LVX VERITAS VIRTVS

Institute for the Wireless Internet of Things at Northeastern University

Platforms for Advanced Wireless Research

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MASSACHUSETTS TECHNOLOGY COLLABORATIVE

COLOSSEUM at Northeastern University

Radio-Frequency Scenarios

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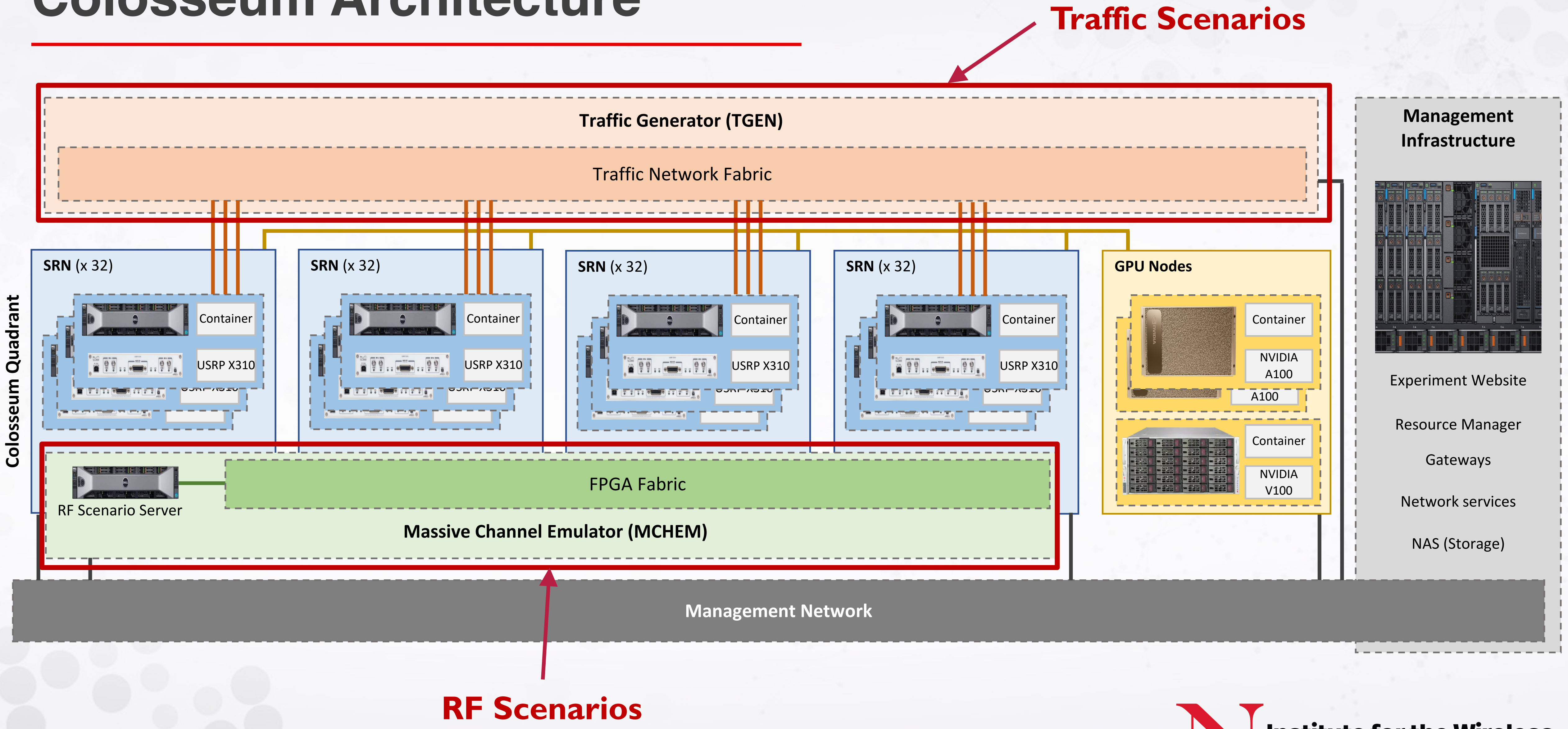
Colosseum Architecture



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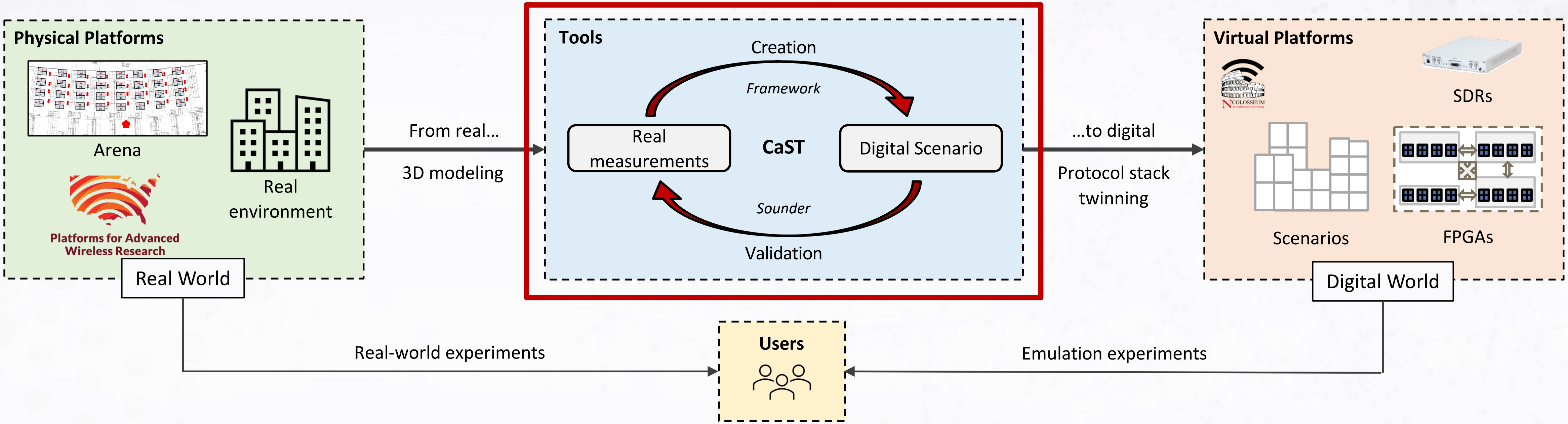
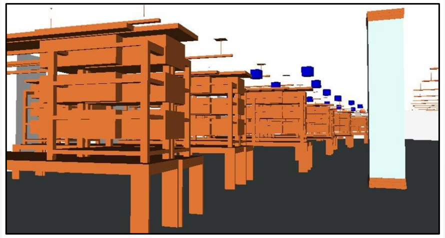
Colosseum as a Digital Twin

Capability: Create digital twin scenarios, run experiments close to reality, evaluate performance



Indoor Environment

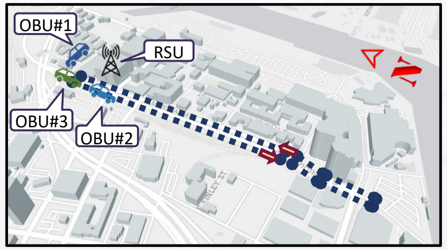
CaST



Real World *Digital World*

Outdoor Environment

CaST



Real World *Digital World*

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,"* pp 1-15, IEEE Transactions on Mobile Computing, in press, 2024.

RF Scenario Creation

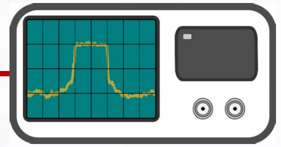
Ways to Generate Filter Taps for Scenarios

- **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

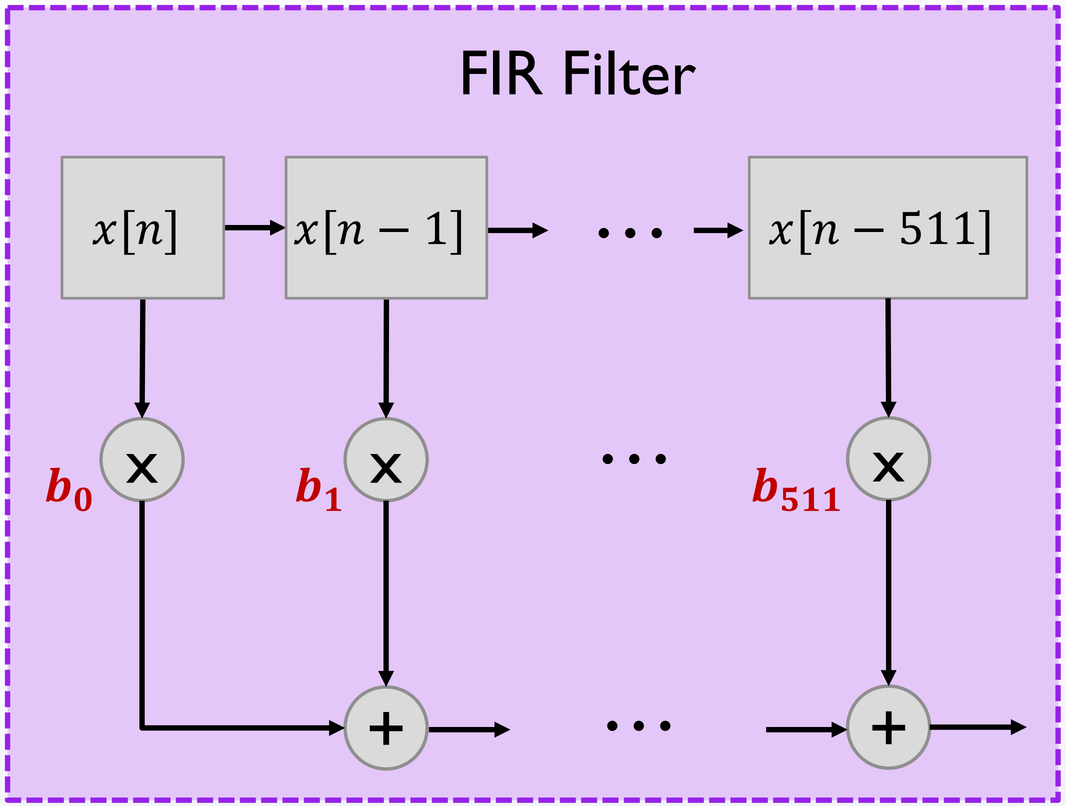
b_i

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

Calibrate w/ measurements

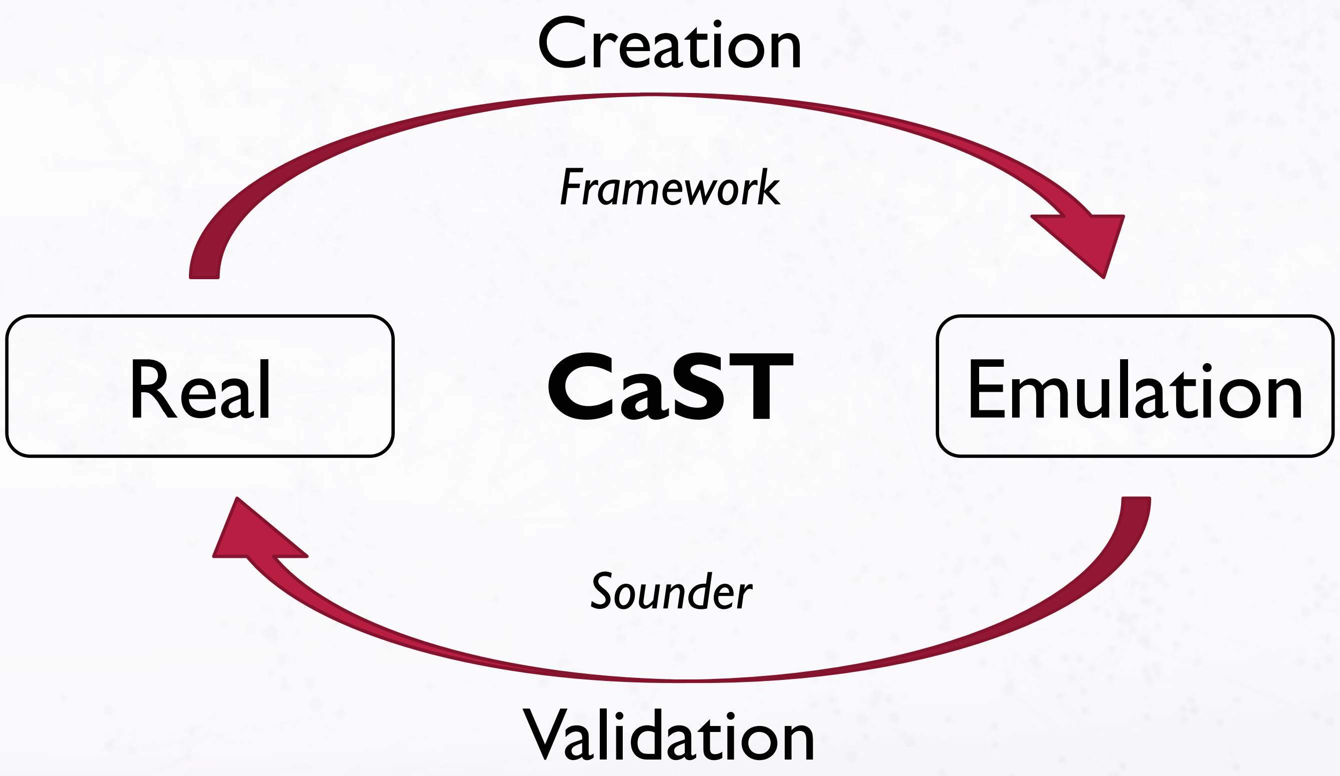
Taps Approximation

b_i



CaST: A Toolchain to Create and Validate Colosseum Scenarios

- **CaST** - Channel emulation scenario generator and Sounder Toolchain:
  - Streamlined **framework** to create realistic mobile wireless scenarios.
  - SDR-based **channel sounder** to characterize emulated RF channels.
- Features:
  - **Accuracy** up to 20 ns for CIR delays and 0.5 dB for tap gains
  - Partially **automated**
  - Fully **open-source**
  - Validated in **Colosseum**



Code: https://github.com/wineslab/cast

D. Villa, M. Tehrani-Moayyed, P. Johari, S. Basagni, and T. Melodia, "CaST: a toolchain for creating and characterizing realistic wireless network emulation scenarios", in Proceedings of the 16th ACM Workshop WiNTECH '22.

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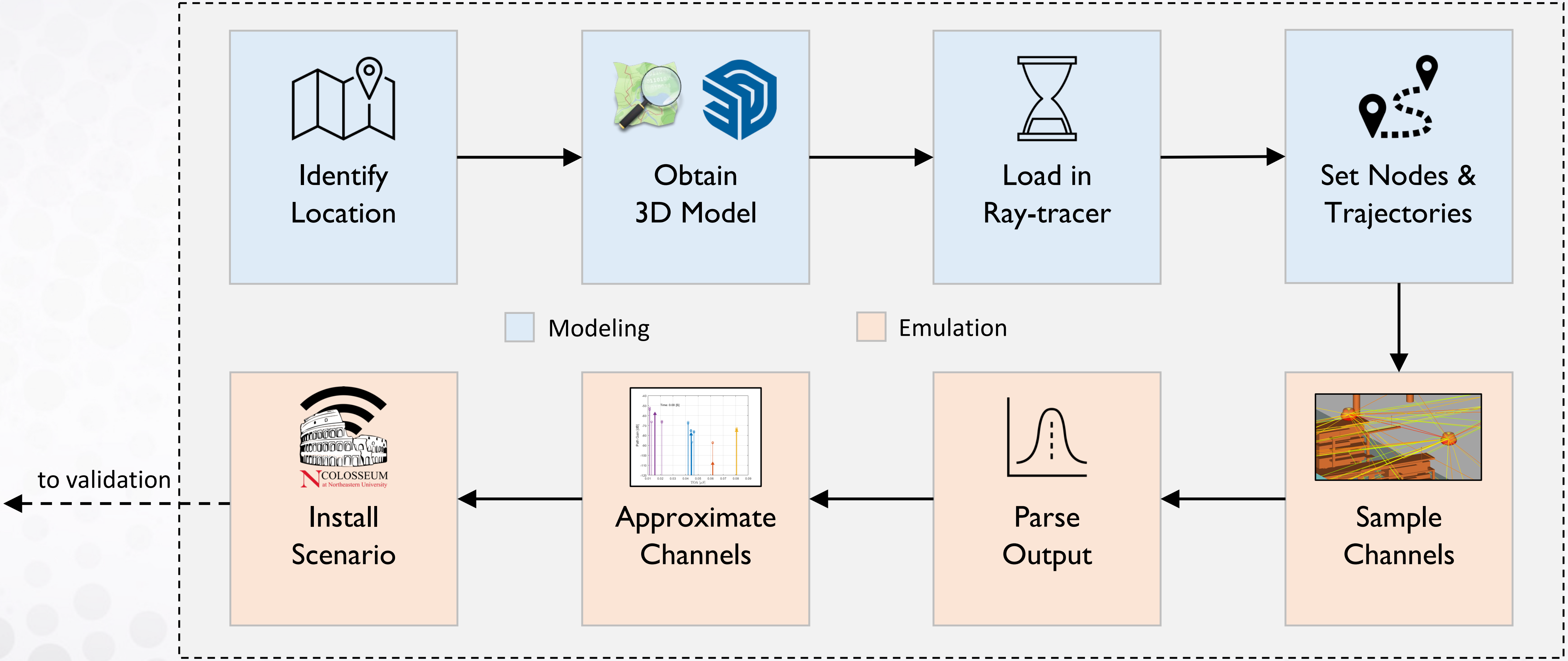
RF Scenario Creation Overview



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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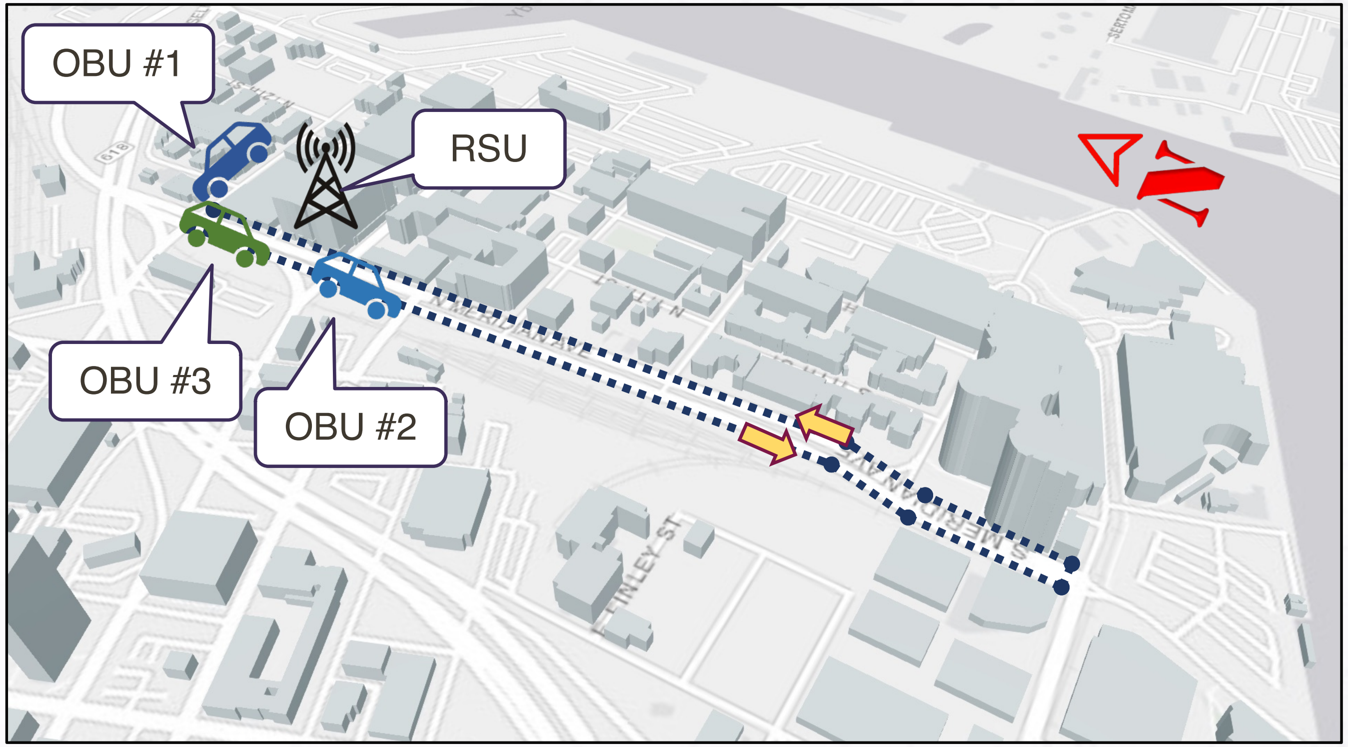
Creating Mobile RF Scenarios

Use case V2X Tampa, FL

1. **Identify** scenario location
2. **Obtain** 3D model from OSM
3. **Convert** model in STL to feed the ray-tracer
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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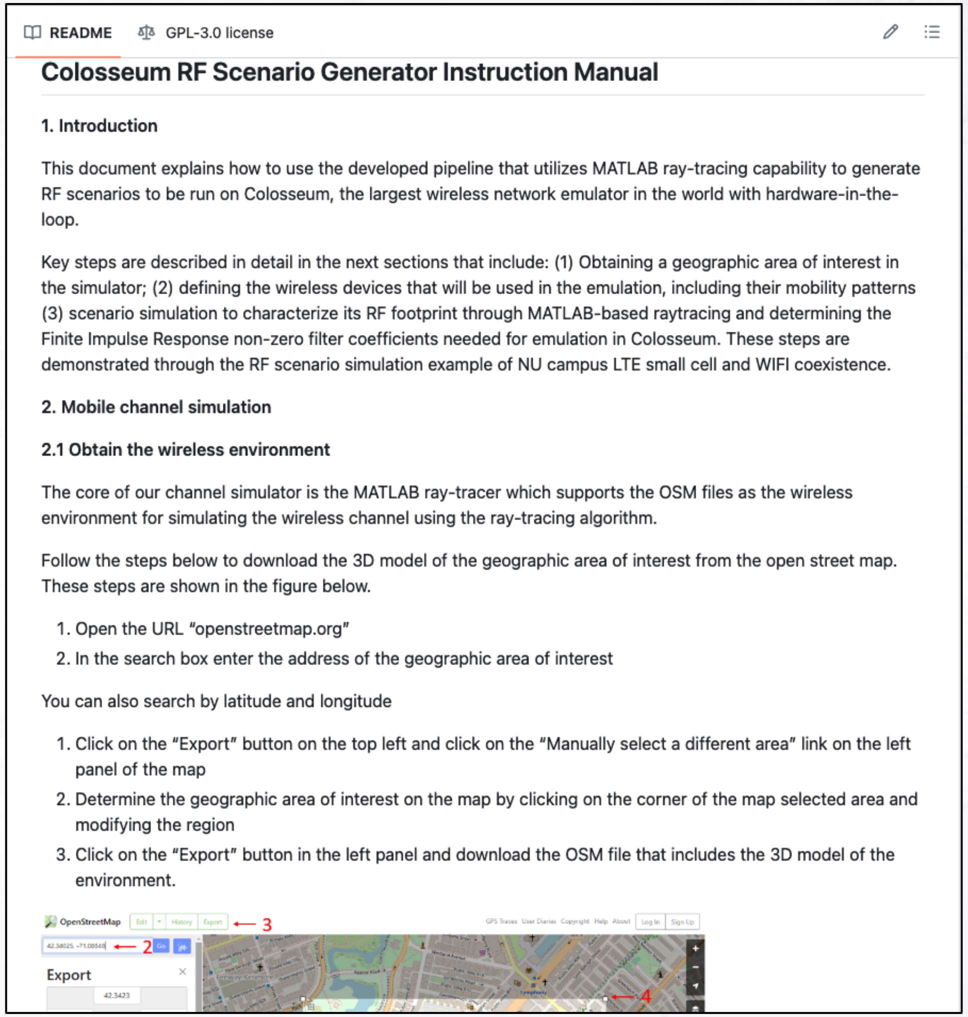
Public GitHub Repo

- Colosseum RF scenario generation instruction manual for MATLAB ray-tracer.
- Step-by-step instructions.
- Easily adjustable parameters.

https://github.com/Colosseum-MATLAB-Project/ColosseumScenarioGenerator



README GPL-3.0 license

Colosseum RF Scenario Generator Instruction Manual

1. Introduction

This document explains how to use the developed pipeline that utilizes MATLAB ray-tracing capability to generate RF scenarios to be run on Colosseum, the largest wireless network emulator in the world with hardware-in-the-loop.

Key steps are described in detail in the next sections that include: (1) Obtaining a geographic area of interest in the simulator; (2) defining the wireless devices that will be used in the emulation, including their mobility patterns (3) scenario simulation to characterize its RF footprint through MATLAB-based raytracing and determining the Finite Impulse Response non-zero filter coefficients needed for emulation in Colosseum. These steps are demonstrated through the RF scenario simulation example of NU campus LTE small cell and WIFI coexistence.

2. Mobile channel simulation

2.1 Obtain the wireless environment

The core of our channel simulator is the MATLAB ray-tracer which supports the OSM files as the wireless environment for simulating the wireless channel using the ray-tracing algorithm.

Follow the steps below to download the 3D model of the geographic area of interest from the open street map. These steps are shown in the figure below.

1. Open the URL "openstreetmap.org"
2. In the search box enter the address of the geographic area of interest

You can also search by latitude and longitude

1. Click on the "Export" button on the top left and click on the "Manually select a different area" link on the left panel of the map
2. Determine the geographic area of interest on the map by clicking on the corner of the map selected area and modifying the region
3. Click on the "Export" button in the left panel and download the OSM file that includes the 3D model of the environment.

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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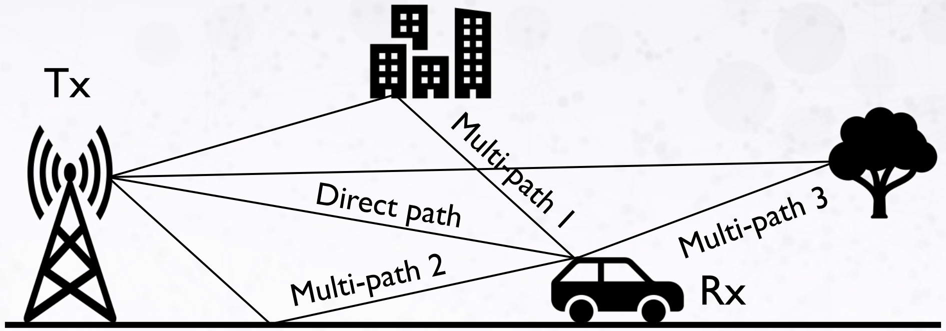
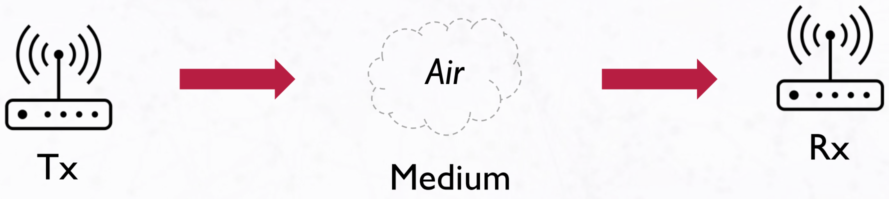
RF Scenario Validation

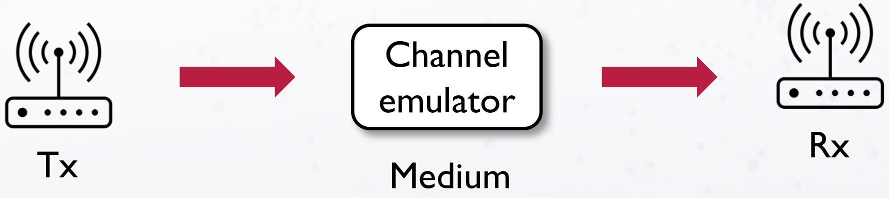
- Channel sounding goals:
  - **Evaluate** an RF channel characteristics
  - **Analyze** the environment
  - **Optimize** the design
- **No over-the-air** communication
- **Emulated** medium
- Sounding goals in emulators:
  - **Validate** original traces:
    - Channel Impulse Response (**CIR**) for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



Communication over-the-air



Communication in emulators



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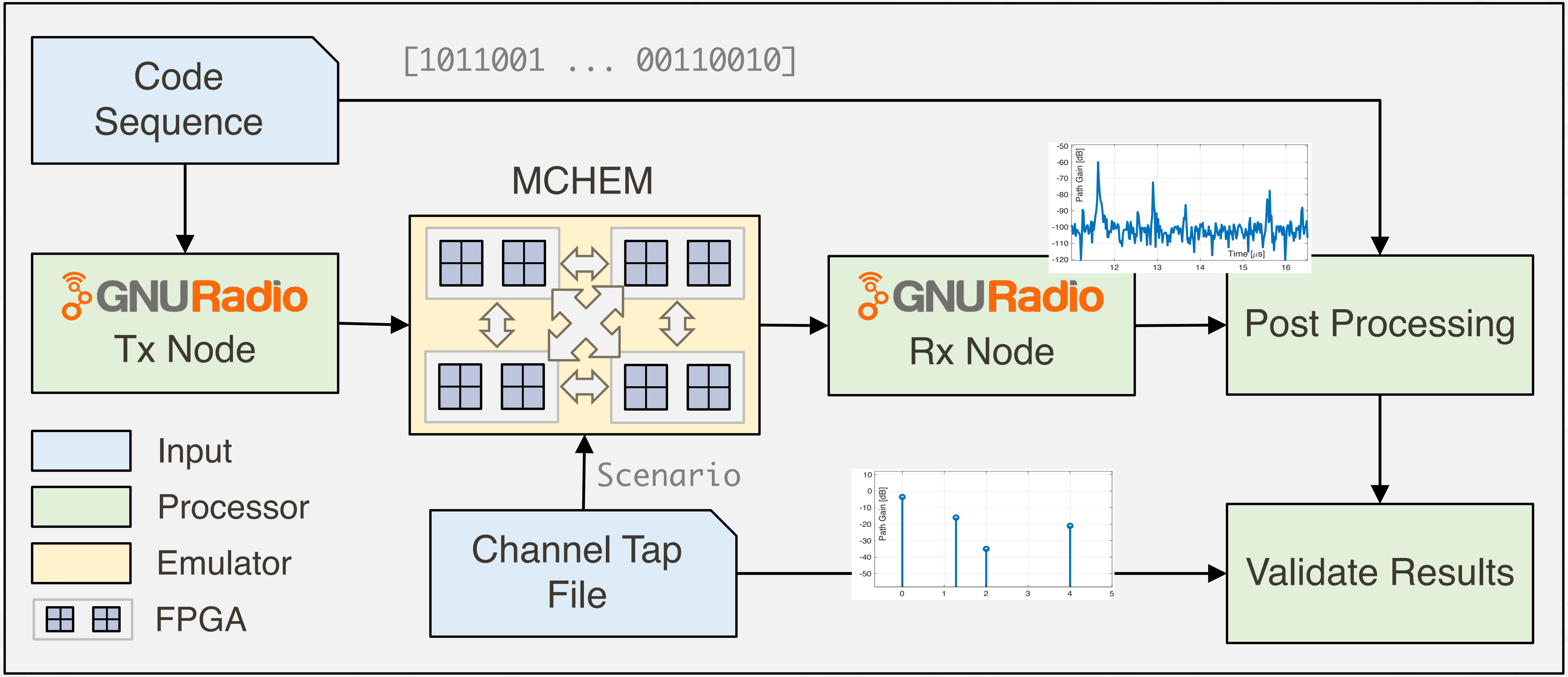
CaST Channel Sounding Workflow



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

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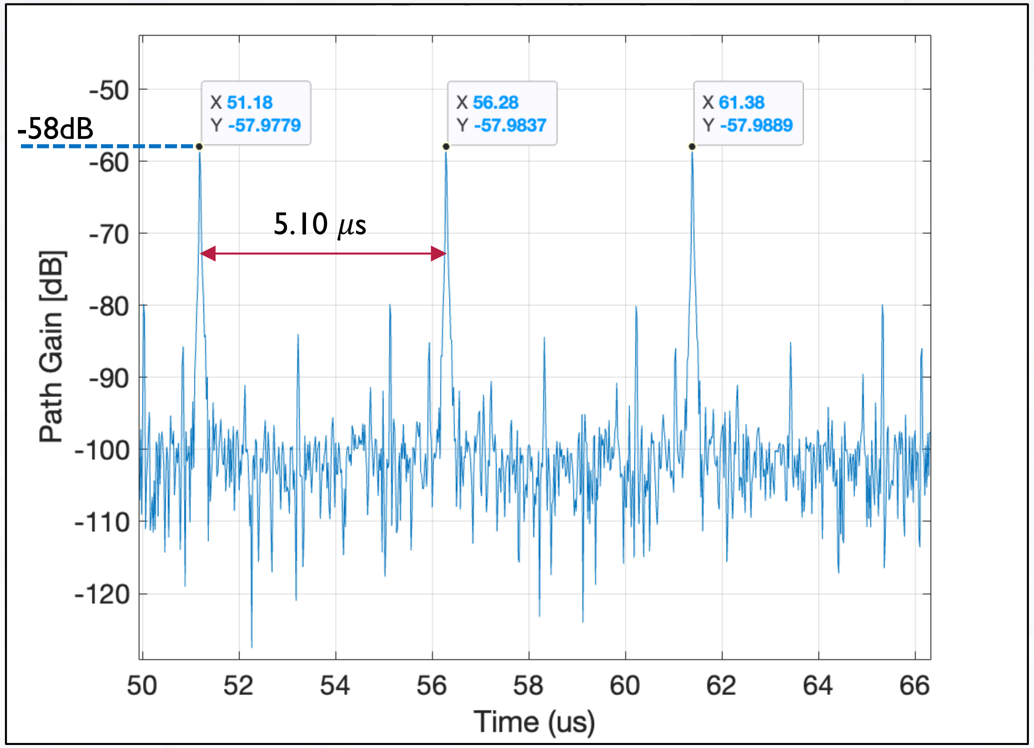
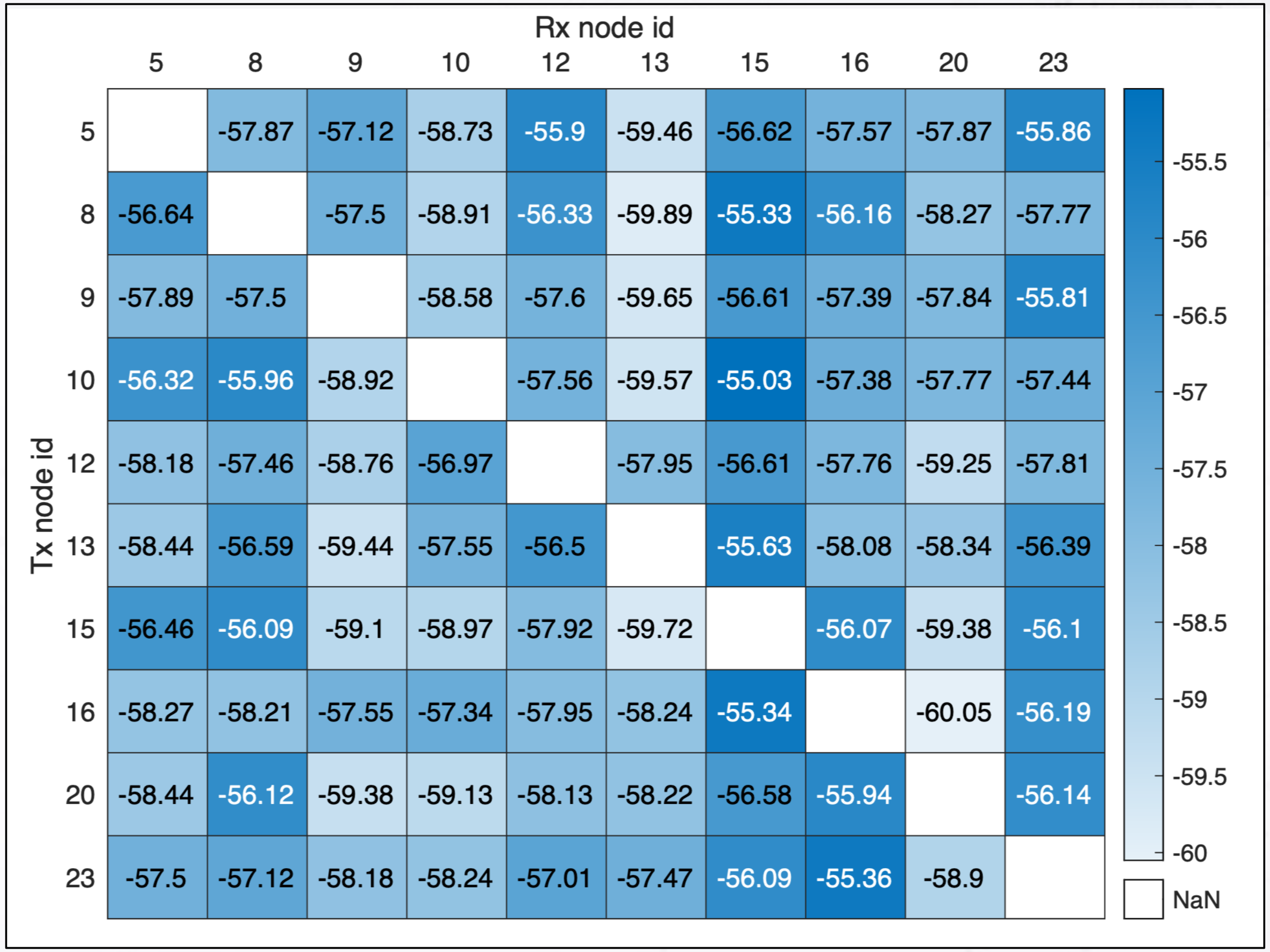
Evaluating Scenario 0dB Loss in Colosseum



0 dB pathloss received CIR



10 nodes heatmap 0dB scenario

- **Colosseum base loss** ~58dB due to equipment in the loop. Signal cycles 5.10 μs. Dynamic range: ~42 dB.
- Colosseum base loss is consistent between 55 dB and 60 dB for all links. ***Avg: 57.55 dB*** *- SD: 1.23 dB*

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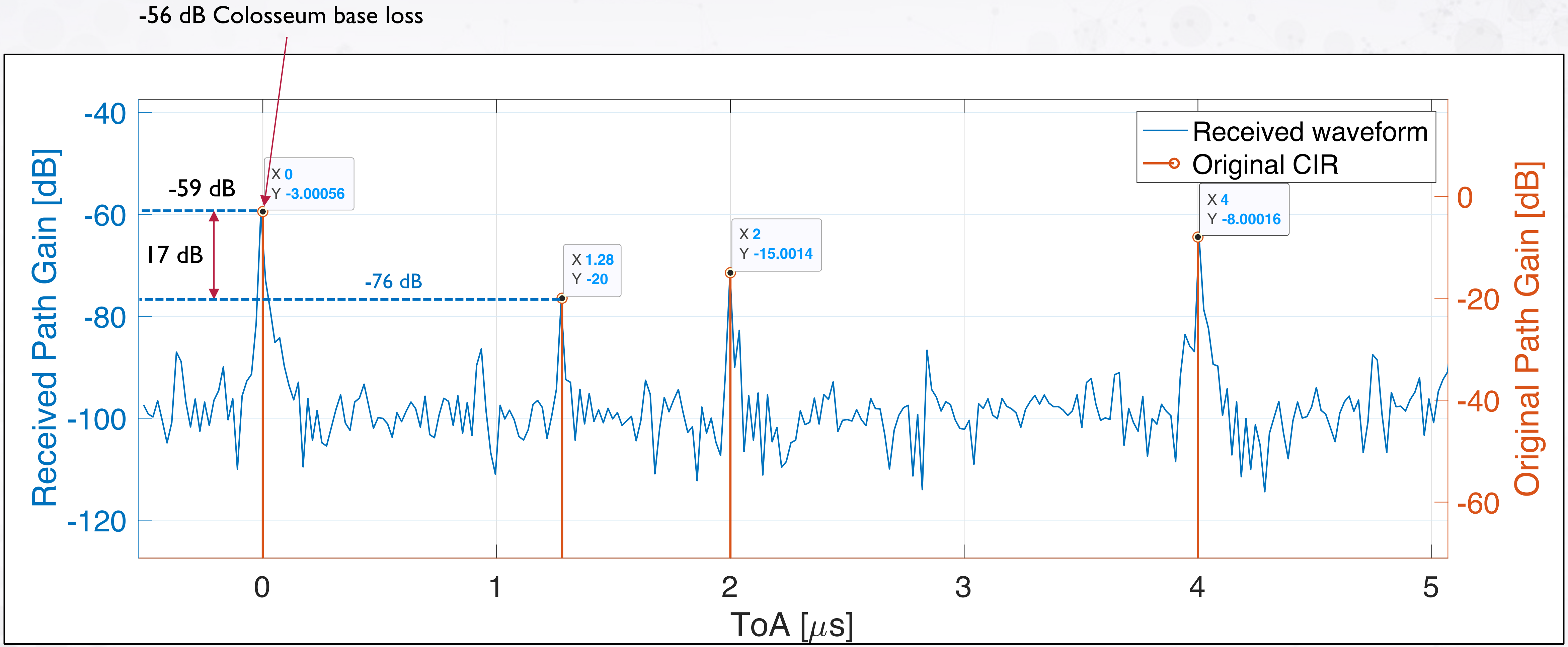
Evaluating Synthetic Scenario 4 Tap



Results 4 taps synthetic scenario

- The **ToA** and the **relative loss** of the received taps are consistent with the original CIR.

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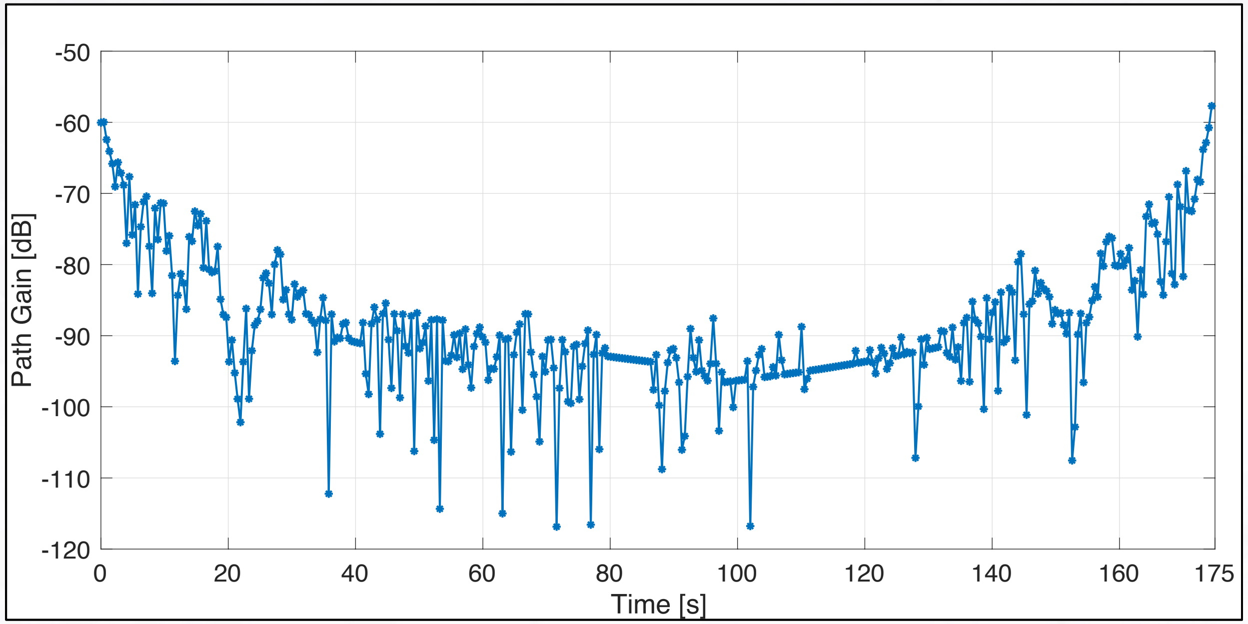
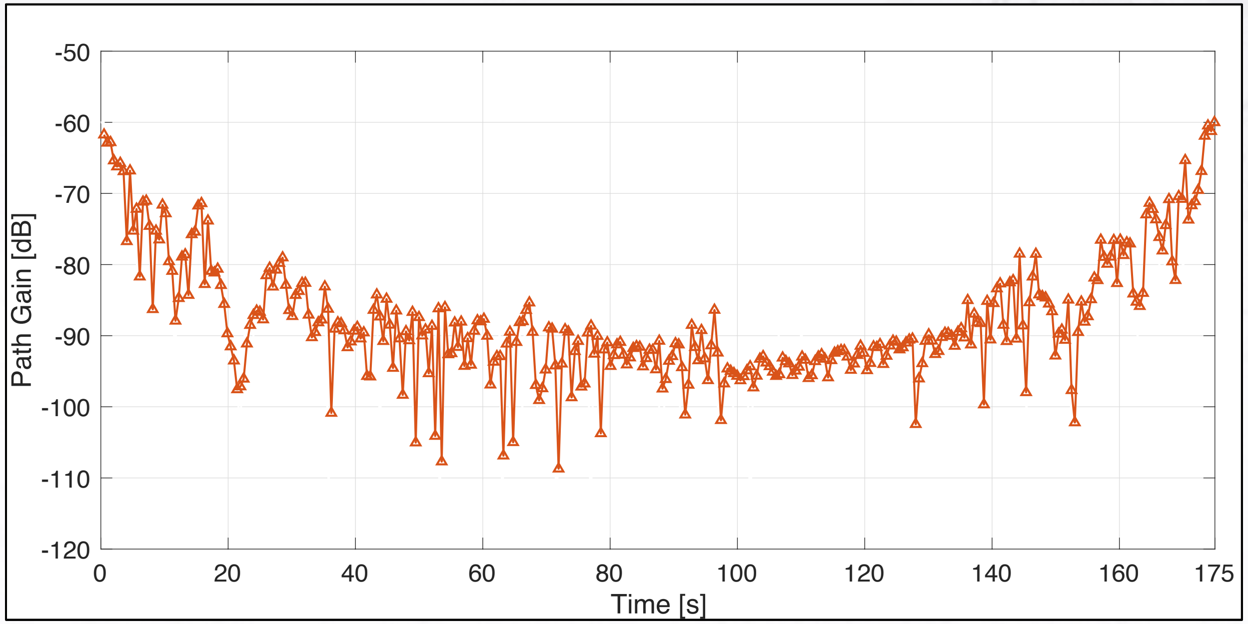
Evaluating V2X mobile scenario in Tampa, FL

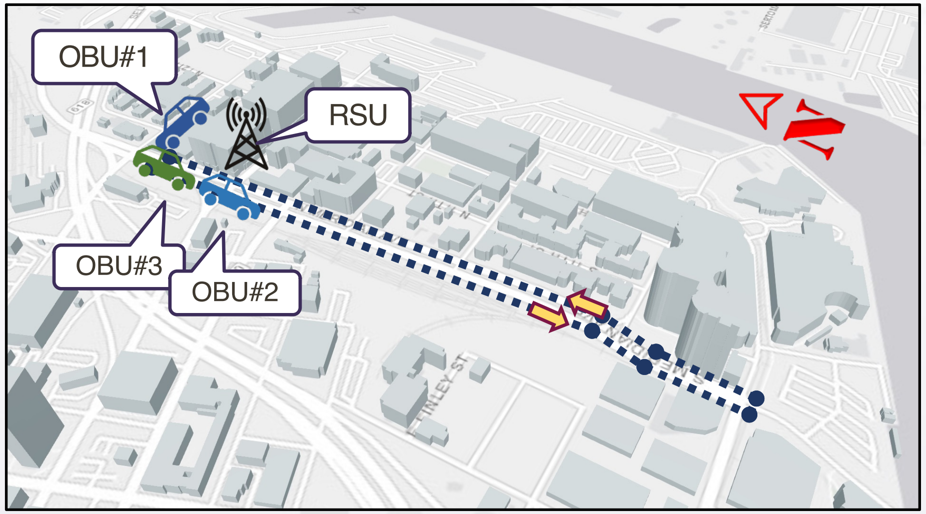


Original taps representation RSU – OBU #3



Received path gains RSU – OBU #3

- Results properly follow the **movement** of OBU w.r.t. RSU.
  - **"V-shape"** of strongest taps in ToA domain
  - **"U-shape"** of path gains in Time domain



How to Request a new RF Scenario

1. Generate channel information.
2. Format the channel info in a MATLAB *.mat* file with:
3. Open a Help Desk ticket with:
   I. Desired name
   II. Center frequency
   III. .mat file.

TxNode1-RxNode1 TxNode1-RxNode2

$$clusteredTapMatrix = \begin{bmatrix} \boxed{X_{11}} & \boxed{X_{12}} \\ \boxed{X_{21}} & \boxed{X_{22}} \end{bmatrix}$$

TxNode2-RxNode1 TxNode2-RxNode2

$$X = \begin{cases} tap.delay\ [1 * 10^{-8}, 0, 0, 0] \\ tap.iq\ [1 + 0j, 0\ , 0\ , 0] \end{cases}$$

Single Tap example: 0 dB, 10 ns

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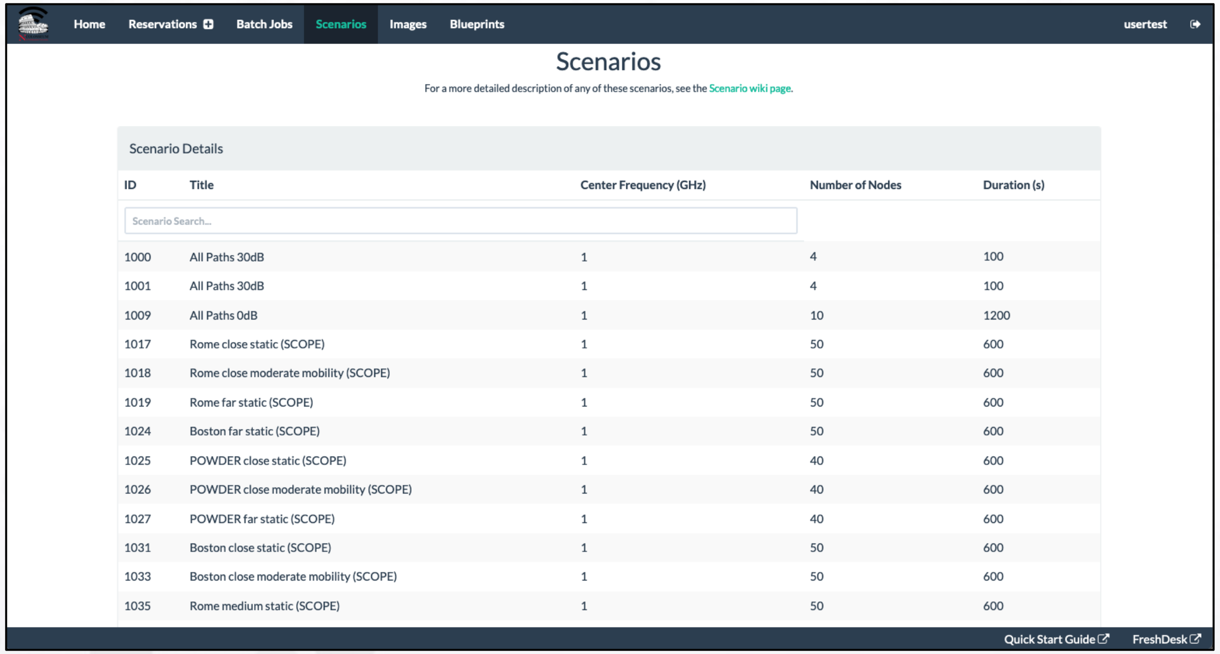
More info: https://colosseumwireless.readthedocs.io/en/latest/scenarios/file_format.html

Scenario Examples

Public Scenarios List

- **Option 1**: Experiment portal, "Scenarios" tab, for a quick view: https://experiments.colosseum.net/scenarios



Home Reservations Batch Jobs Scenarios Images Blueprints usertest

Scenarios

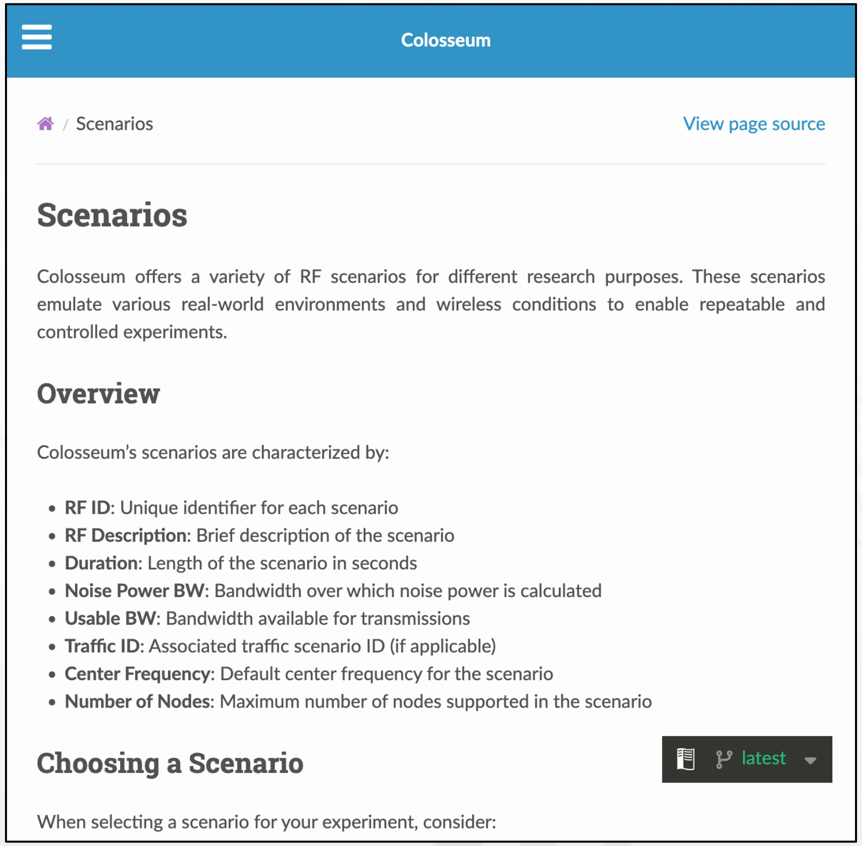
For a more detailed description of any of these scenarios, see the Scenario wiki page.

Scenario Details

ID	Title	Center Frequency (GHz)	Number of Nodes	Duration (s)
1000	All Paths 30dB	1	4	100
1001	All Paths 30dB	1	4	100
1009	All Paths 0dB	1	10	1200
1017	Rome close static (SCOPE)	1	50	600
1018	Rome close moderate mobility (SCOPE)	1	50	600
1019	Rome far static (SCOPE)	1	50	600
1024	Boston far static (SCOPE)	1	50	600
1025	POWDER close static (SCOPE)	1	40	600
1026	POWDER close moderate mobility (SCOPE)	1	40	600
1027	POWDER far static (SCOPE)	1	40	600
1031	Boston close static (SCOPE)	1	50	600
1033	Boston close moderate mobility (SCOPE)	1	50	600
1035	Rome medium static (SCOPE)	1	50	600

Quick Start Guide FreshDesk

- **Option 2**: Help Desk for a more detailed description of each scenario: https://colosseumwireless.readthedocs.io/en/latest/scenarios/index.html



Colosseum

Scenarios View page source

Scenarios

Colosseum offers a variety of RF scenarios for different research purposes. These scenarios emulate various real-world environments and wireless conditions to enable repeatable and controlled experiments.

Overview

Colosseum's scenarios are characterized by:

- **RF ID**: Unique identifier for each scenario
- **RF Description**: Brief description of the scenario
- **Duration**: Length of the scenario in seconds
- **Noise Power BW**: Bandwidth over which noise power is calculated
- **Usable BW**: Bandwidth available for transmissions
- **Traffic ID**: Associated traffic scenario ID (if applicable)
- **Center Frequency**: Default center frequency for the scenario
- **Number of Nodes**: Maximum number of nodes supported in the scenario

Choosing a Scenario

latest

When selecting a scenario for your experiment, consider:

Current RF Scenario Types

Synthetic:

Fixed path losses.

Fixed frequencies.

Mathematical Models:

Free-space path loss.

3GPP standard equations.

Ray-tracers:

MATLAB Ray-tracer.

Wireless InSite.

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Synthetic with Fixed Values (1009, 51005 – 51030, 52001 - 52006)

Scope: General testing and validation with fixed behaviors.

- **0 dB pathloss at 1 GHz**
  - Base scenario (1009).
- **Varying pathloss at 1 GHz**
  - 510XX where XX is the path loss (e.g., 51010 → 10 dB).
- **0 dB pathloss at varying frequencies**
  - Frequency ranges from 832 MHz to 5.9 GHz (52001 – 52006).

All scenarios are **single-tap** with a delay of 10ns.

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Channel Sounding Scenarios (90001-90009)

Scope: Validate MCHEM behavior.

- **Varying taps, losses, and delays at 1 GHz.**
  - 5 nodes and each link has a different behavior (90001, 90002, 90003).
- **Increasing losses at various frequencies.**
  - Increased loss by 5 dB each link.
  - Frequency increases from 1 GHz till 6 GHz.
  - Single tap with 5 nodes (90004 – 90009).

Link	Taps Delay [ns]	Taps Gain [dB]
1 ⟷ 2	[0]	[0]
1 ⟷ 3	[0]	[-5]
1 ⟷ 4	[0]	[-10]
1 ⟷ 5	[0]	[-15]
2 ⟷ 3	[0]	[-20]
2 ⟷ 4	[0]	[-25]
2 ⟷ 5	[0]	[-30]
3 ⟷ 4	[0]	[-35]
3 ⟷ 5	[0]	[-40]
4 ⟷ 5	[0]	[-45]

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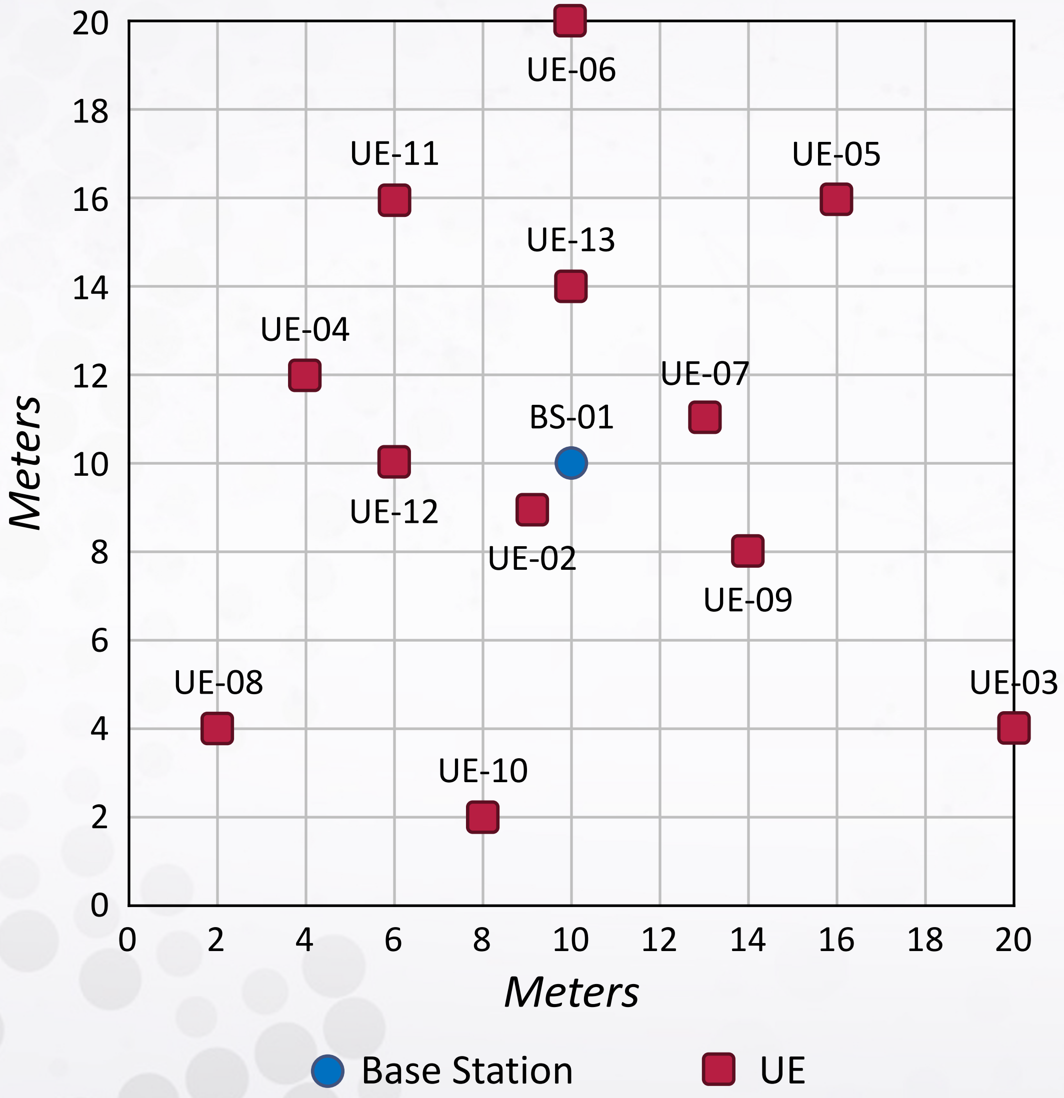
Cellular Rural Small Static (35001 - 35005)



Scope: Rural generic cellular deployment.

- 13 nodes: 1 BS and 12 UEs
- Heights: UE (1m), BS (3m)
- Channel: Free-Space Path Loss

$$FSPL = 20log_{10}(\frac{4\pi df}{c})$$

f = frequency (1 GHz, 3.6 GHz)

c = speed of light

d = 3D distance BS-UE

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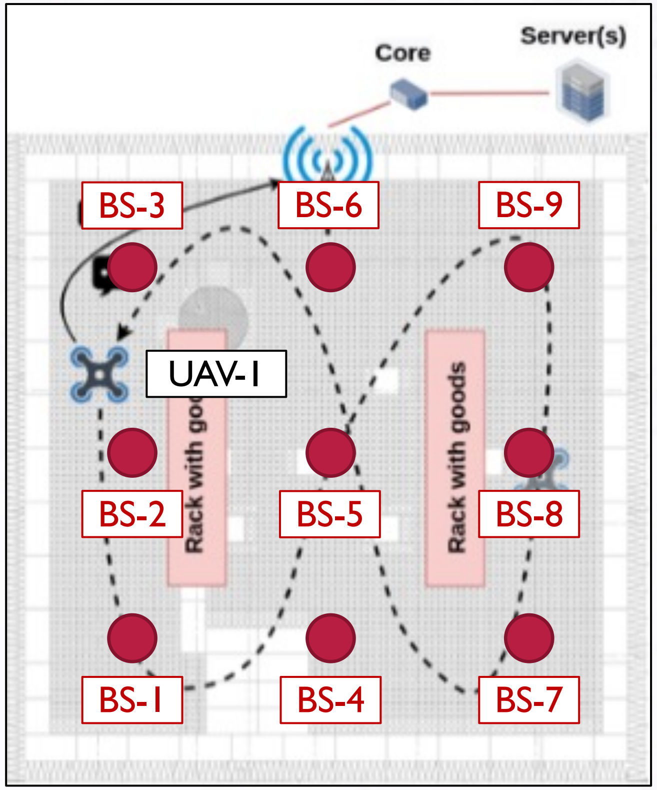
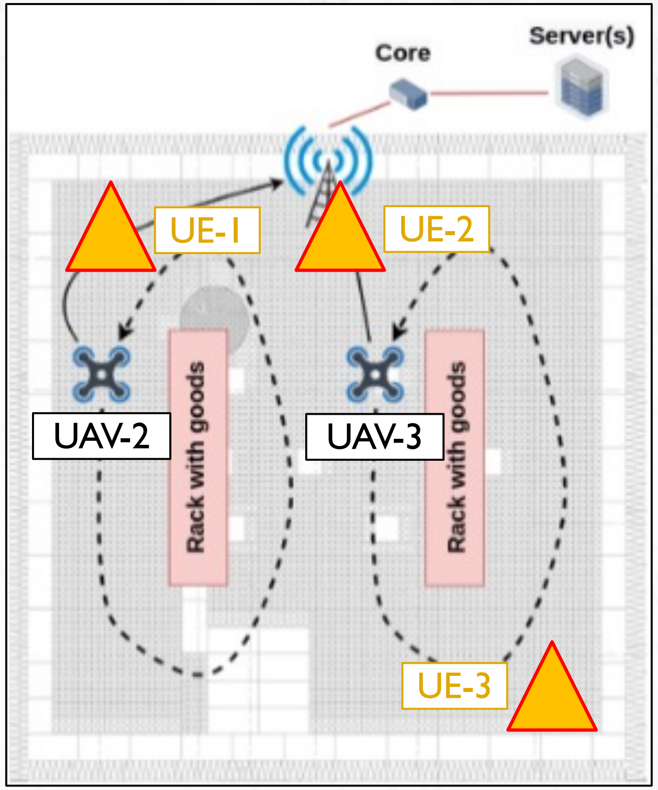
Anechoic Chamber and Drones (12350-12356)

Scope: Indoor factory use cases with rack of goods and drones.

- 9 BSs in a 3x3 grid.
  - Ceiling mounted.
- 3 UAVs
  - UAV-1 8-shaped flight.
  - UAV-[2-3] circle around rack.
  - 240 seconds of mobility.
- 3 UEs for UAV-[2-3].
- Channel is single-tap and multi-tap with fading.



Anechoic chamber with BSs and UAV-1



Anechoic chamber with BSs, UEs and UAVs

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Rome Real-World Outdoor Location (1017-1041)

Scope: Real-world cellular deployments.

- 50 Nodes
  - 10 BSs real locations from OpenCelliD db.
  - 4 UEs scattered around each BS.
- 3 distances BS-UEs:
  - *Close:* 20m.
  - *Medium:* 50m.
  - *Far*: 100m
- 3 mobility patterns around BS:
  - *Static*: No mobility.
  - *Moderate*: 3 m/s.
  - *Fast*: 5 m/s.
- Free-space path loss equation.

Rome Downtown, Italy

L. Bonati, S. D'Oro, S. Basagni, and T. Melodia, "SCOPE: An Open and Softwarized Prototyping Platform for NextG Systems," in Proceedings of ACM MobiSys, June 2021.

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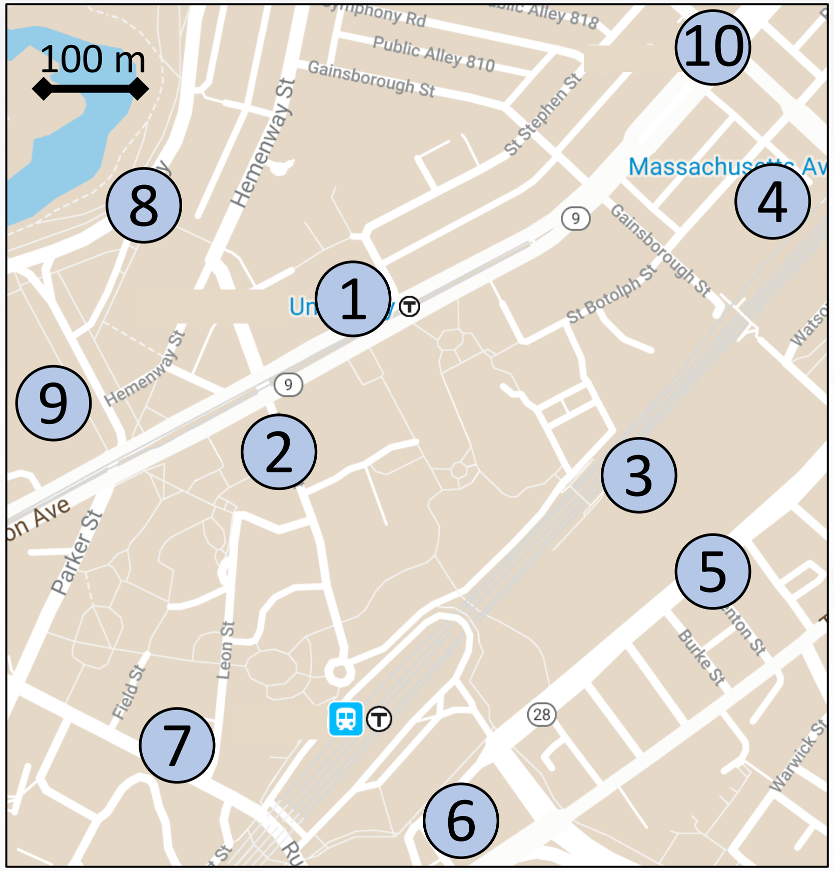
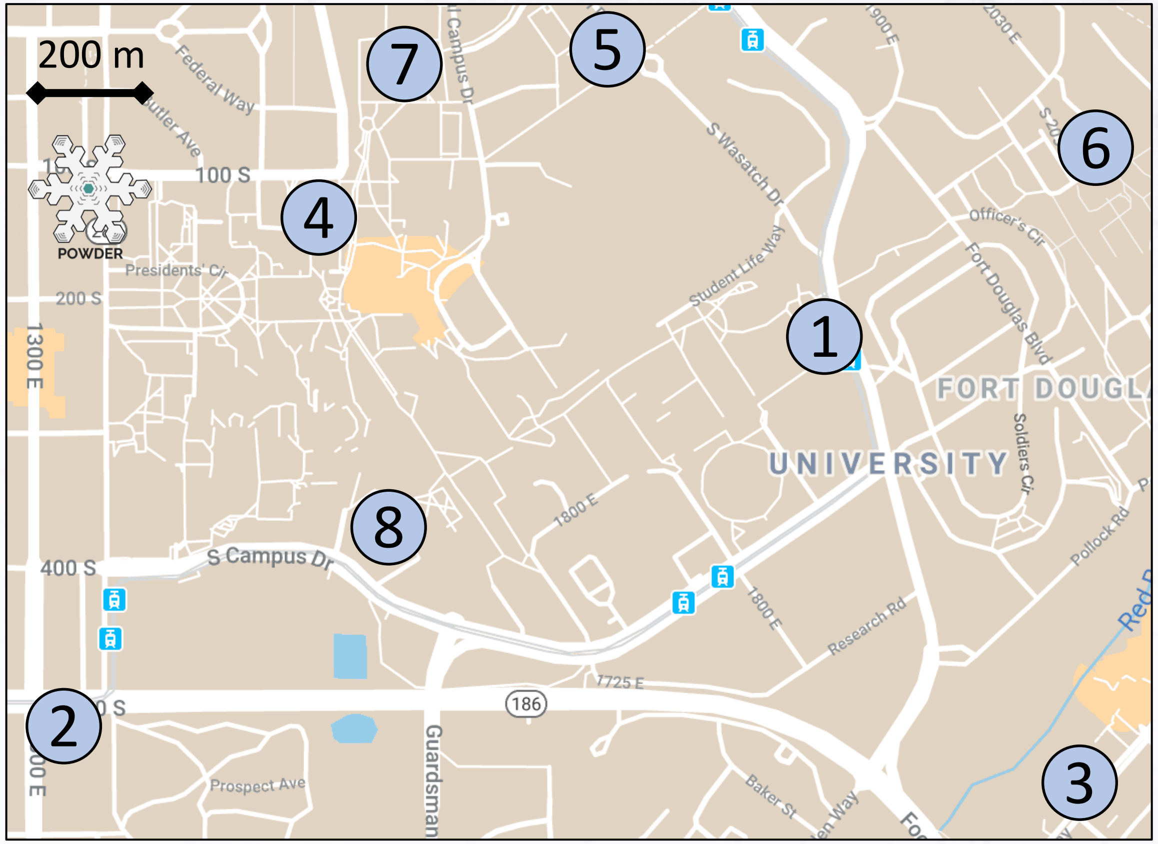
Boston and POWDER Real-World Outdoor Location (1017-1041)



Boston, MA



POWDER PAWR – University of Utah, Salt Lake City, UT

- Similar specifications as Rome scenario.
- POWDER locations mirror Rooftop BSs POWDER nodes.

L. Bonati, S. D'Oro, S. Basagni, and T. Melodia, "SCOPE: An Open and Softwarized Prototyping Platform for NextG Systems," in Proceedings of ACM MobiSys, June 2021.

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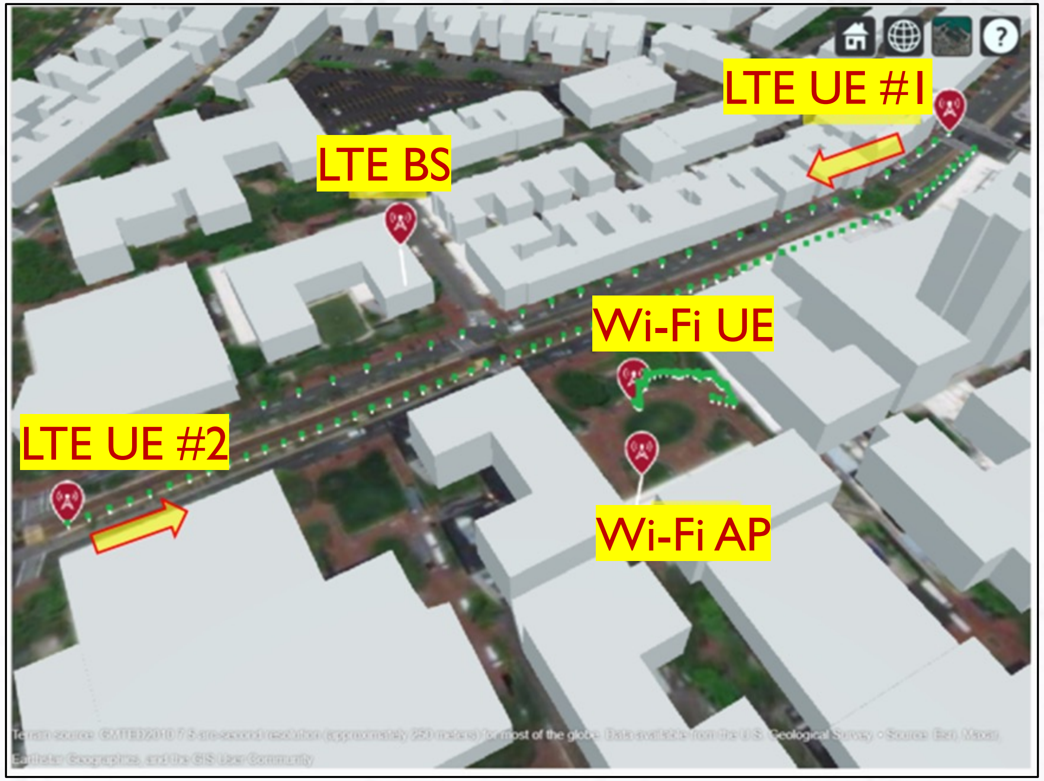
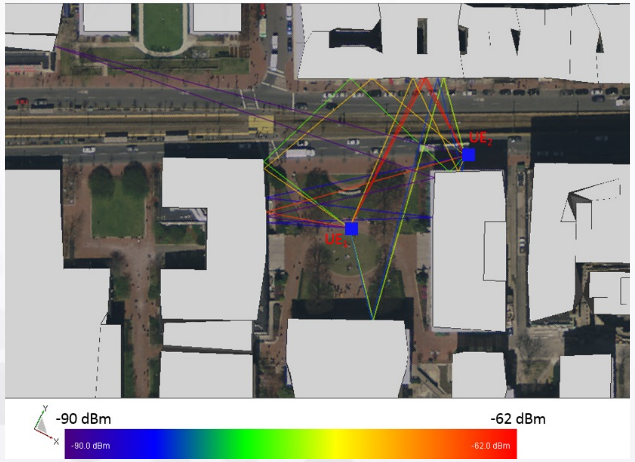
Northeastern University LTE - Wi-Fi Scenario (50005)

Scope: NEU campus location to study the coexistence between LTE and Wi-Fi nodes.

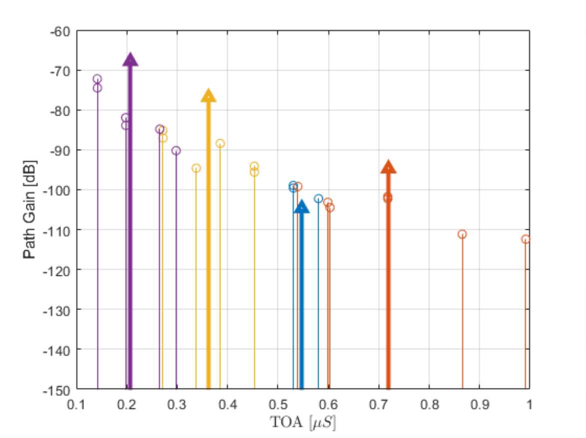
- Wireless InSite as ray-tracer.
  - Ray-tracing frequency: 5.8 Ghz
- LTE: 1 fixed BS, 2 mobile UEs on the road.
- Wi-Fi: 1 fixed AP, 1 mobile UE in the park.



Northeastern Boston campus



Wireless InSite Simulated Channel



Clustering 4-Tap Approximation

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

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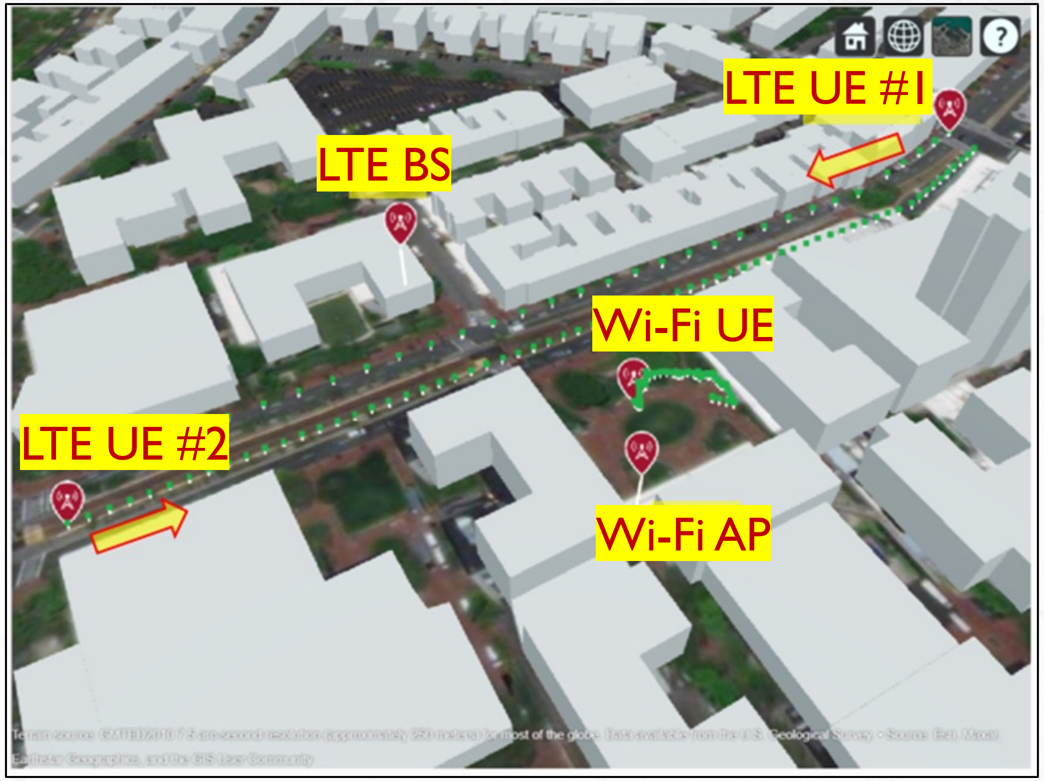
Traffic Patterns for the Northeastern Scenario

- Wi-Fi nodes: video traffic
- LTE UE 1: VOIP traffic
- LTE UE 2: low bandwidth data transmission (e.g., for in-vehicle security, emergency services, remote diagnostics systems, etc.)

Node	Traffic Type	Characteristics
WiFi	Video	Periodic traffic, 83.66 pkt/s, 1400 bytes/pkt
LTE UE 1	VOIP	Periodic traffic, 39 pkt/s, 130 byte/pkt
LTE UE 2	Vehicle Safety	Periodic traffic, 0.5 pkt/s, 130 byte/pkt



Northeastern Boston campus

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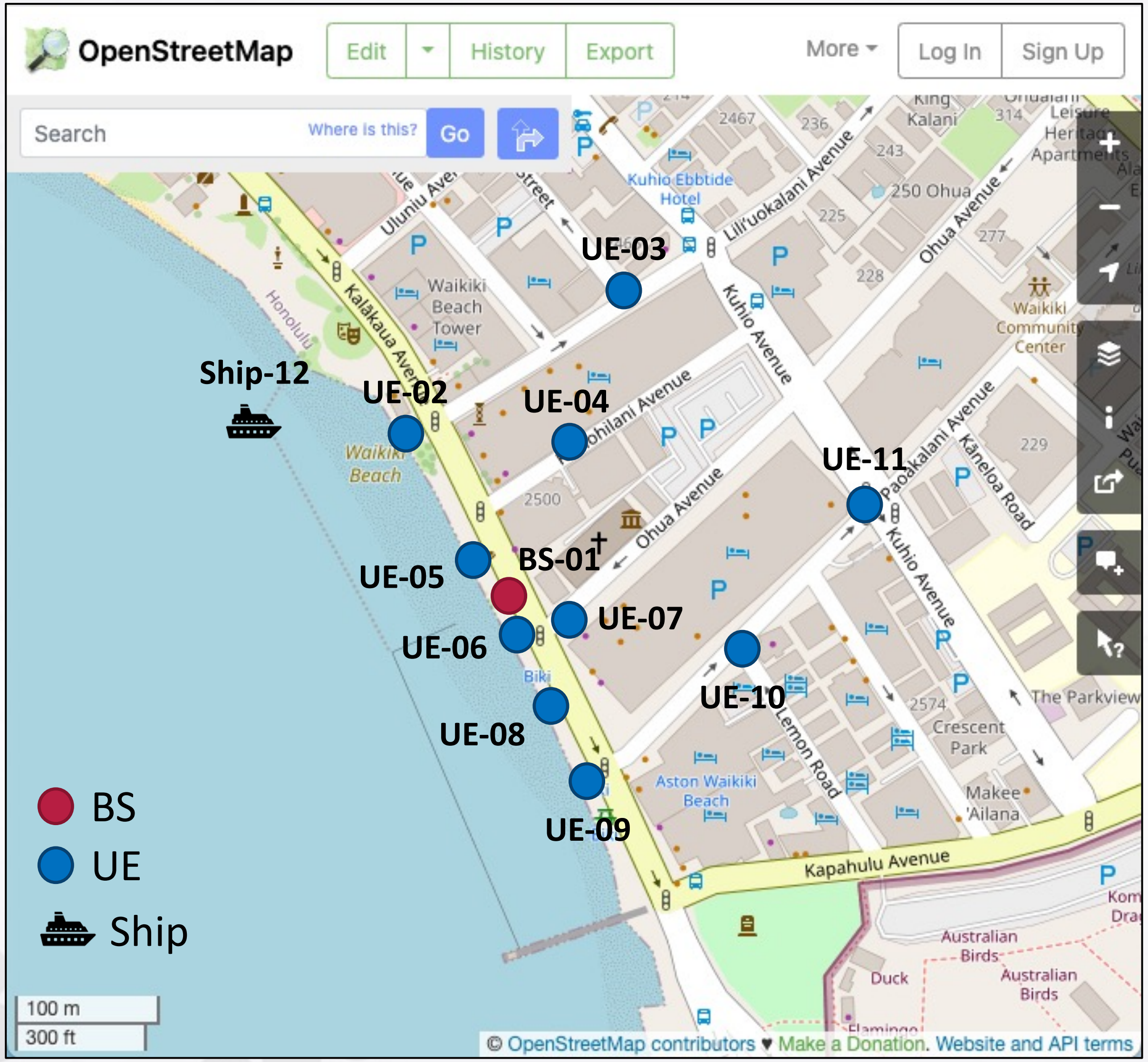
M. Tehrani-Moayyed, L. Bonati, P. Johari, T. Melodia, and S. Basagni, "*Creating RF Scenarios for Large-Scale, Real-Time Wireless Channel Emulators,*" in Proc. of MedComNet, Virtual Conference, June 2021.

Waikiki Beach, Honolulu (45101 - 45104)



Scope: Real cellular deployment involving a Navy radar ship moving along the coast for sensing purposes.

Parameter	Value
Number of nodes	12 (1 BS, 10 UEs, 1 Ship)
BS location	Real from opencellid.org
UE locations	Randomly scattered
Ship location	Moving N-S along the coast
Ship speed	10 m/s (~20 knots)
Ray-tracing SW	MATLAB Ray-tracer
Ray-tracing Frequency	3.6 GHz
Emulation Frequency	1 GHz
Signal bandwidth	20 MHz

D. Villa, D. Uvaydov, L. Bonati, P. Johari, J. M. Jornet, and T. Melodia, "Twinning Commercial Radio Waveforms in the Colosseum Wireless Network Emulator," Proc. of the 17th ACM WiNTECH 2023, Madrid, Spain, October 2023.

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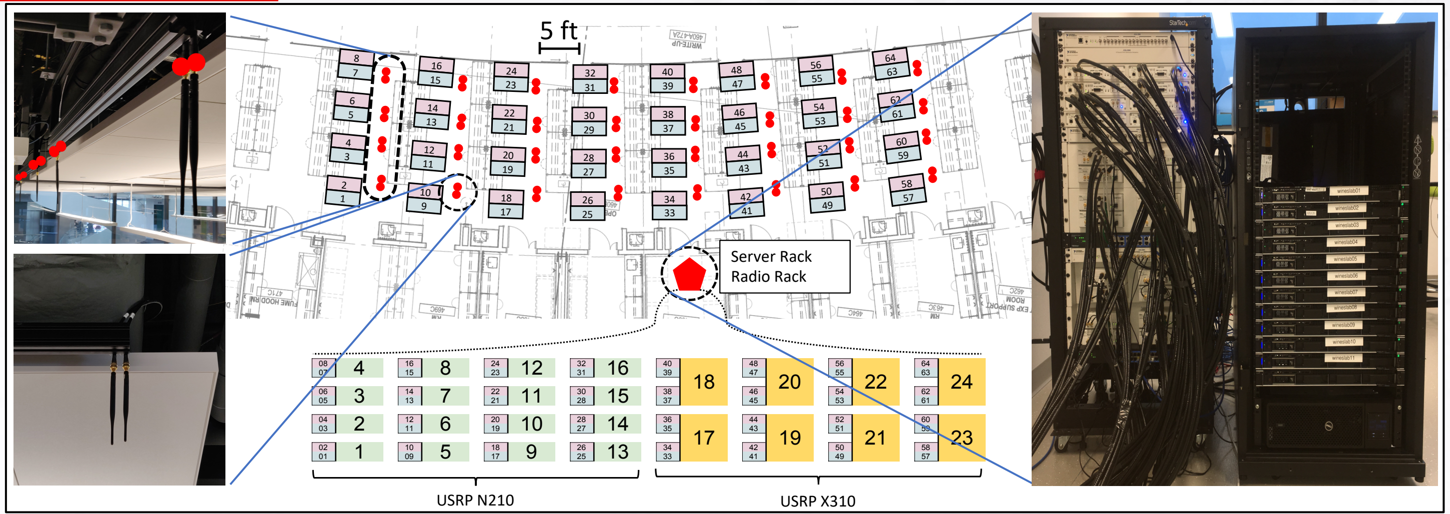
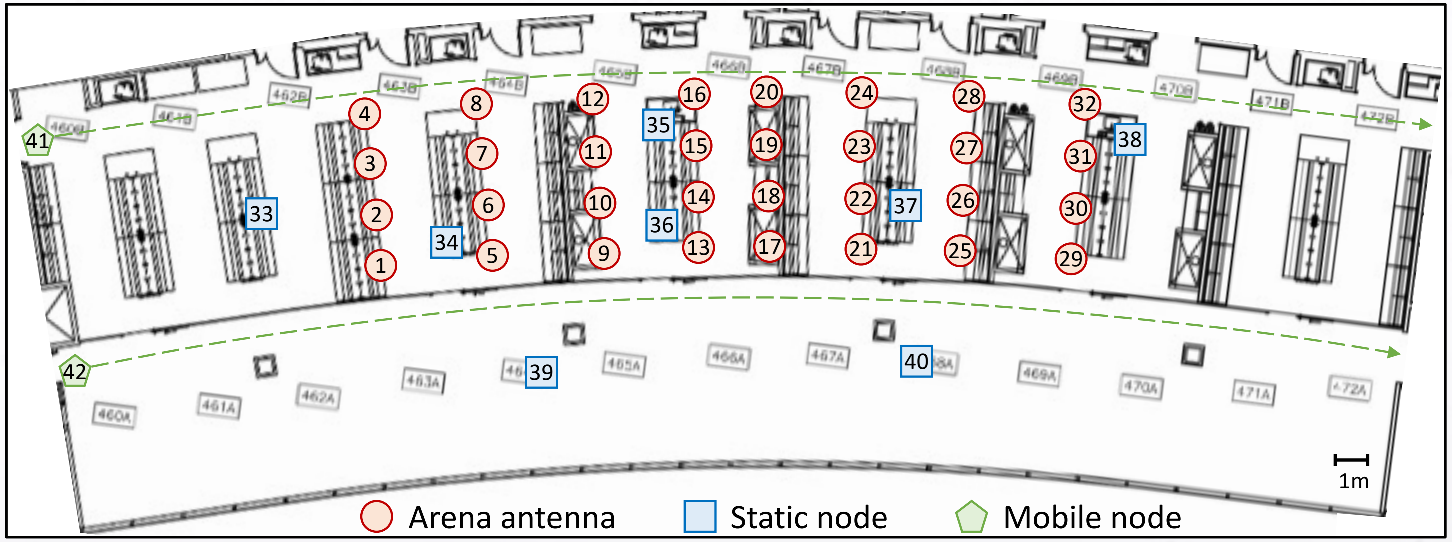
Twinning OTA Indoor Testbed Arena (45001 - 45003)

Scope: Twin Arena.

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

- 42 nodes
  - 32 BSs (Arena antennas)
  - 10 UEs (8 static, 2 mobile)
- Matlab Ray-tracer.
- Frequencies: 1-2.4 GHz.





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

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,"* pp 1-15, IEEE Transactions on Mobile Computing, in press, 2024.

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Current & Future Developments

Dynamic Scenarios in Colosseum

Goal

Enable the creation of dynamic scenarios in Colosseum

Tools

- *Dynscen*: Dynamic Scenario Generator
- *Colossumo*: Integration with SUMO
- *TwinNet*: Live communications with Colosseum
- *Boston Twin*: A dataset for realistic, large-scale ray-tracing simulation

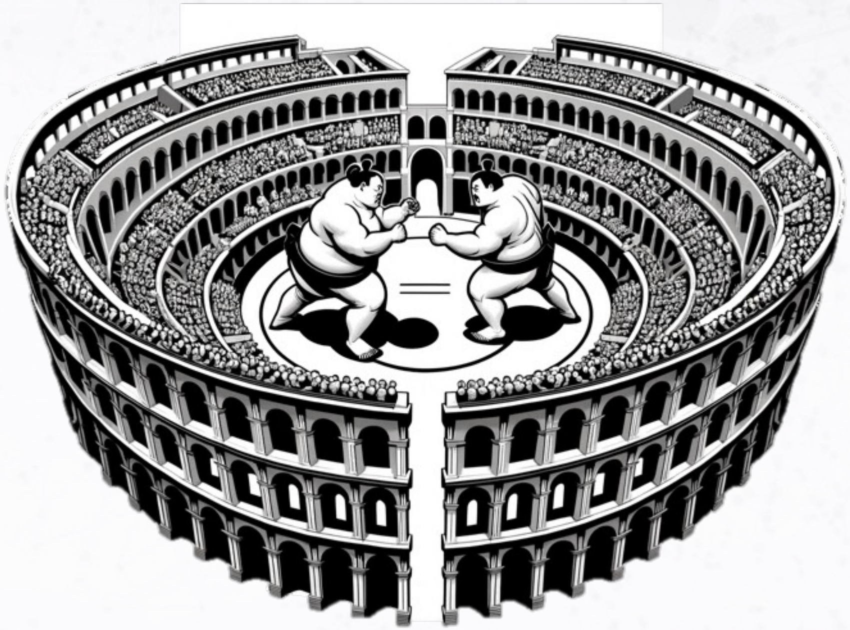
Simulation of Urban Mobility (SUMO)

- Open-Source Road Traffic Simulator [1]
- Leverages OpenStreetMap (OSM) or custom road graphs to create realistic traffic flows
- Various models already available for large European cities
  - Luxemburg, Munich, Turin, Bologna, etc
- Usually coupled with Network simulators:
  - Veins [2] integrates Omnet++
  - Eclipse Mosaic[3] integrates with either NS3 or Omnet++

[1] https://sumo.dlr.de/docs/index.html
[2] https://veins.car2x.org/
[3] https://www.dcaiti.tu-berlin.de/research/simulation/

Real-time Control of Radio Scenarios – Vehicular Networks

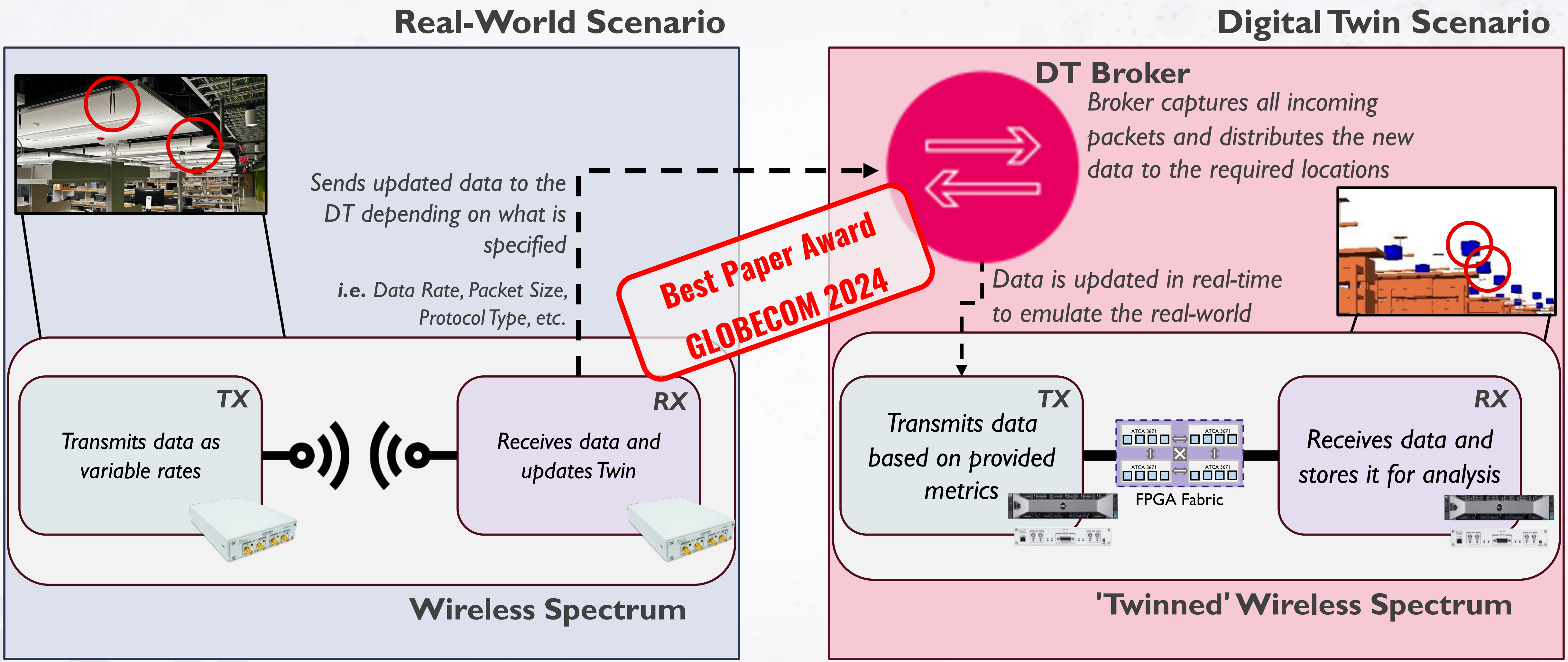
- Framework for live communication between a simulation and emulation platform
  - Colosseum as HIL Emulator for RF comms
  - SUMO as vehicular Simulator
  - Leverages MQTT
  - Validation with a 5G-enabled vehicular application
- Future plans:
  - Validate O-RAN use-cases for Vehicular communication
  - Replace Simulation with real-world RAN



G. Gemmi, P. Johari, P. Casari, M. Polese, T. Melodia, and M. Segata, "*ColosSUMO: Evaluating Cooperative Driving Applications with Colosseum*", in **Proc. of the IEEE Vehicular Networking Conference (VNC)**, Kobe, Japan, May 2024. **Best Short Paper Award**

Public Wireless Supply Chain INNOVATION FUND

TwiNet: Digital Twin Connection Through MQTT



C. Robinson, A. Lacava, P. Johari, F. Cuomo, T. Melodia, ***"TwiNet: Connecting Real World Networks to their Digital Twins Through a Live Bidirectional Link,"***, in Proc. of IEEE Global Communications Conference (GLOBECOM), Cape Town, South Africa, December 2024. **Best Paper Award.**

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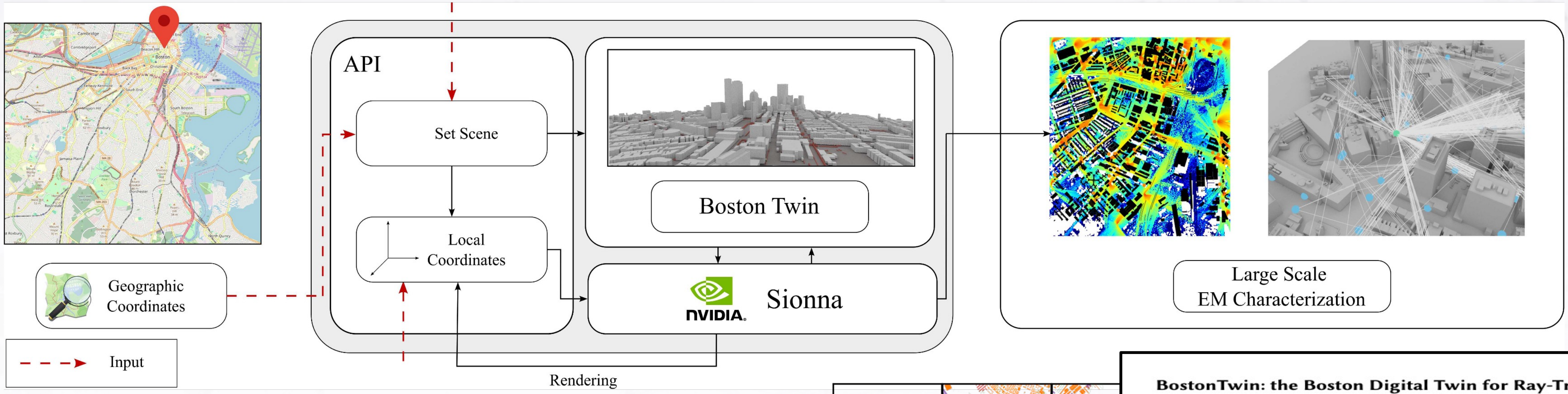
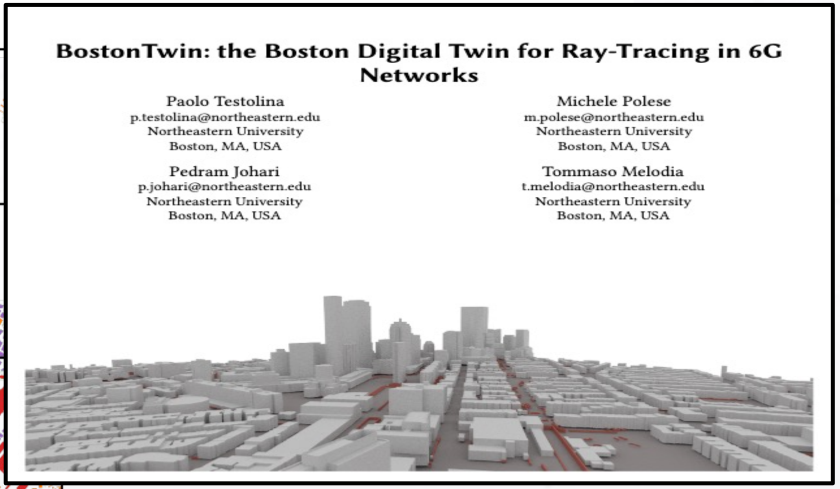
Large-scale Ray Tracing with Real-World 3D Models



Boston Twin

- Format compatible with multiple ray tracers (Sionna, Opal, etc)
- Geolocated -> easy to interface from OpenStreetMap, SUMO, etc..
- Add your points of interest (base stations, RF sensors, RA antennas, etc)


BostonTwin: the Boston Digital Twin for Ray-Tracing in 6G Networks

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Testolina, Paolo, et al. "Boston Twin: the Boston Digital Twin for Ray-Tracing in 6G Networks." *Proceedings of the 15th ACM Multimedia Systems Conference*. 2024.

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Thank You! (Questions?)

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Platforms for Advanced Wireless Research

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