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at Northeastern University

RF and Traffic Scenarios Overview

Colosseum Team:
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Platforms for Advanced Wireless Research

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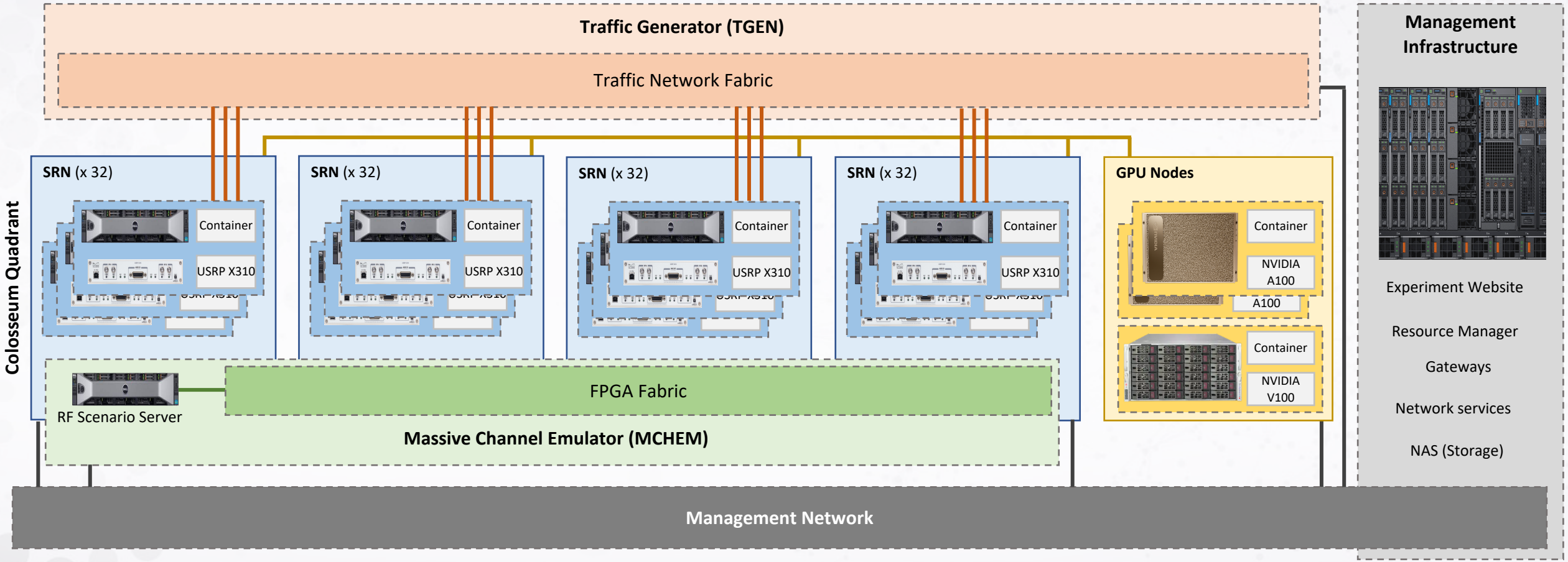
The World's Largest Wireless Network Emulator

Large-scale experimentation of wireless RF systems with **hardware-in-the-loop**

- 170+ high-performance servers w/ CPUs / GPUs
- **256 USRP X310s** → 128 as user devices, 128 as part of Colosseum Massive Channel Emulator (MCHEM)
- **65,536 80 MHz** emulated RF channels
- Full-mesh networking capability
- **Diversified scenarios** for better generalization of **AI/ML models**
- Fosters **large-scale data collection**

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, T. Melodia, "*Colosseum: Large-Scale Wireless Experimentation Through Hardware-in-the-Loop Network Emulation,*" Proc. of IEEE Intl. Symp. on Dynamic Spectrum Access Networks (DySPAN), Virtual Conference, December 2021

Colosseum Architecture



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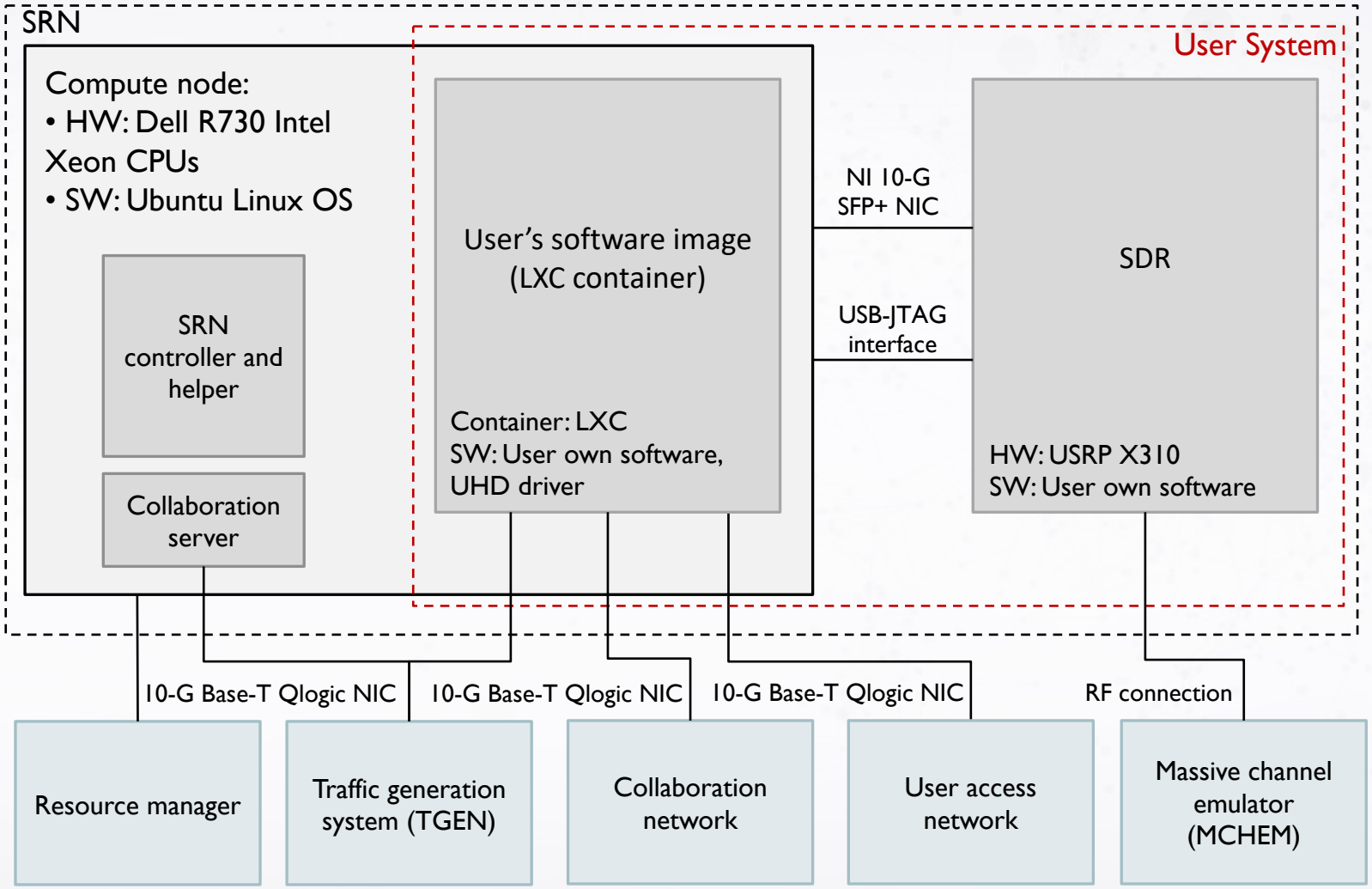
Standard Radio Node (SRN)



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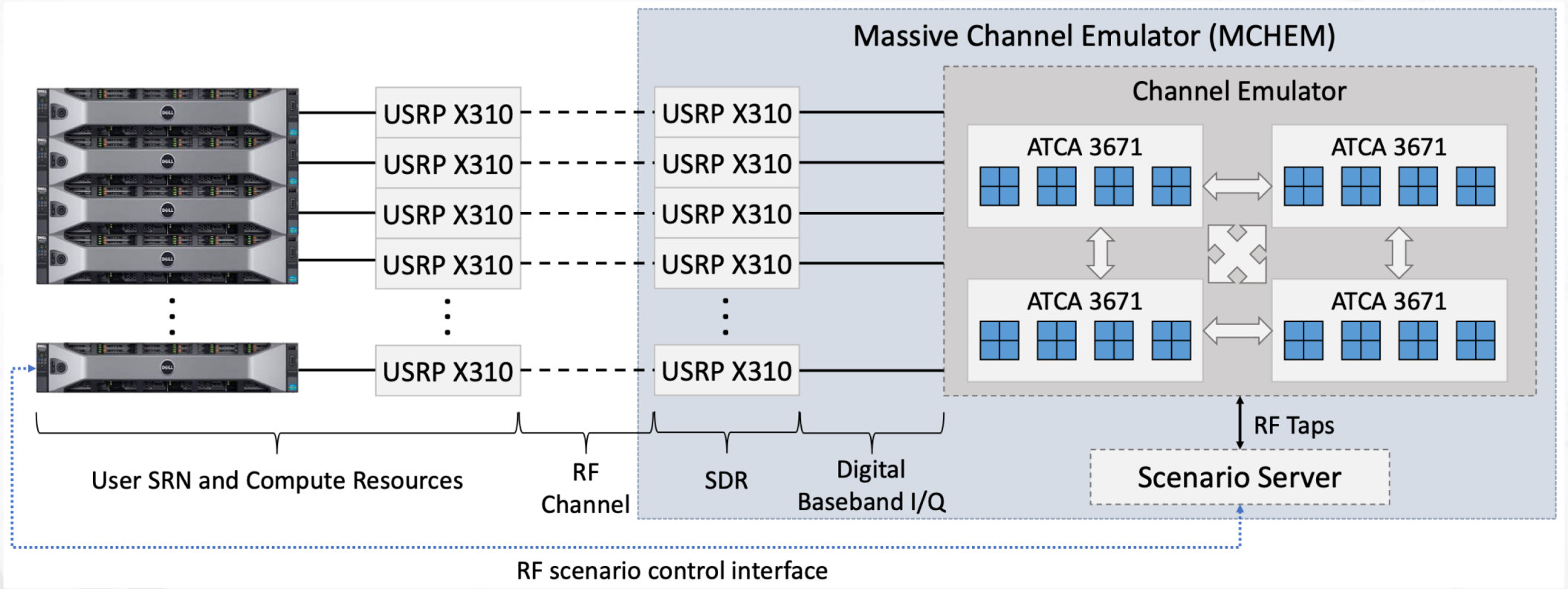
Massive Channel Emulator (MCHEM)

- 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 in Colosseum

- 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

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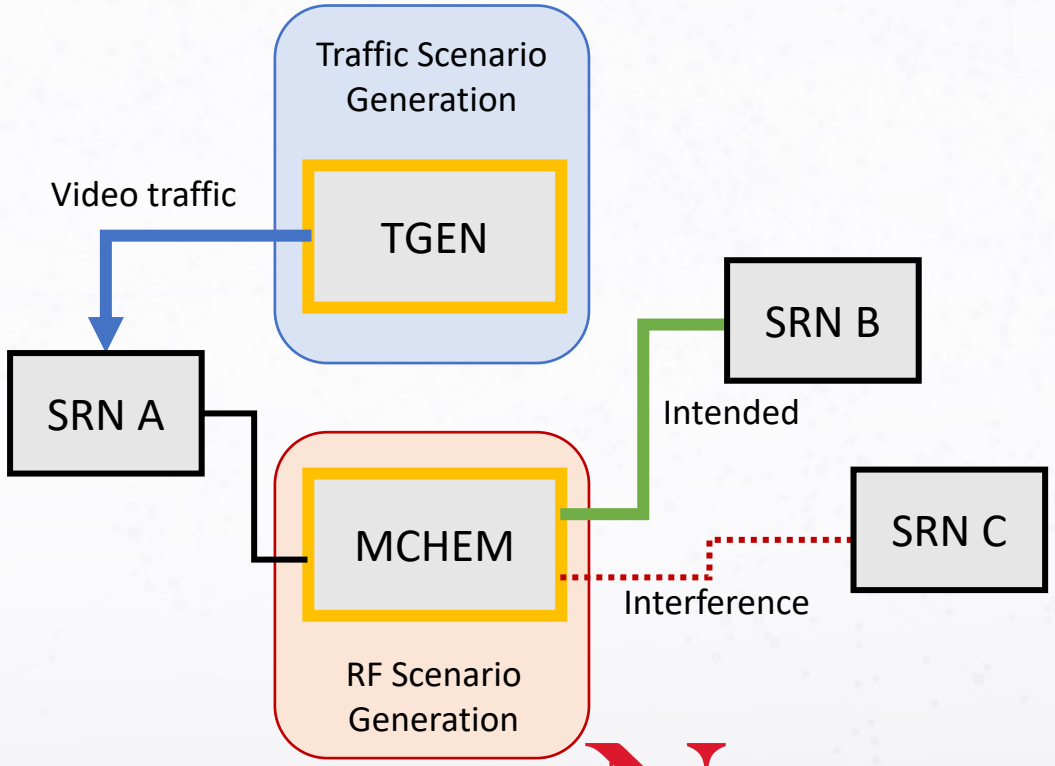
Scenarios: The Colosseum Way

- 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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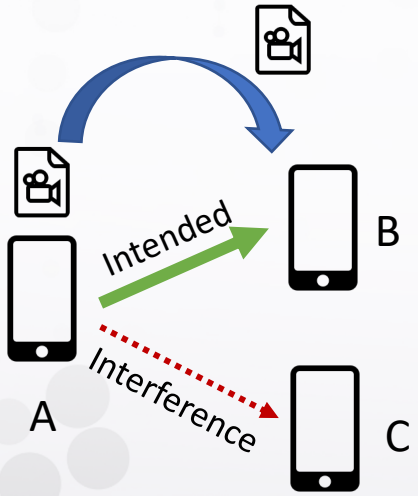
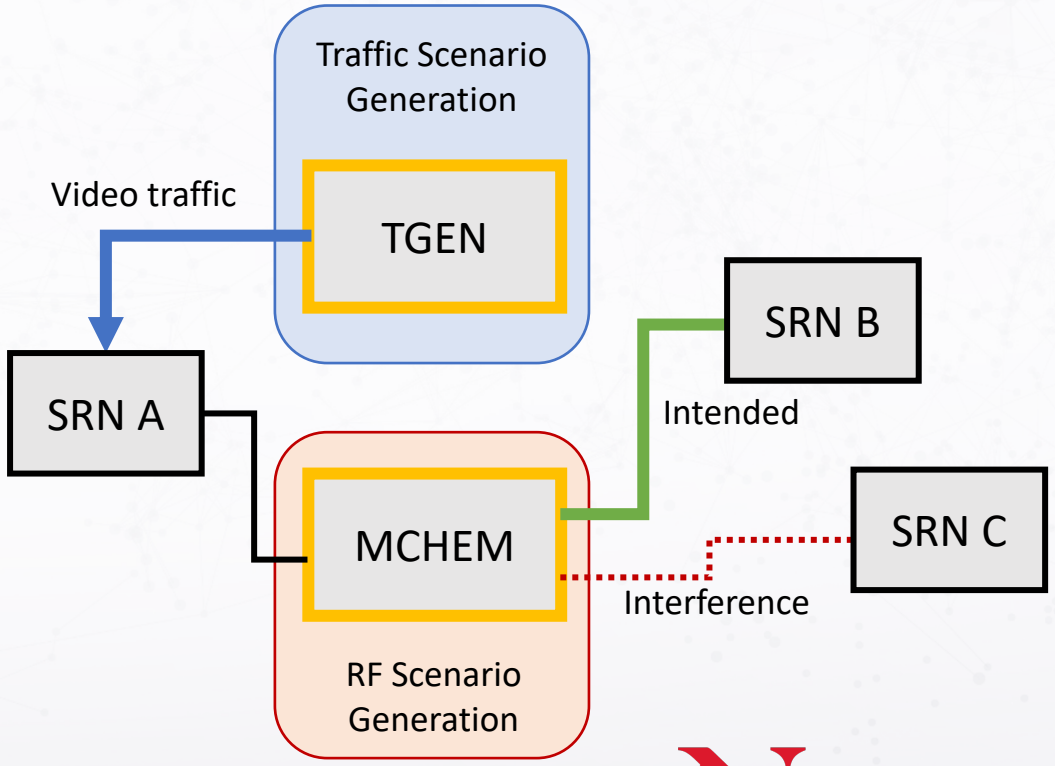
High-level Overview

- 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

Colosseum implementation



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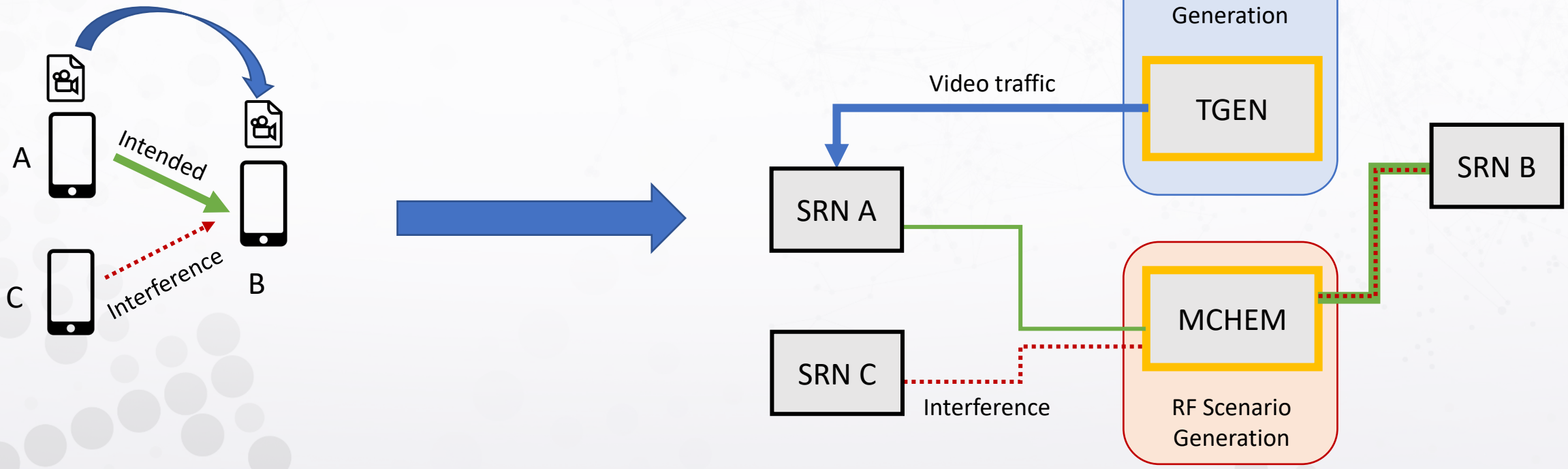
High-level Overview, Cont'd

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

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



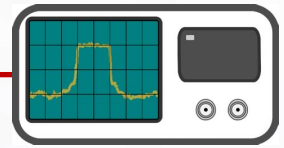
Ways to Generate Filter Taps

- **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

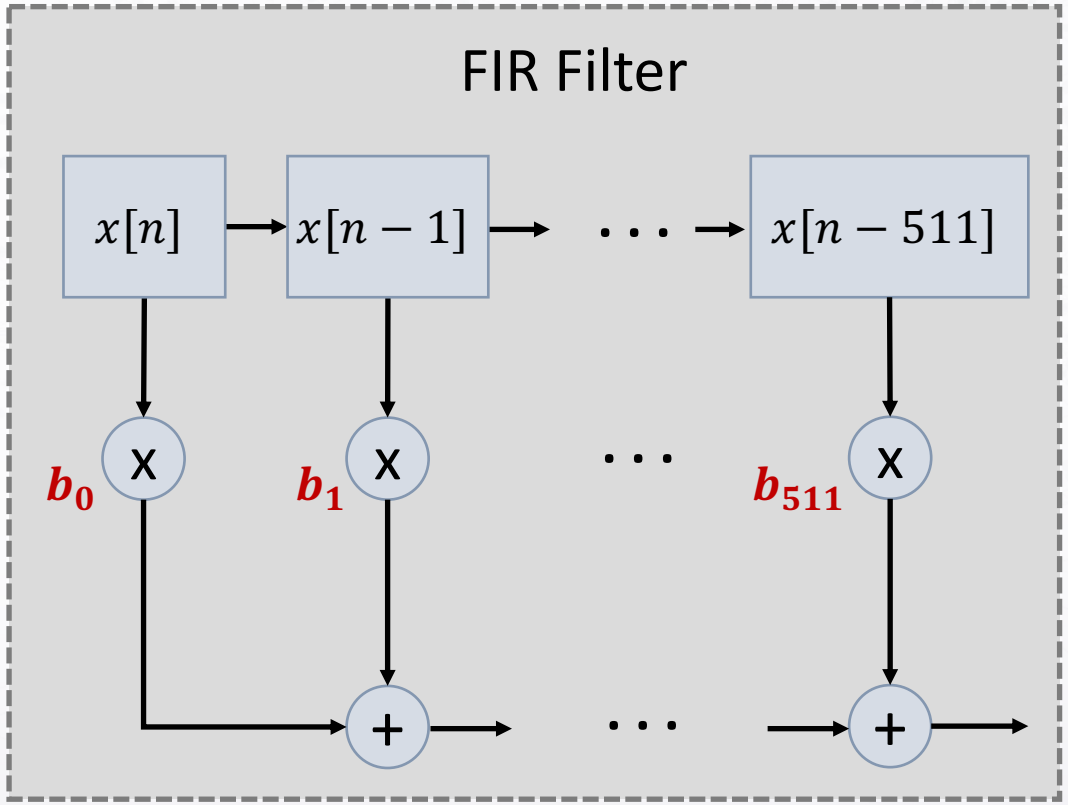
b_i

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

Calibrate w/ measurements

Taps Approximation

b_i



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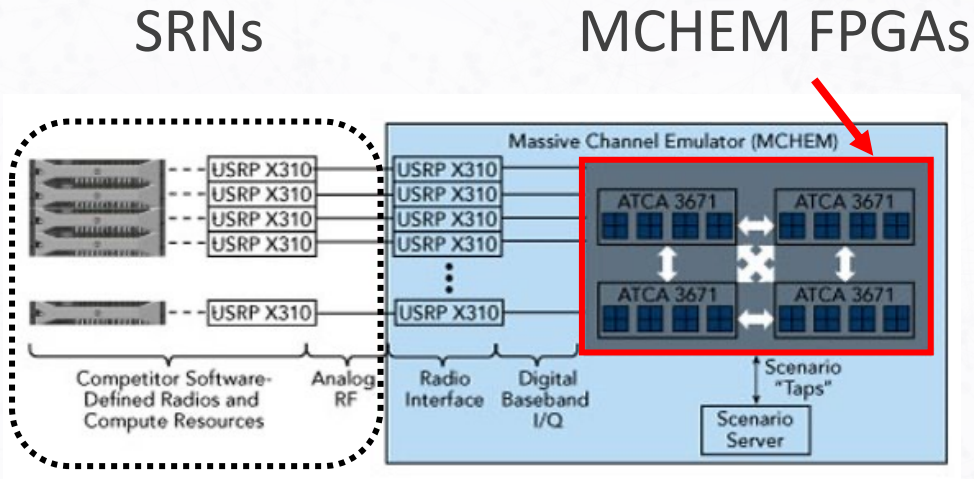
Complexity vs. Accuracy

- **FIR taps:**
  - 512 complex-valued FIR taps
  - **Sparse filter: only 4 are non-zero**

- **Why?**
  - Colosseum has 1 ms channel resolution
  - Scenarios are **VERY** complex
  - **Example:**
    - single-tap
    - 10 nodes
    - 10 minutes duration
    - > 100 GB storage needed (FIR taps only!!)
    - > 2 days 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**

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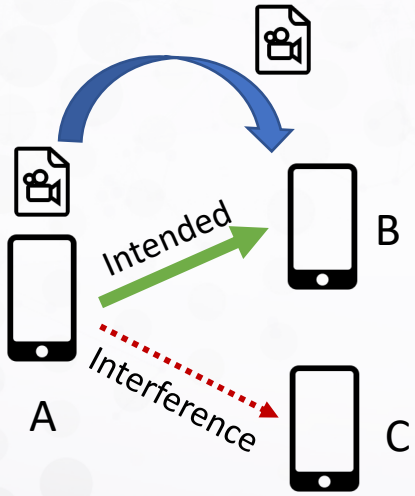
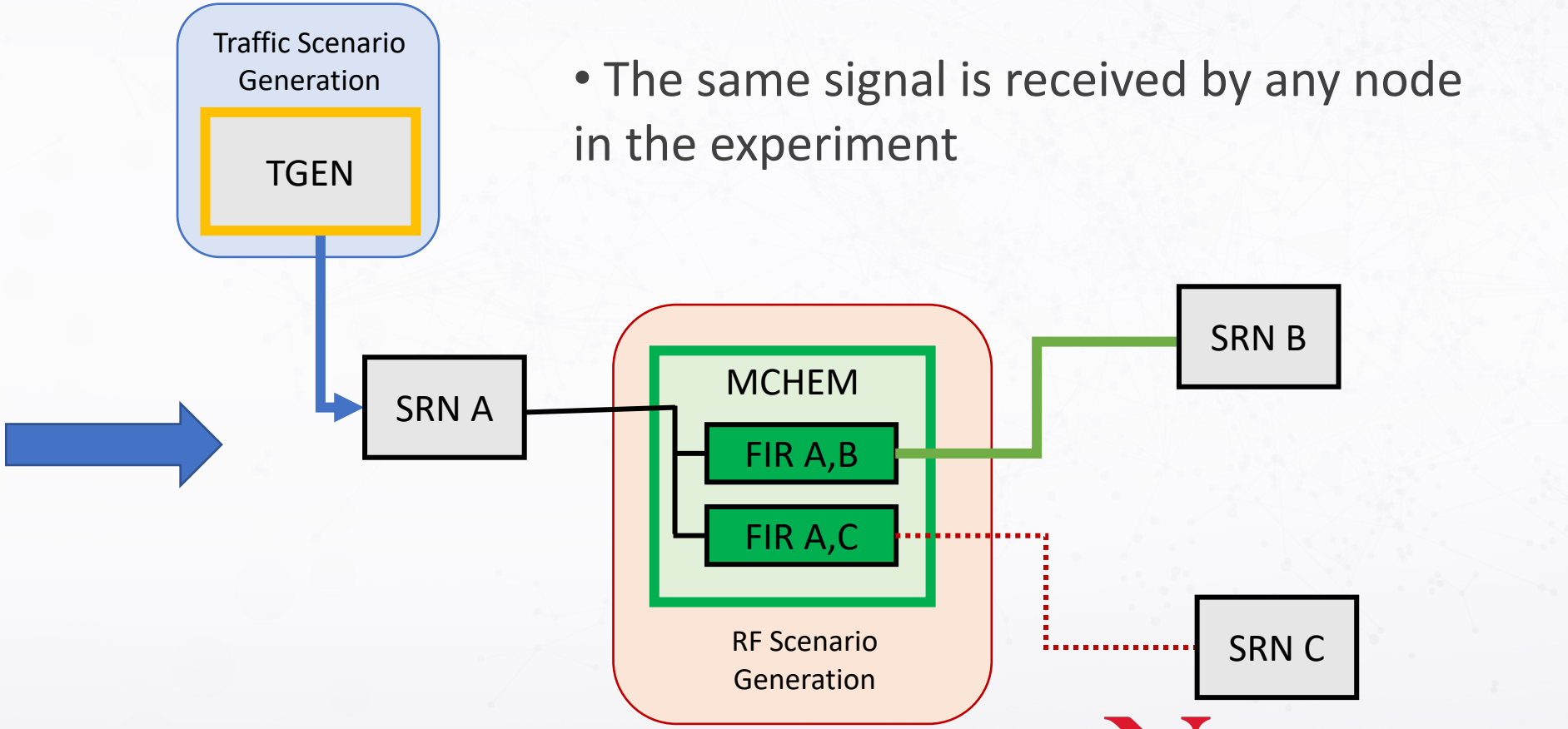
RF Scenarios in Practice

- Colosseum has a FIR for each pair (A,B)
- The same signal is received by any node in the experiment





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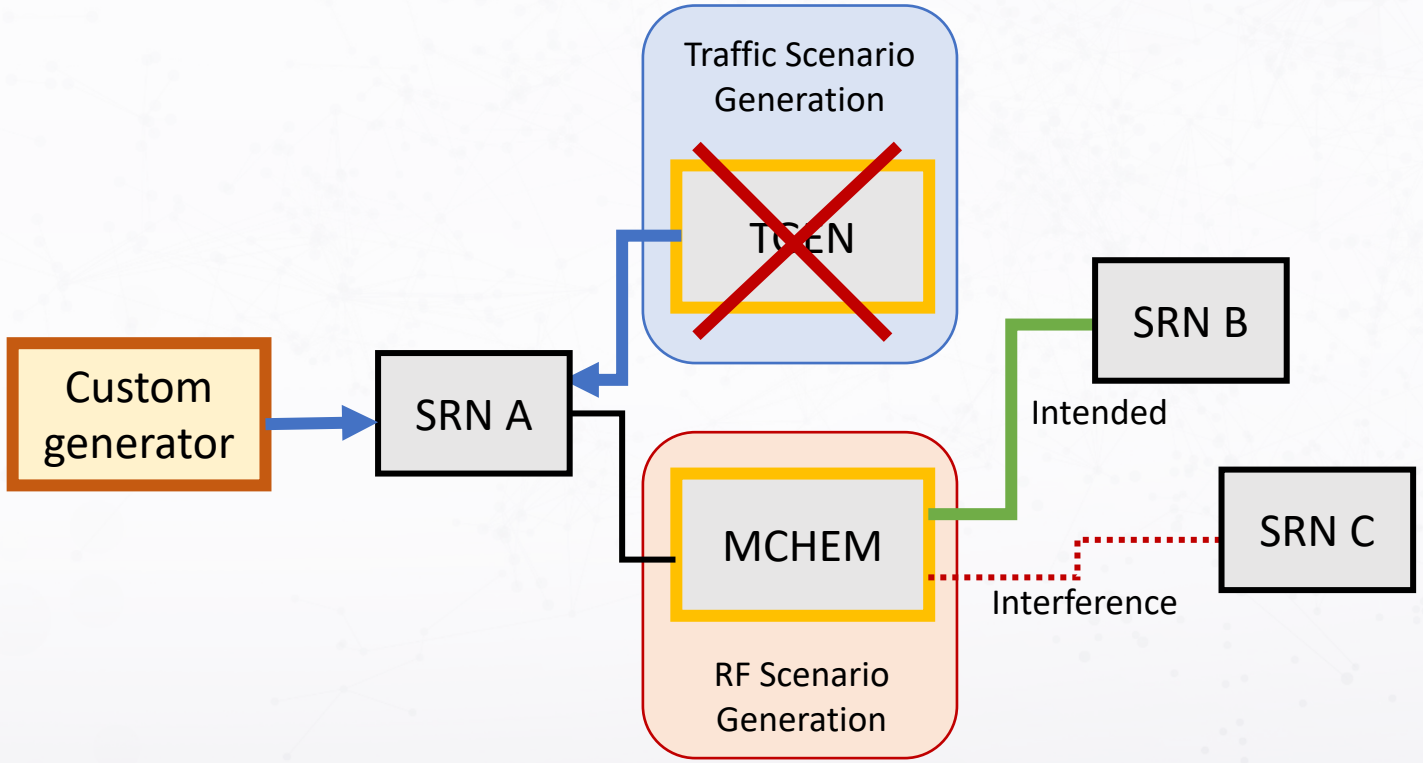
Traffic Scenarios - Customization

- Users can use custom traffic generators

- Examples:
  - iPerf2
  - iPerf3
  - Netperf
  - MTR

- TGEN gets bypassed



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Scenario Creation Overview

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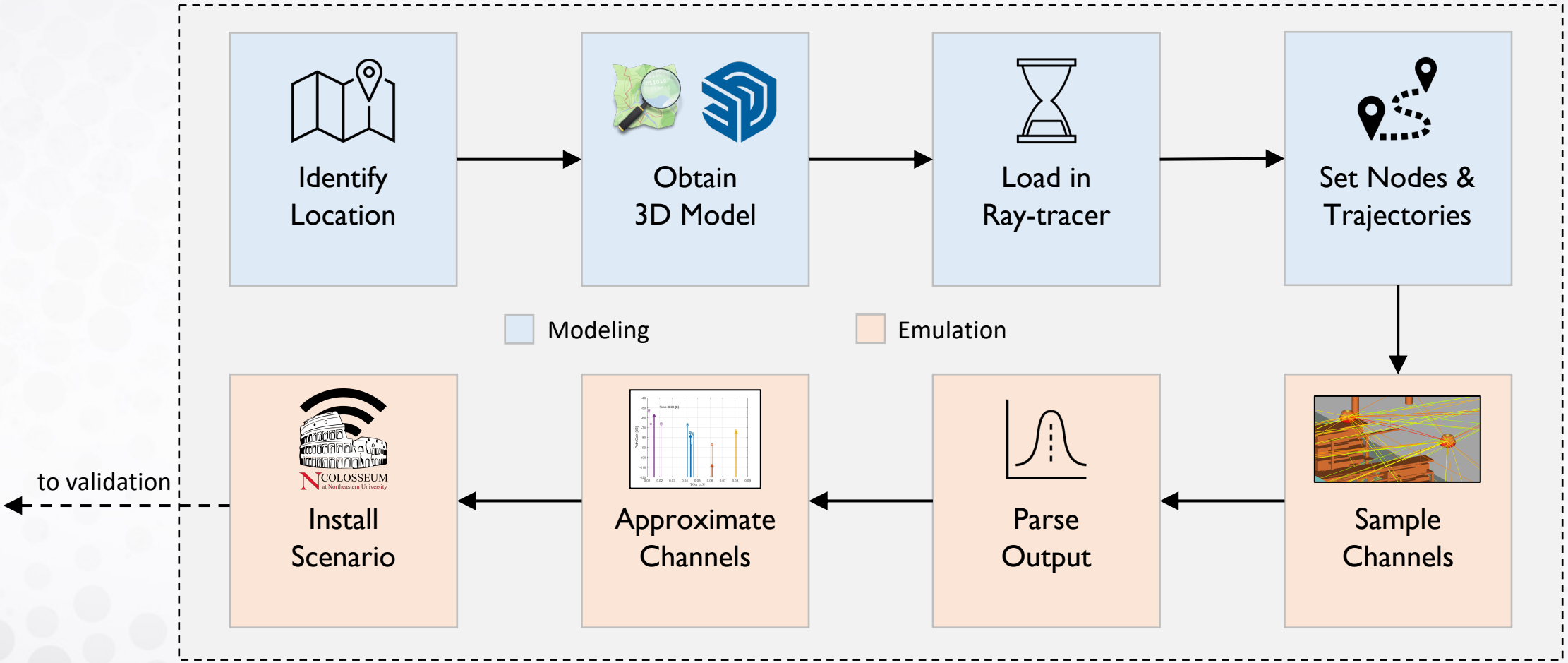
Scenario Creation Overview



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

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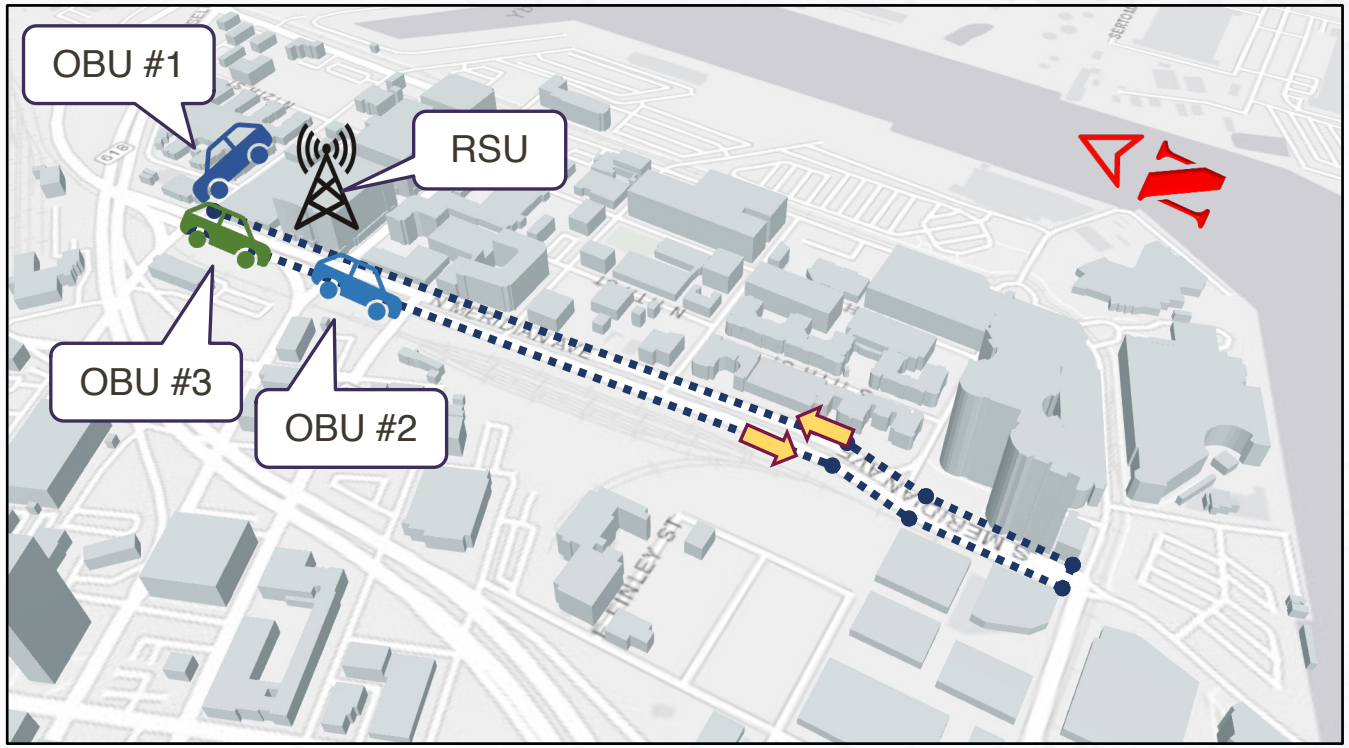
Creating Mobile RF Scenarios

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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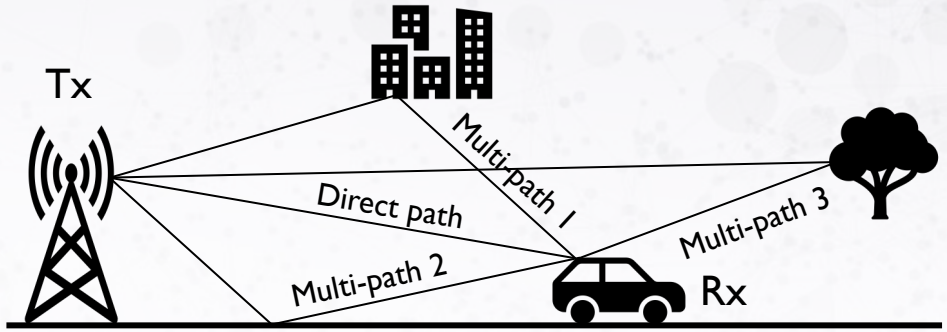
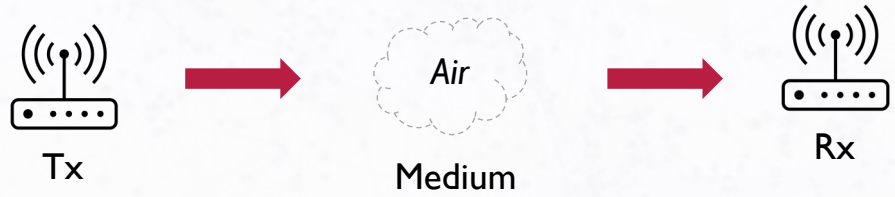
Scenario Validation

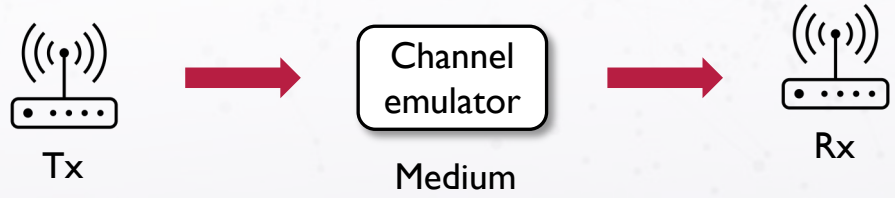
- Channel sounding goals:
  - **Evaluate** an RF channel characteristics
  - **Analyze** the environment
  - **Optimize** the design
- **No over-the-air** communication
- **Emulated** medium
- Sounding goals in emulators:
  - **Validate** original traces:
    - Channel Impulse Response (**CIR**) for 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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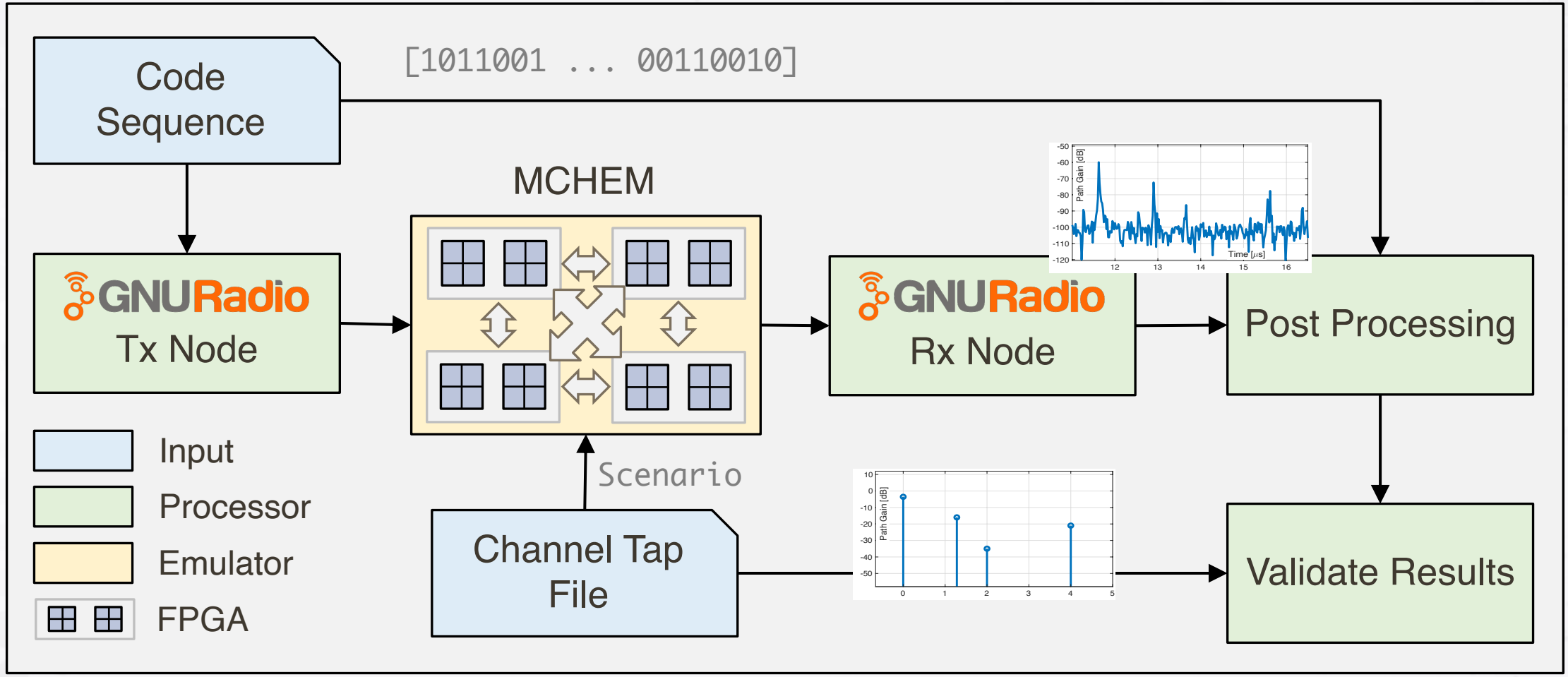
CaST Channel Sounding Workflow



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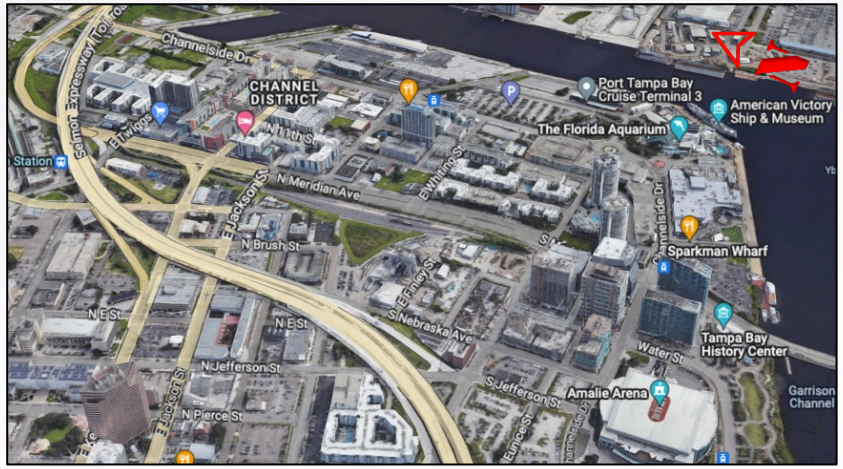
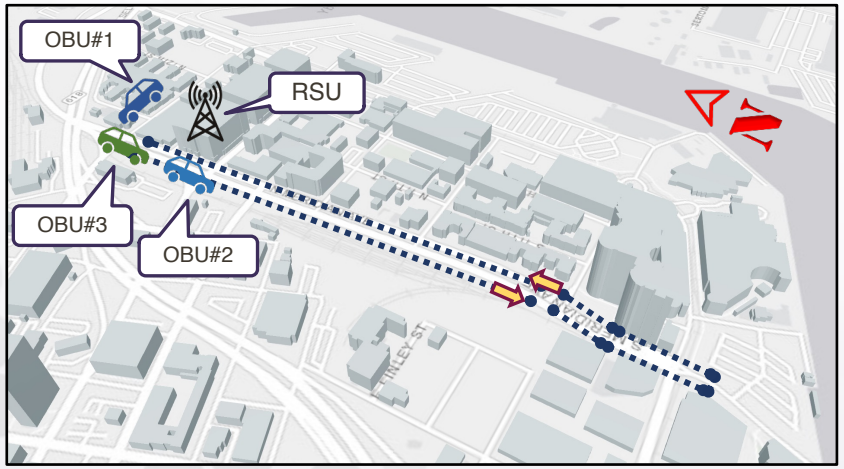
Some Results: Use Case V2X Tampa, FL



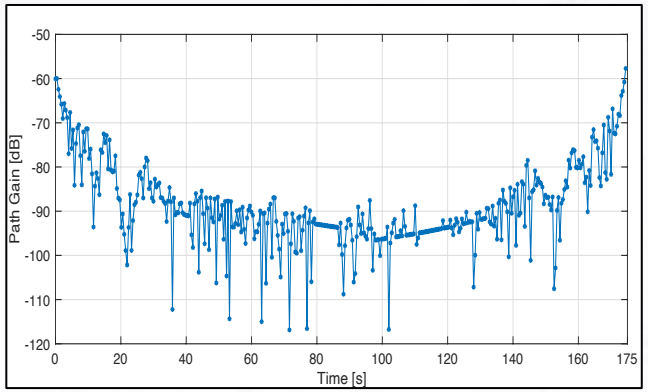
Real Environment

CaST Framework

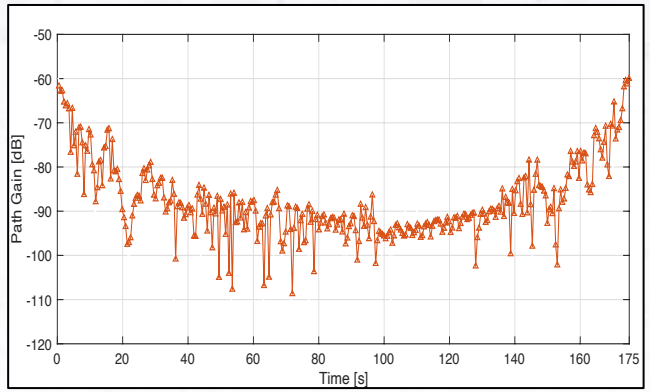


Digital Environment

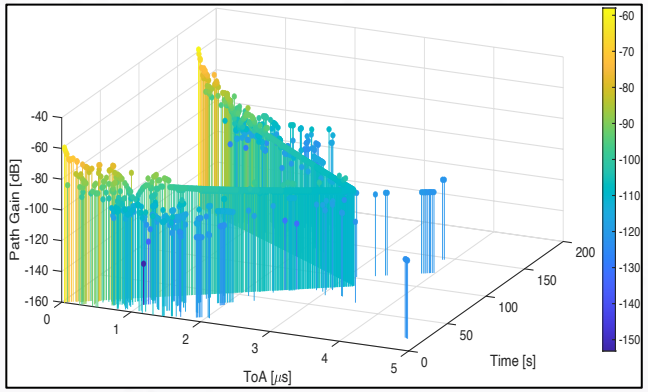
CaST Sounder



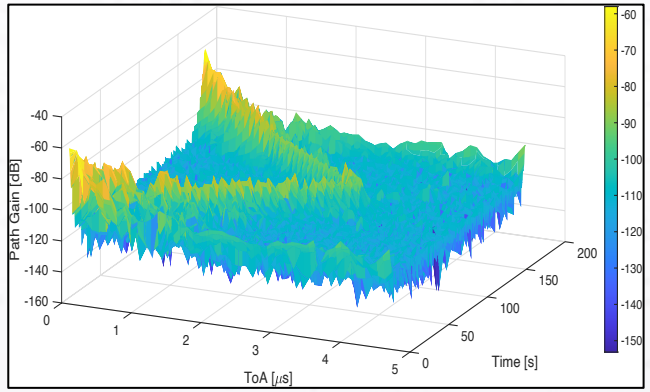
Theoretical path gains RSU-OBU#2



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

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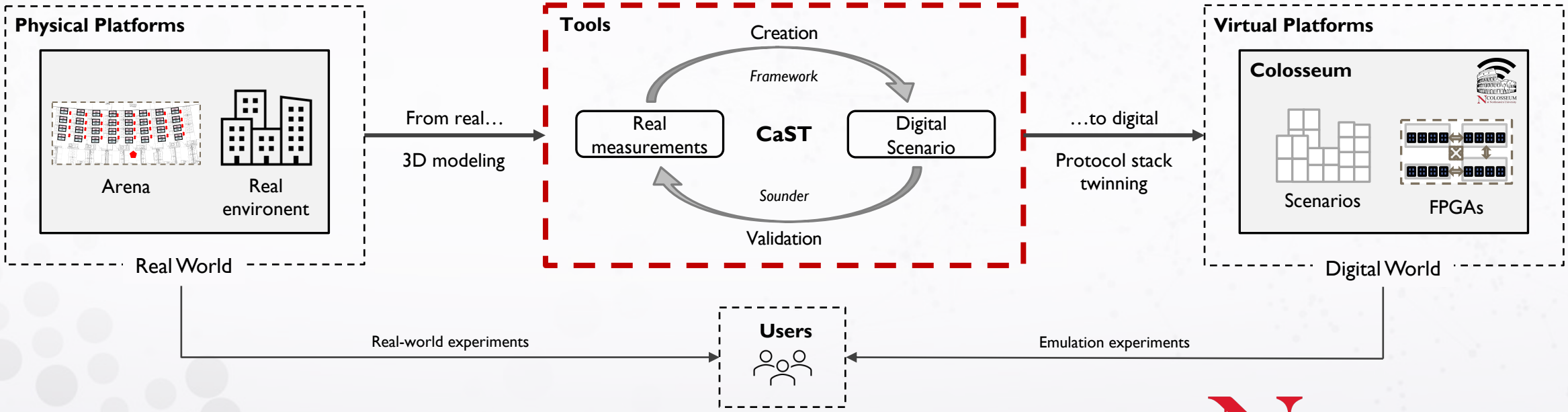
Colosseum as a Digital Twin

- **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

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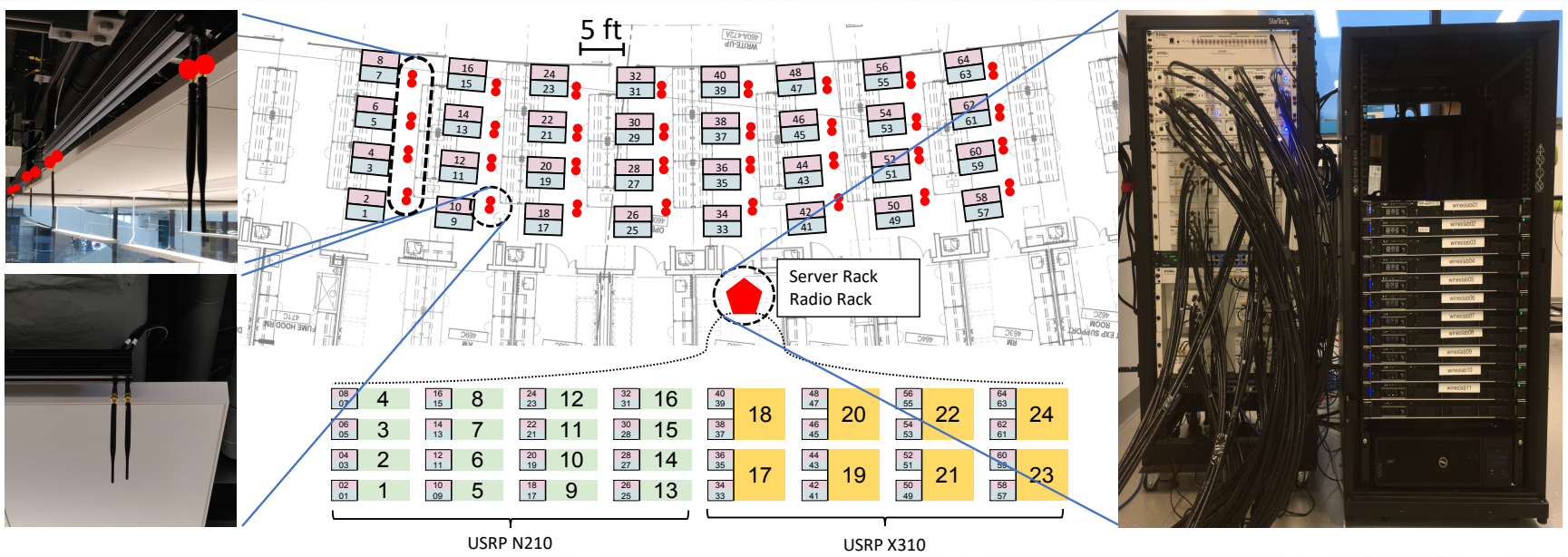
Example of Physical Environment in Digital Twin: Arena

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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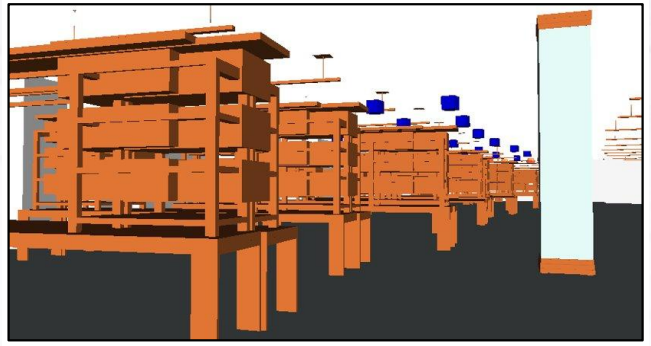
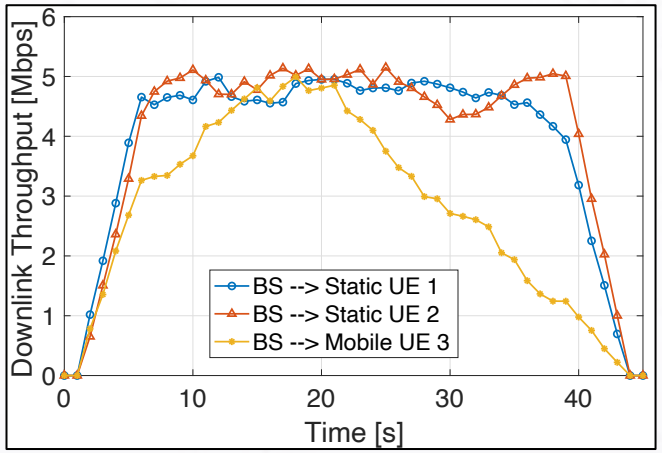
From Real to Digital

- 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

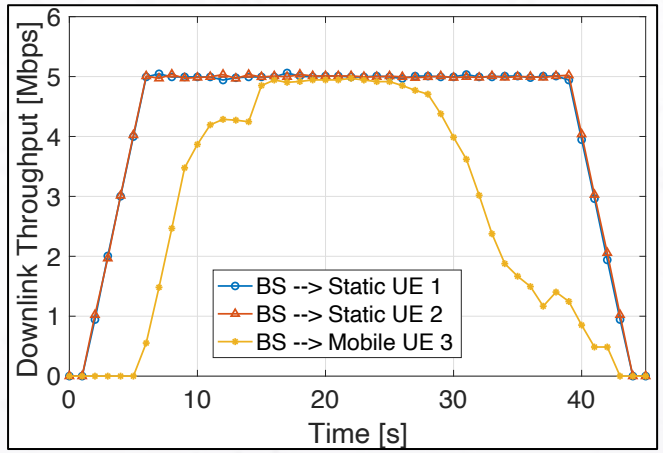
Real world



Digital world



Real world



Digital world

Good match between real and digital environment

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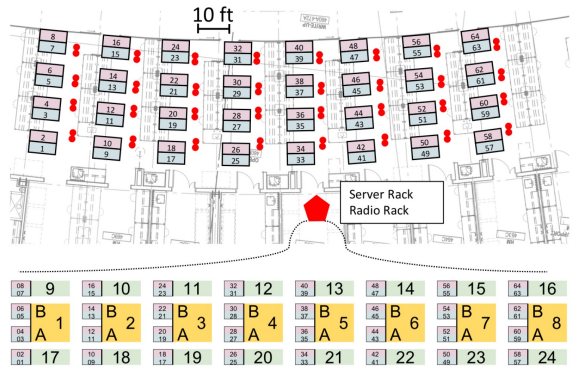
Prototype At-scale, Test in the Wild

- **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

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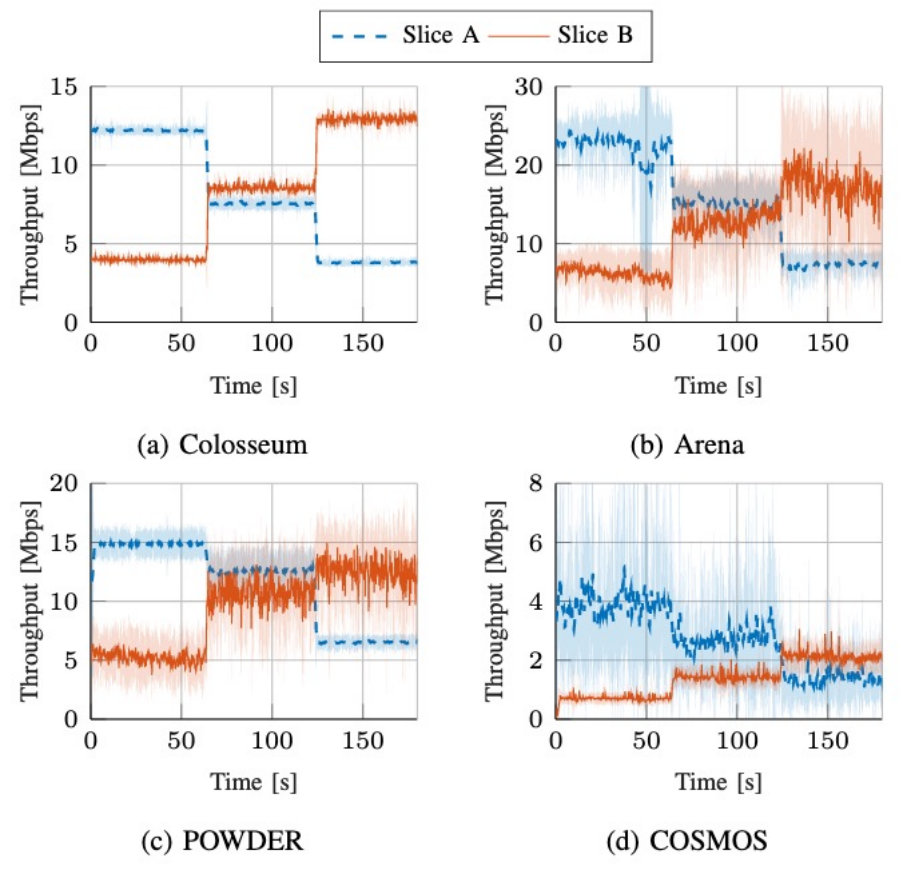
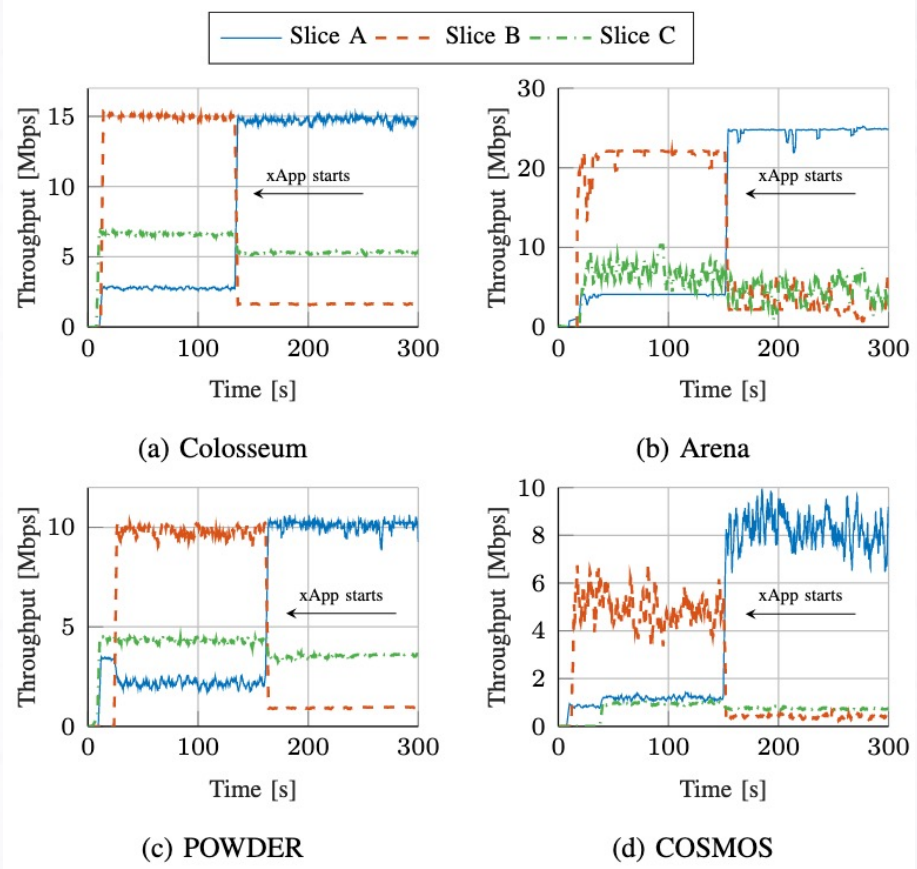
From Colosseum to PAWR

Periodic change of slicing resources



xApp closed-control loop



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

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

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Thank You! (Questions?)

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