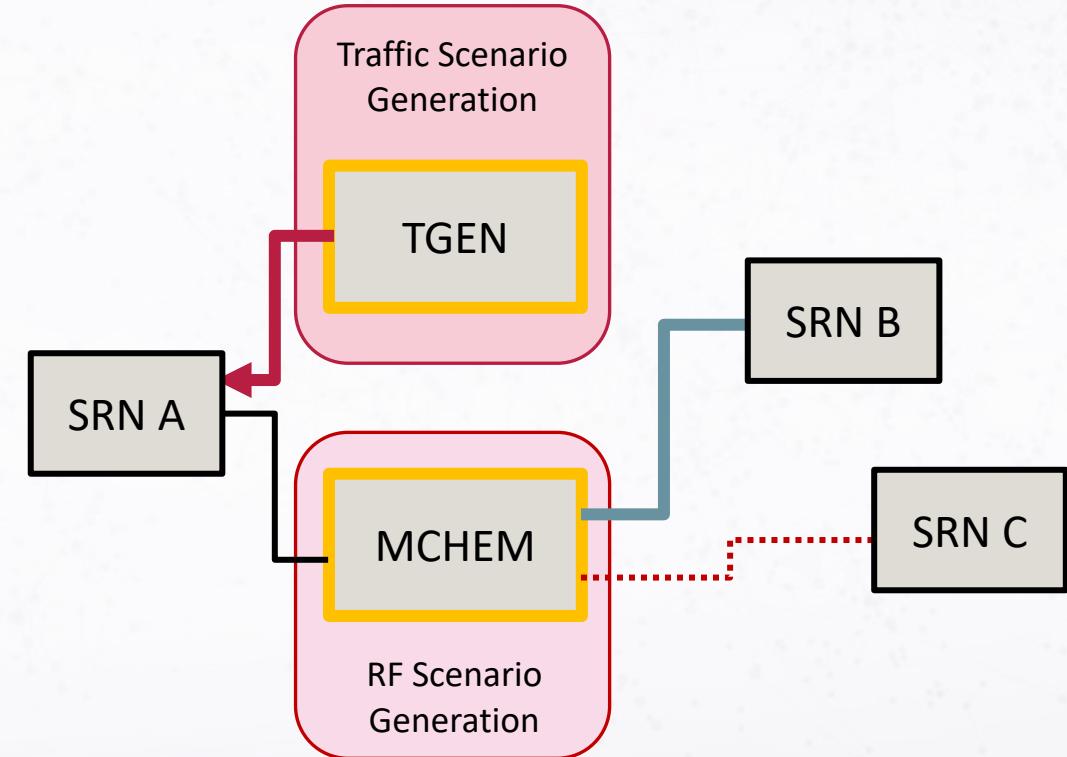
High-level Overview

- All signals are **summed** at the receiver
- **Each node can experience interference from all the other 255 transceivers**



Traffic Generator

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



MGGEN 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]

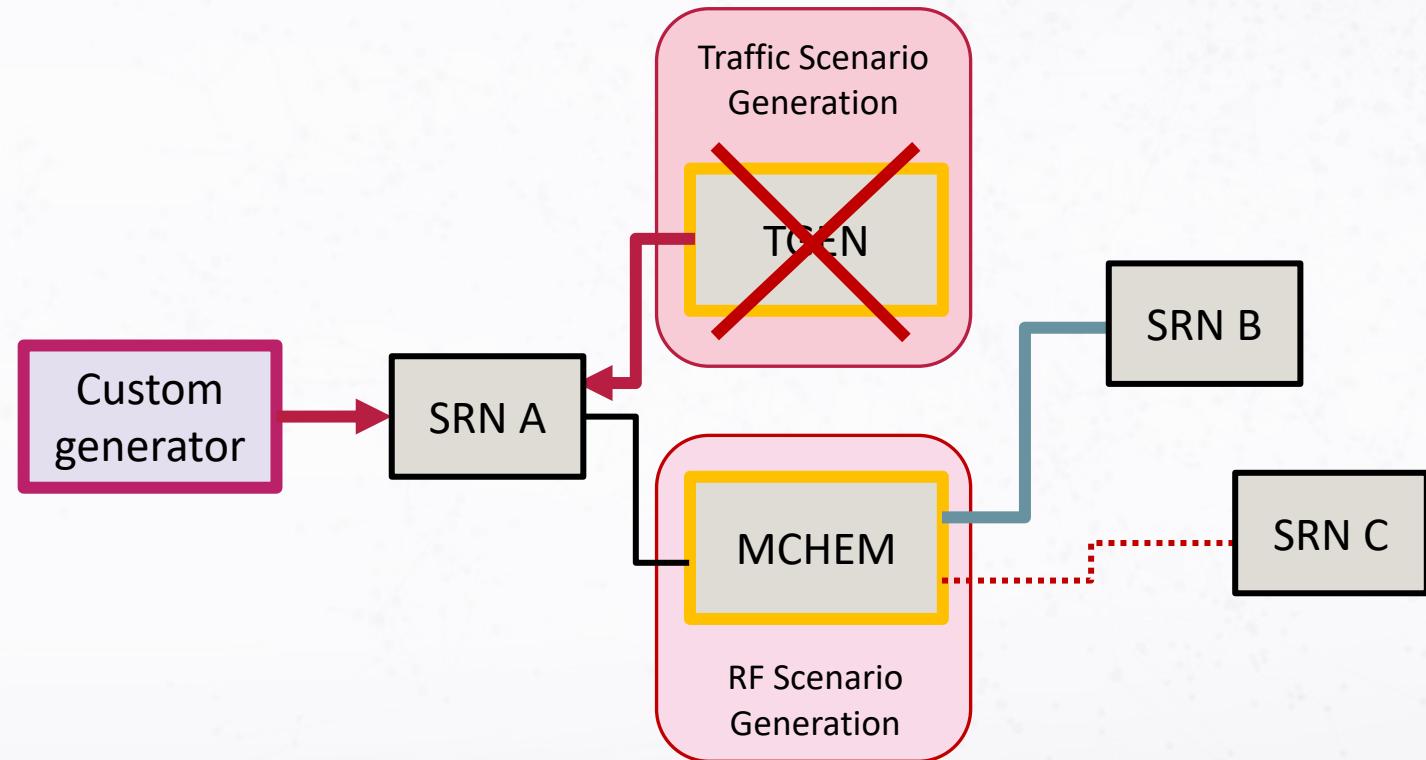
Use Custom Traffic Generators

- Users can use custom traffic generators

- Examples:

- iPerf2
- iPerf3
- Netperf
- MTR

- TGEN gets bypassed



Advanced Traffic Patterns

For advanced scenarios, **3 traffic patterns** are available.

- **Periodic**: fixed size at regular rate
 - *PERIODIC [10.0 1024]* → 10 pkts/sec with size 1024 bytes.
- **Poisson**: fixed size with average rate
 - *POISSON [10.0 1024]* → 10 average pkts/sec with size 1024 bytes.
- **Burst**: periodicity of burst and duration with various parameters
 - *BURST [RANDOM 10.0 PERIODIC [10.0 1024] FIXED 5.0]* → Bursts randomly, 10s between bursts, 5s per burst, 10 pkts/sec periodic.

More info on MGEN Navy official guide <https://www.nrl.navy.mil/itd/ncs/products/mgen>

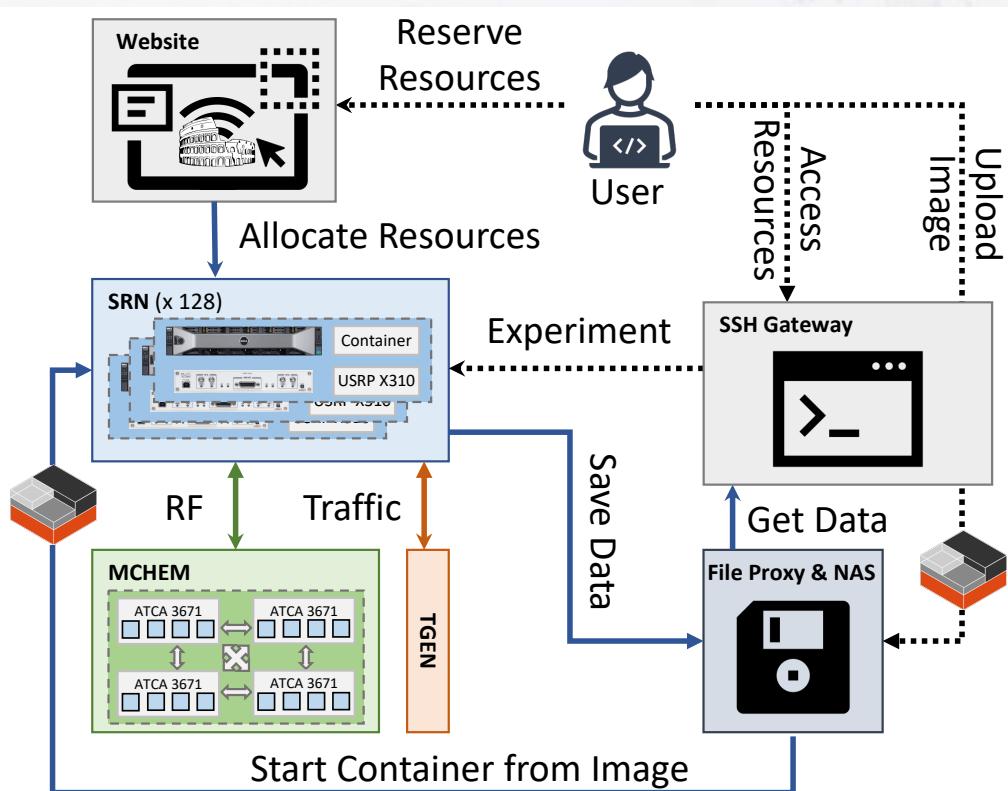
How to Get Access

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



How to Ask for Access

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



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.

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* Indicates required question



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Thank You! Q&A



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