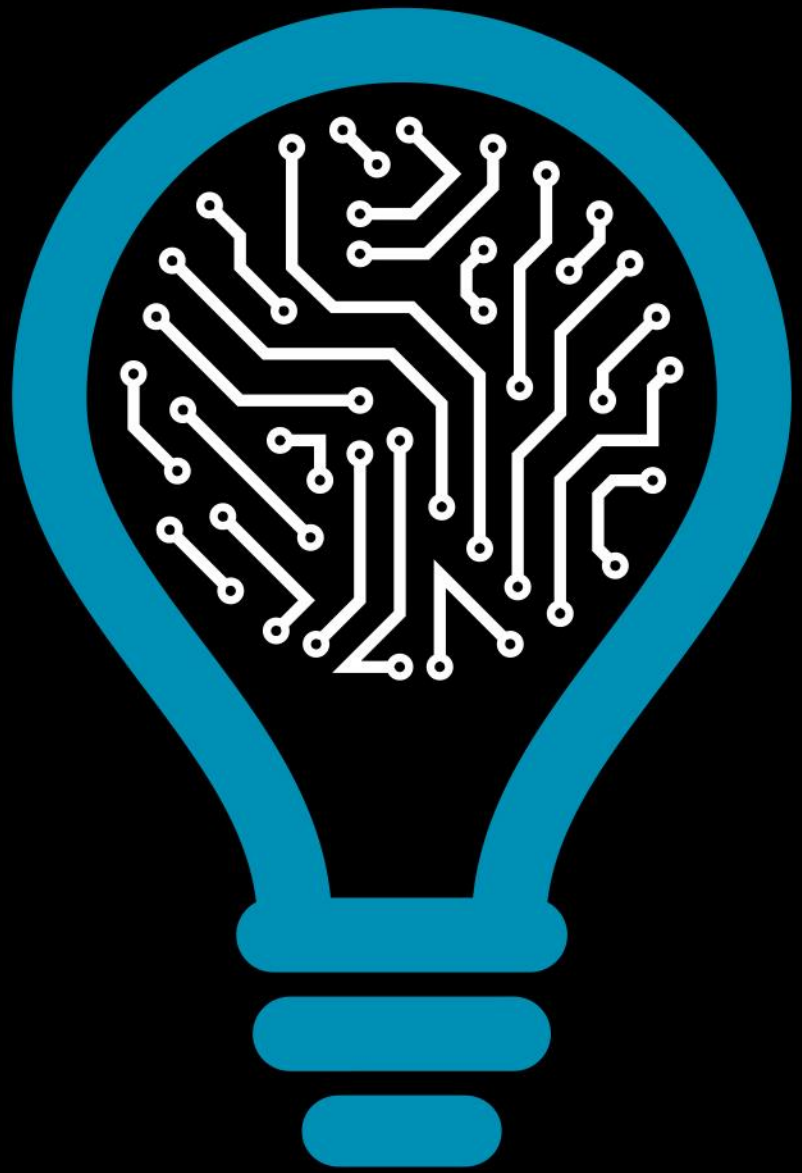
ns-3 as a Digital Twin for Wireless Testbeds



29º Seminário da RTCM

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INESCTEC

INSTITUTE FOR SYSTEMS AND COMPUTER ENGINEERING, TECHNOLOGY AND SCIENCE

- Introduction to ns-3
- ns-3 as a Digital Twin for Wireless Testbeds
  - Trace-based Simulation Approach
- Main Conclusions
- Future Work

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Introduction to ns-3

- Network Simulation
- ns-3 Overview
- ns-3 - some Protocols and Models
- ns-3 Simulation and Emulation

Network Simulation

- Goal
  - build a software **simulation model** of a system
  - analyze/study/improve/develop **network protocols** or **applications**
- Motivation
  - **real testbeds** are **expensive**, **complex**, **unavailable**
- Advantages
  - relatively **easy to use** and **less time consuming**
- Disadvantages
  - **simplified view** of complex interactions
  - could be immensely **misleading** → e.g., if inadequate models are used, bad abstractions, etc.

Dependence on <u>assumptions</u> and <u>accuracy</u> of the simulated models

Typical Simulation Steps

- Define network scenario
  - Choose the right **simulation models** and **configure** them properly
    - Propagation Delay
    - Propagation Loss
    - Mobility
    - Channel and Wi-Fi standard
    - Network Traffic Routing
    - Applications for traffic generation
    - Random variables (for stochastic models)
- Run simulations
  - Multiple runs with different seeds for the random variables
- Process results
  - Analyze throughput, delay, packet loss, delay jitter, fairness, …

ns-3 Overview

- ns-3 project started around mid 2006
  - First release in June 2008
  - Latest release **January 2021 → ns-3.33**

- ns-3 is a discrete-event network simulator for Internet systems
  - **Packet level** resolution

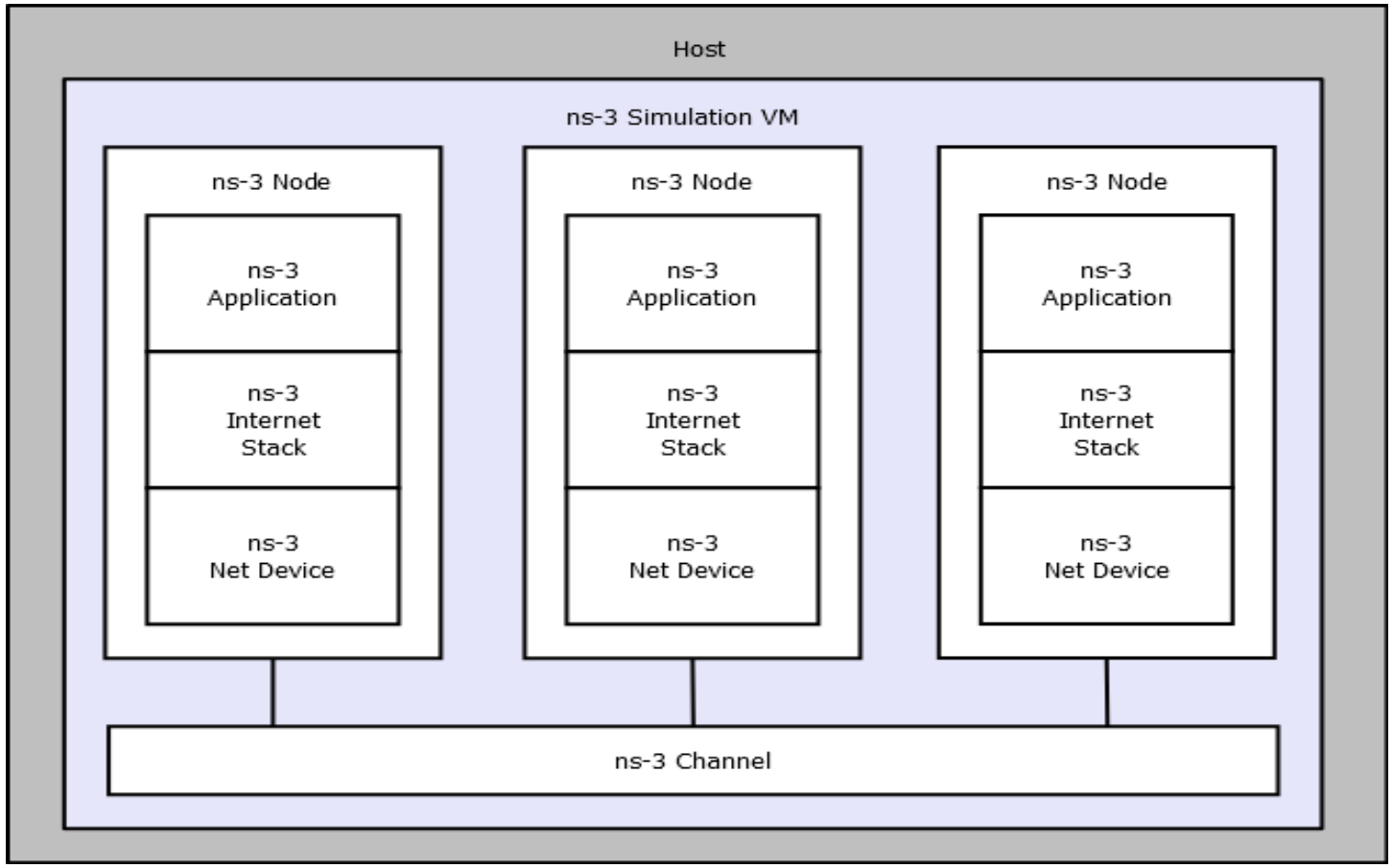
- ns-3 was written from scratch
  - Not an evolution of ns-2
  - Targeted for research and education
  - Community-oriented open-source development

- Programing languages
  - C++ (e.g., Core, Models)
  - Python (e.g., Scripting, Visualization)

ns-3 – some Protocols and Models

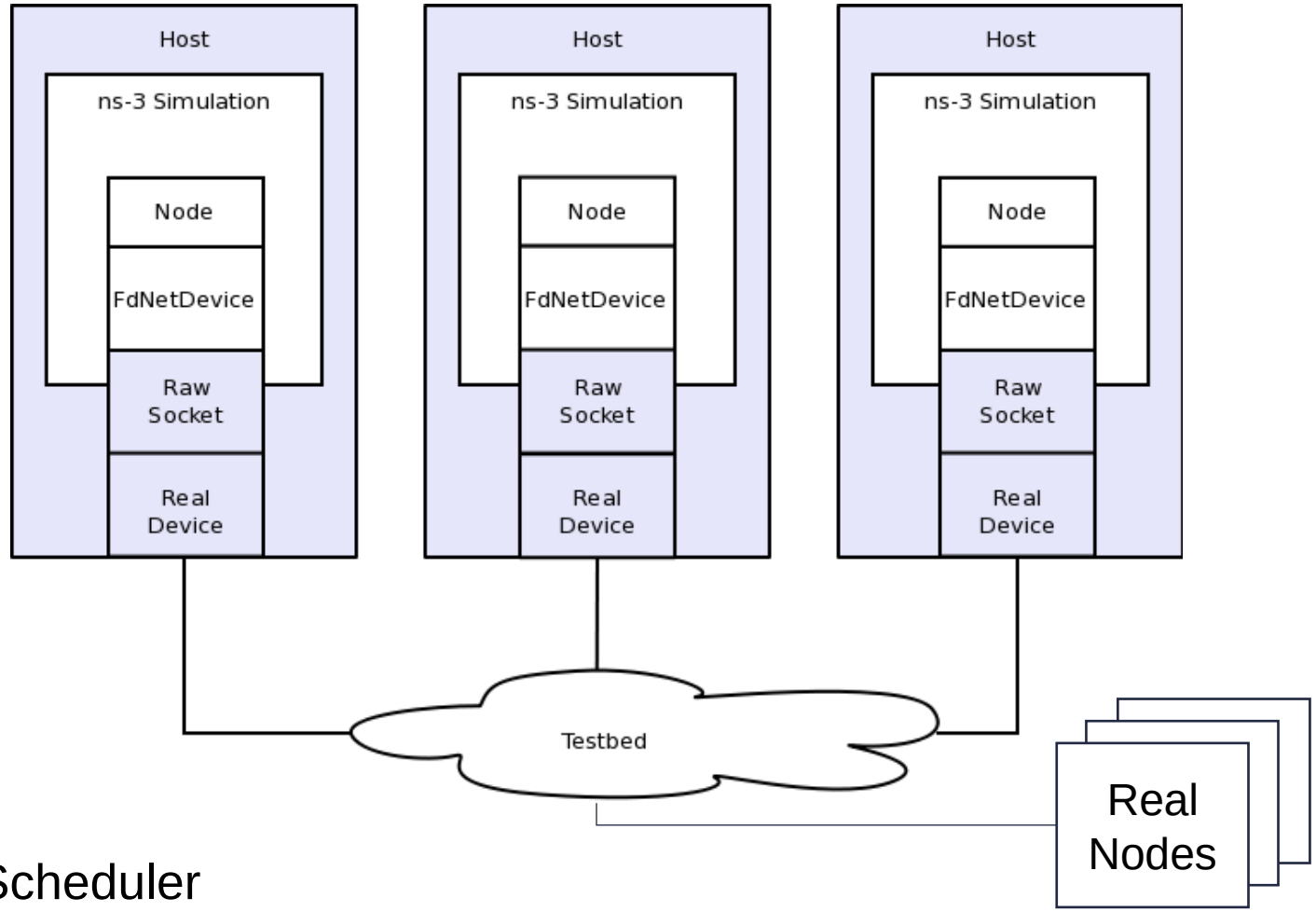
- Mobility models
  - Fixed, Random direction, way-point, …
- Channels and NetDevices
  - Point-to-Point, CSMA/CD, 802.11, LTE, …
- Propagation Delay Models
  - Constant Speed, …
- Propagation Loss Models
  - Friis, 2-Ray, Fixed, …
- IPv4 and IPv6 support
- Routing
  - Static, OLSR, AODV, …
- Socket-like API
  - TCP and UDP support
- Traffic generation
  - On/Off application, Bulk send application, UdpEchoApplication, …
- Helpers

ns-3 Simulation



- Event Scheduler
  - Simulated time

ns-3 Emulation

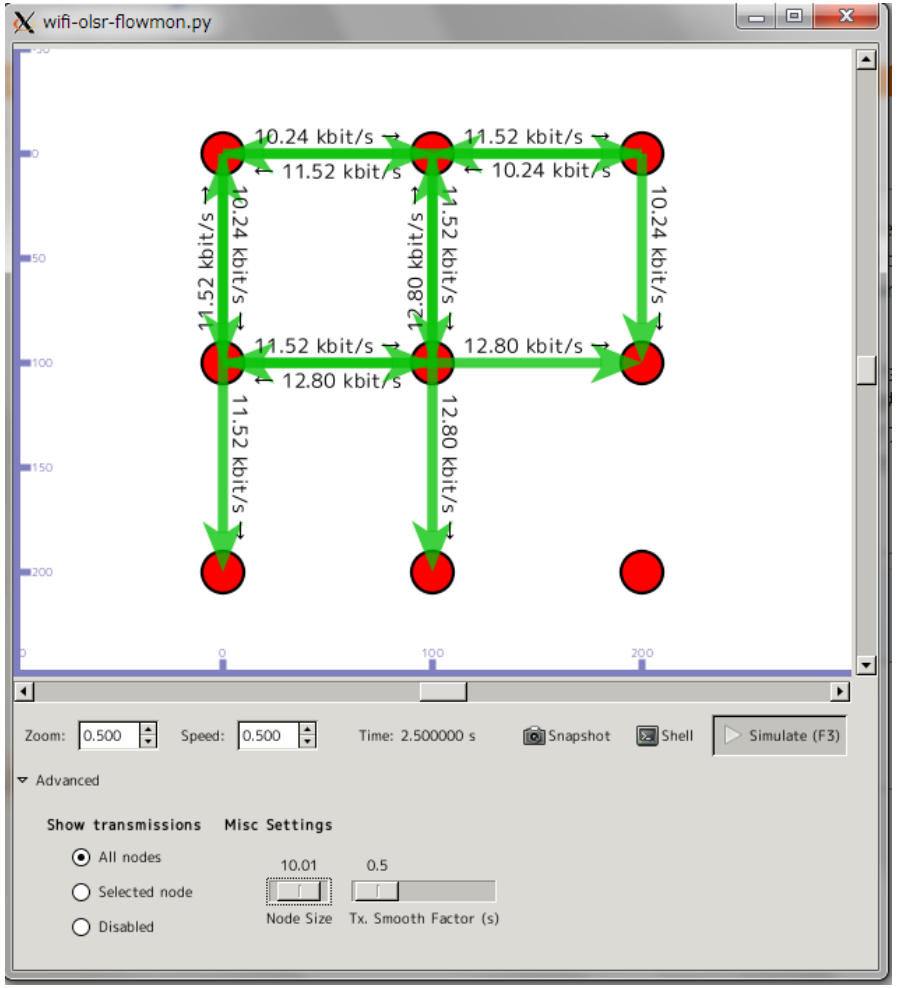


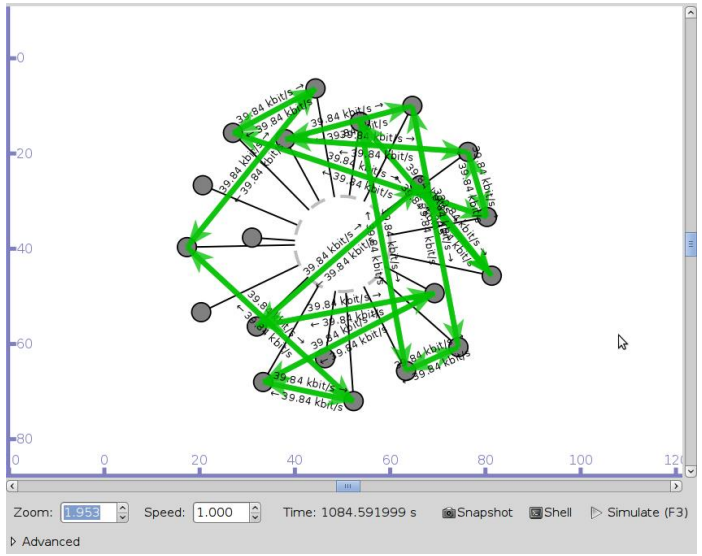
- Event Scheduler
  - Real time
- CRC checksum calculation enabled

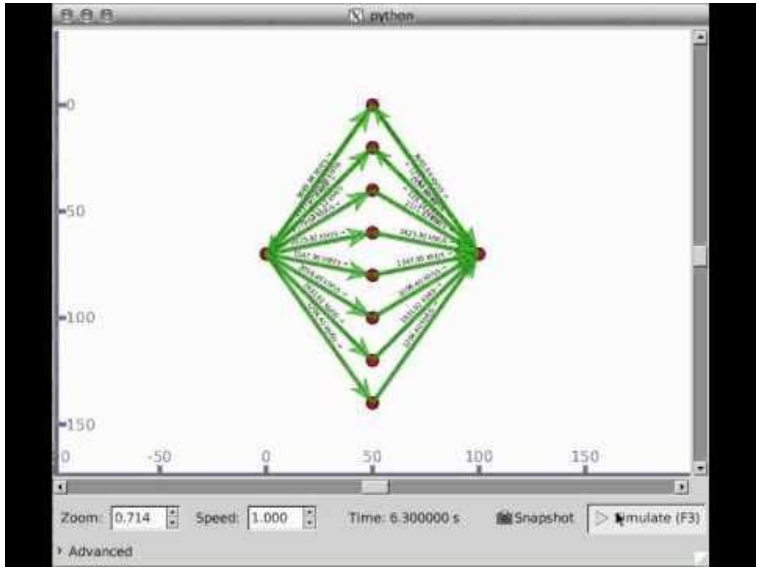
ns-3 – Results: Trace Files and FlowMonitor

- Trace Files
  - ASCII traces
    - Write your own *std::couts, etc.* in the code
    - Enable automatic traces of network events
      - Packet arrival and characteristics, …
  - PCAP traces
    - E.g., to open and analyze in Wireshark
- FlowMonitor
  - TCP and UDP support
  - Gathers network flows statistics at IP level – *xml* file that can be **parsed**
    - Packet delay histogram
    - Packet size histogram
    - Start and end time of each flow
    - Packet loss ratio
    - Average throughput

ns-3 – Python Visualizer







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ns-3 as a Digital Twin for Wireless Testbeds

- Background and Motivation
- Trace-based Simulation Approach (by INESC TEC)
  - New upcoming ns-3 apps
- Main Conclusions
- Future Work

Background and Motivation

Problem

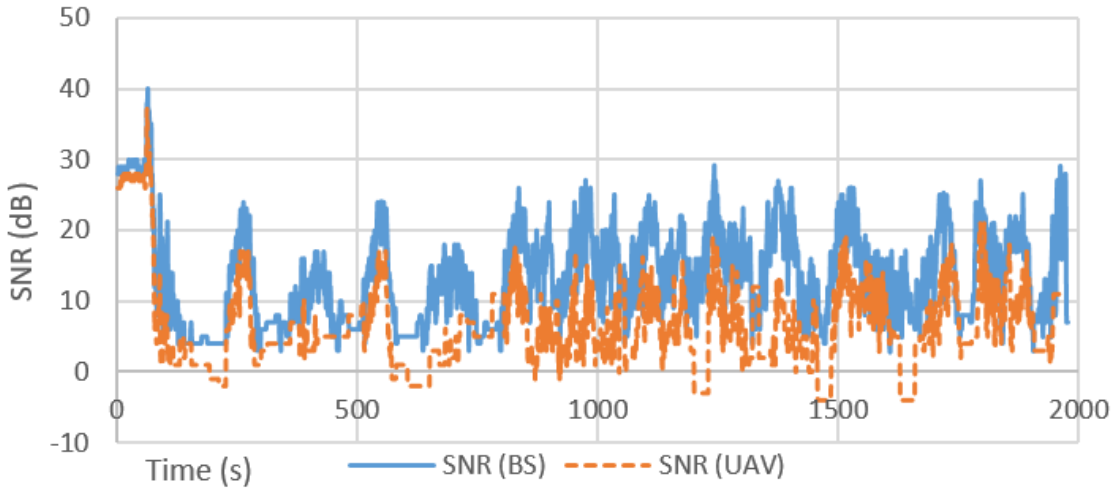
- Emerging Testbeds experiments **are difficult to repeat and reproduce**
  - **Unstable physical conditions**
  - **Cost and operational constraints**
  - **Simulation** is too **optimistic**

Objective

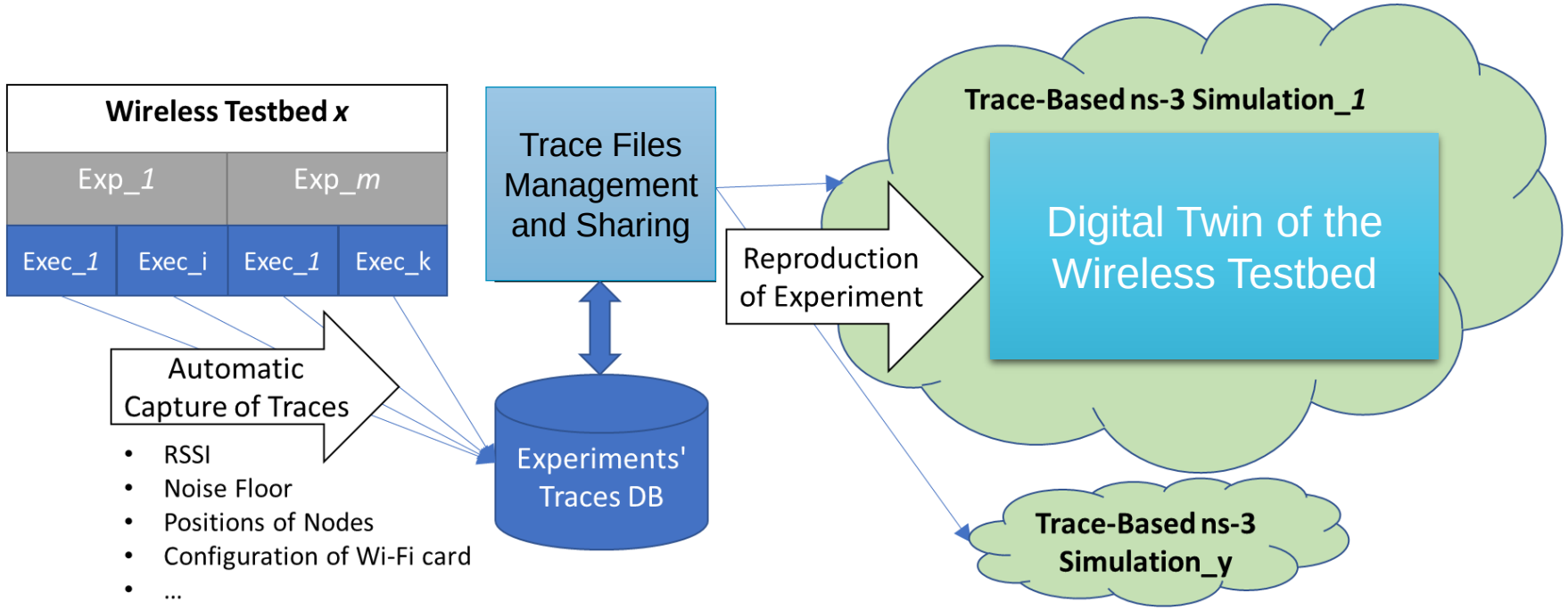
- Enable **repeatable** and **reproducible experiments without access to the testbed**
  - Accurately reproduce Real-World Experiments conditions in ns-3

Trace-based Simulation Approach

- **Capture Traces of Real Experiments**
  - Position of Nodes
    - GPS or cartesian coordinates
  - Radio link quality
    - Signal-to-Noise Ratio (SNR)
    - Other metrics



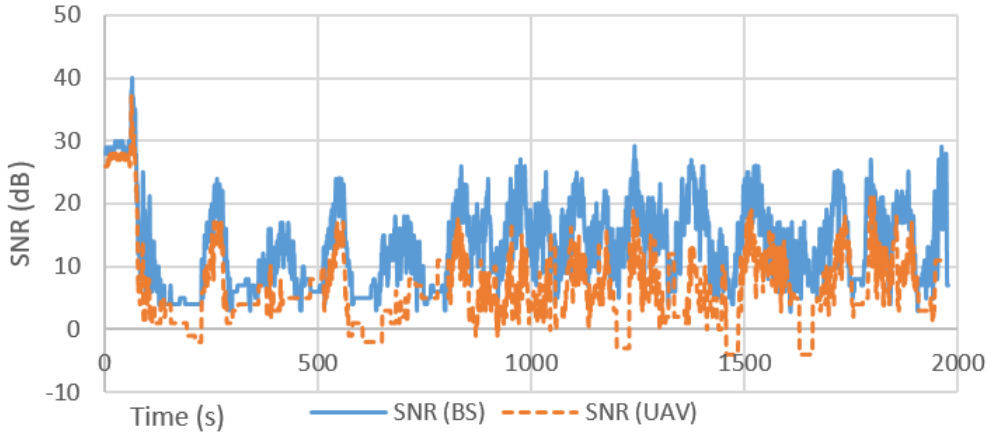
Trace-based Simulation Approach



- **Reproduce Traces in ns-3**
  - Configuration of Wi-Fi Cards → Channel, BW, standard, etc.
  - Positions of Nodes → WaypointMobilityModel
  - Link Quality → Trace-based Simulation Models

Trace-based Propagation Loss

Concept

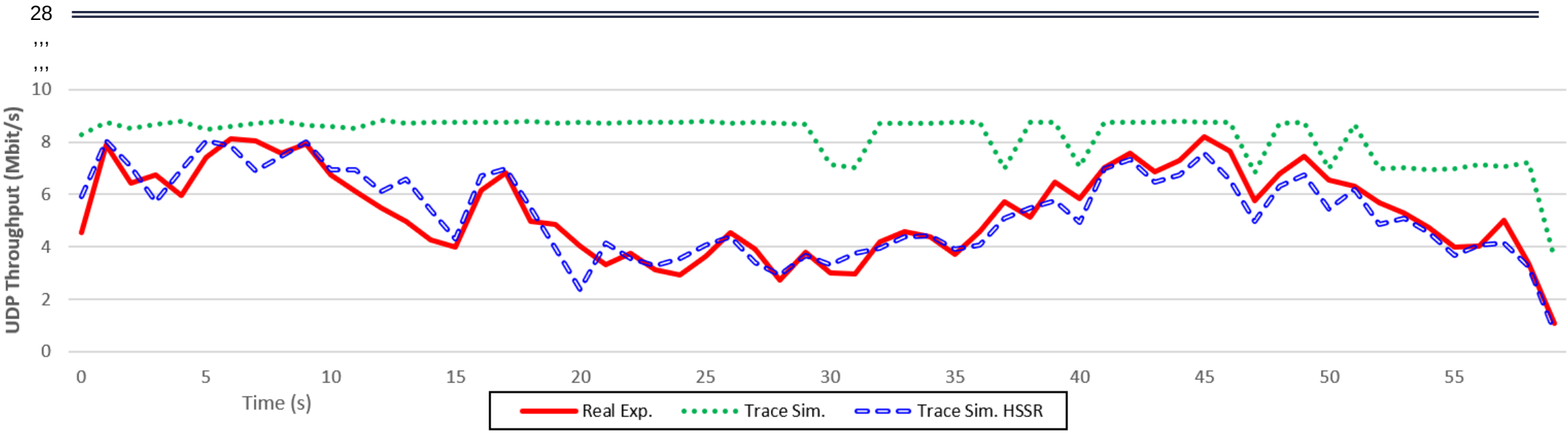


- Reproduces the **asymmetric SNR** between neighboring nodes
  - Each received successfully received frame is a valid **RSSI** sample
  - The reported **noise floor** is also considered
- ErrorRateModel
  - *Input:* PHY rate, Frame size, SNR (from real node)
  - *Output:* FER
- FER causes frame retransmissions → closer to real **throughput and delay**
  - ns-3 Minstrel **auto-rate** adaptation is used

Trace-based Propagation Loss

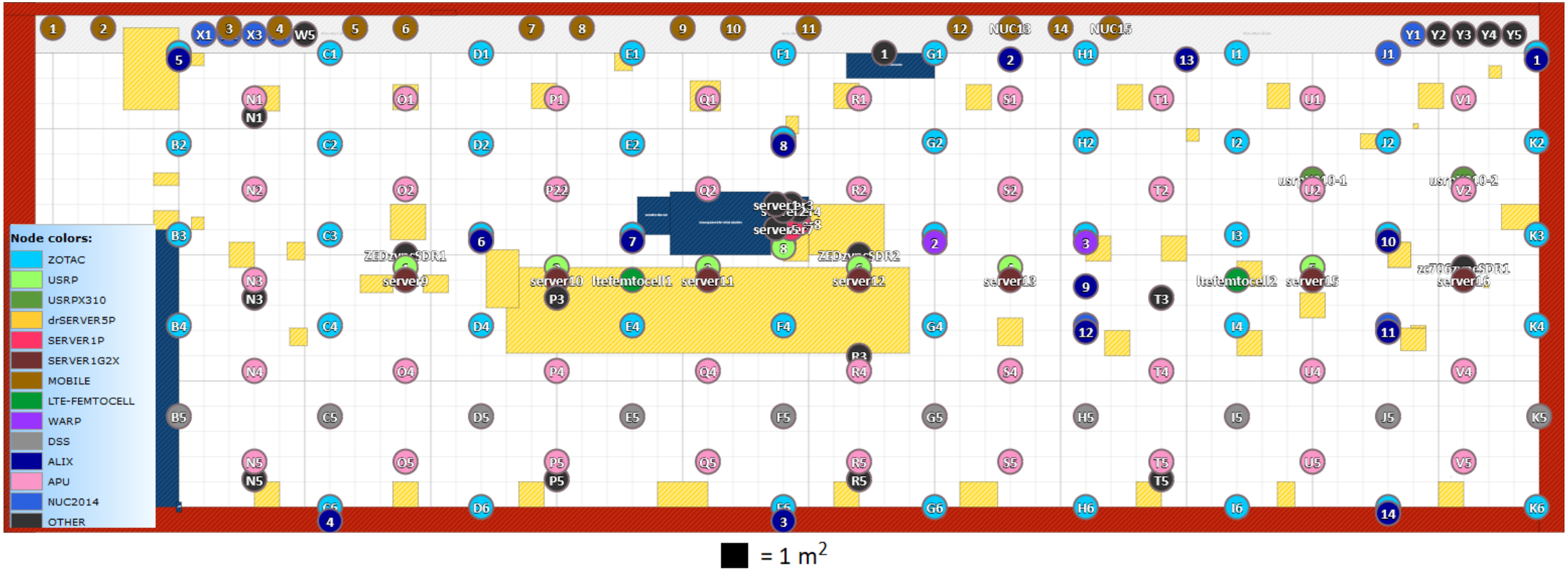
Low *vs.* High SNR Sampling Rate

		Average UDP Throughput (Mbit/s)				*Relative Error*		
Exp.#	Flow	Real Exp.	Trace Sim. HSSR	Trace Sim.	Pure Sim.	Trace Sim. HSSR	Trace Sim.	Pure Sim.
5 (second run)	C->A	5.4	5.3	8.3	28.2	1.4%	53.9%	426.2%



Trace-based Propagation Loss

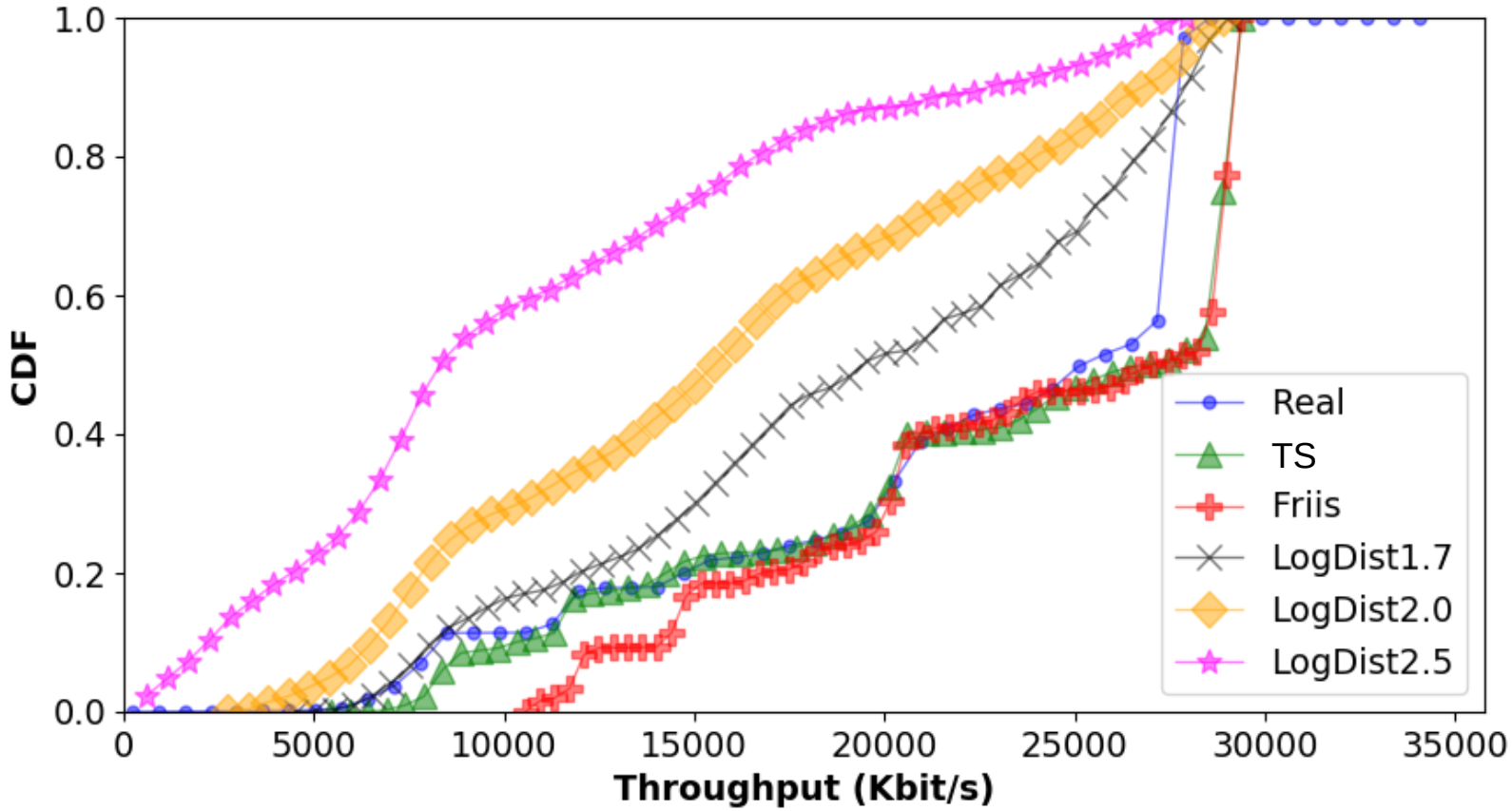
Evaluation – Fed4FIRE+ w-iLab.2 Testbed (SIMBED Project)



- Varying distance and TX power

Trace-based Propagation Loss

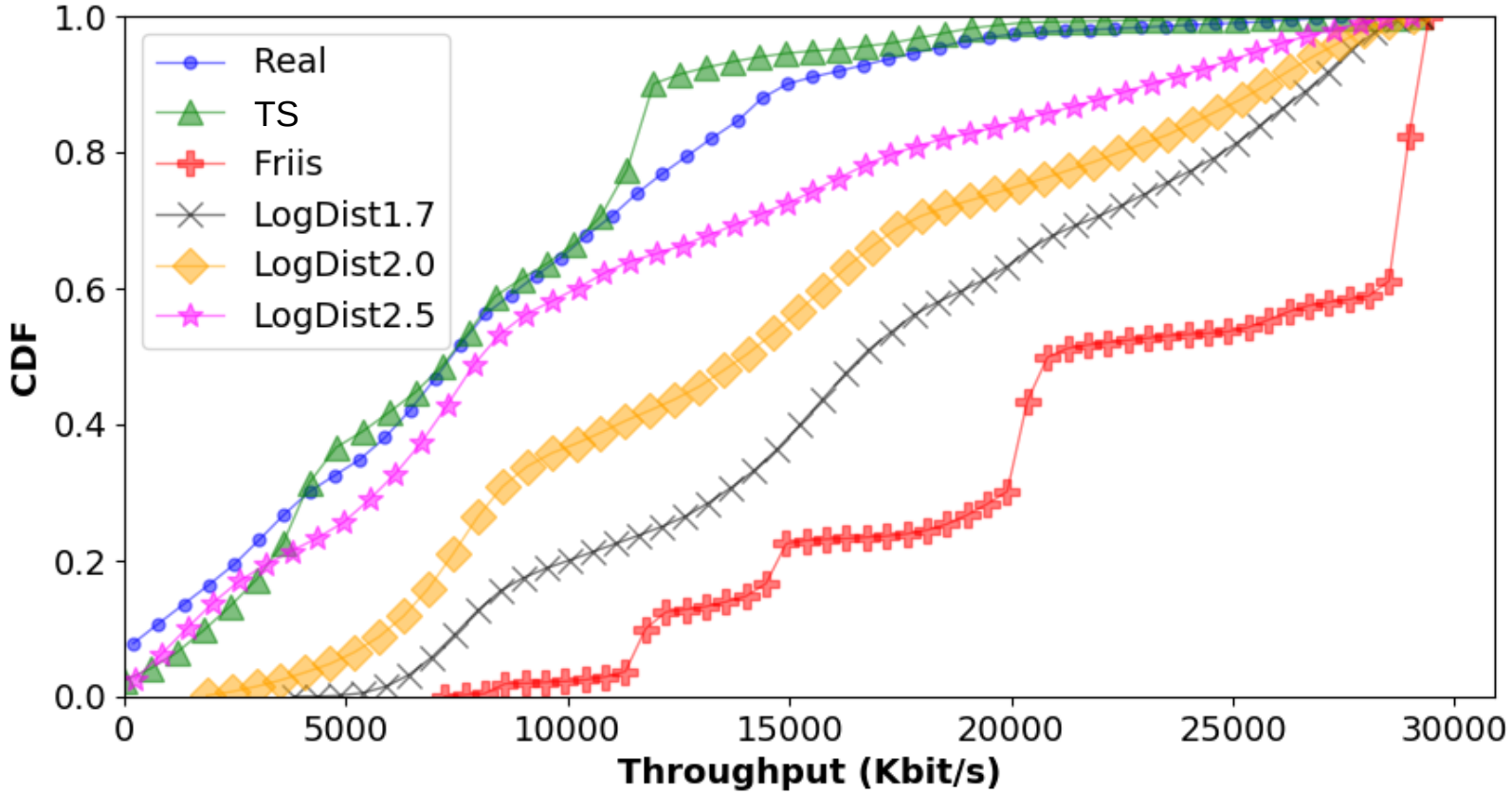
Evaluation – Static Scenario @ Wi-Lab.2 (SIMBED Project)
802.11a, SISO



Trace-based Propagation Loss

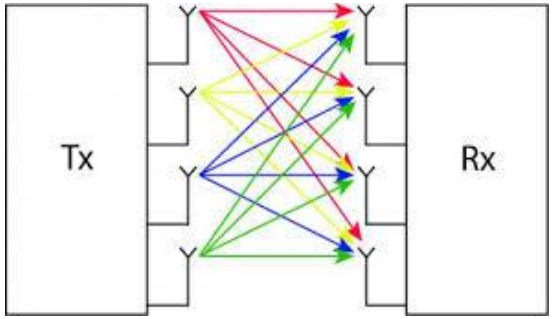
Evaluation – Mobile Scenario @ Wi-Lab.2 (SIMBED Project)

802.11a, SISO



Trace-based Wi-Fi Rate Adaptation

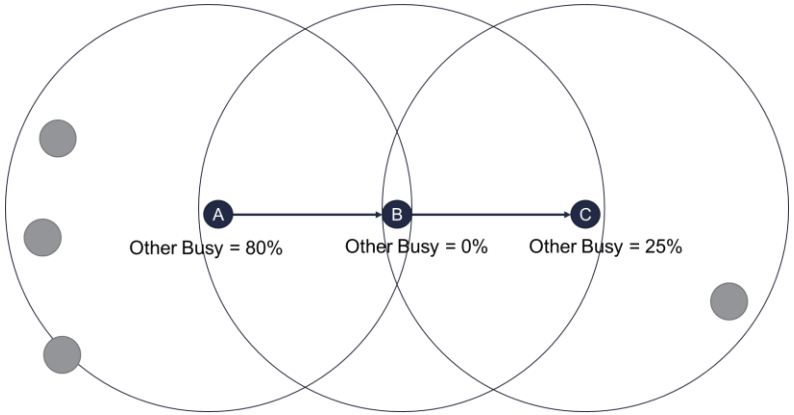
Concept



- **SNR trace** alone is **not enough for MIMO** scenarios
  - The **number of radio streams** depends on the **CSI** influenced **multipath environment**
- Captures and Reproduces the **MCS** and **number of radio** streams used to transmit frames to each of the neighboring nodes
  - Each successfully received frame is a valid sample
  - A modified **Wi-Fi Station Manager** is used to reproduce the traces
- Resulting **auto-rate adaptation** is now **deterministic**, based on the real traces
- **Frame losses** remain based on the ns-3 **ErrorRateModel**
  - **MCS** is, however, **not affected by** MAC layer **retransmissions**

Trace-based Wi-Fi Channel Occupancy

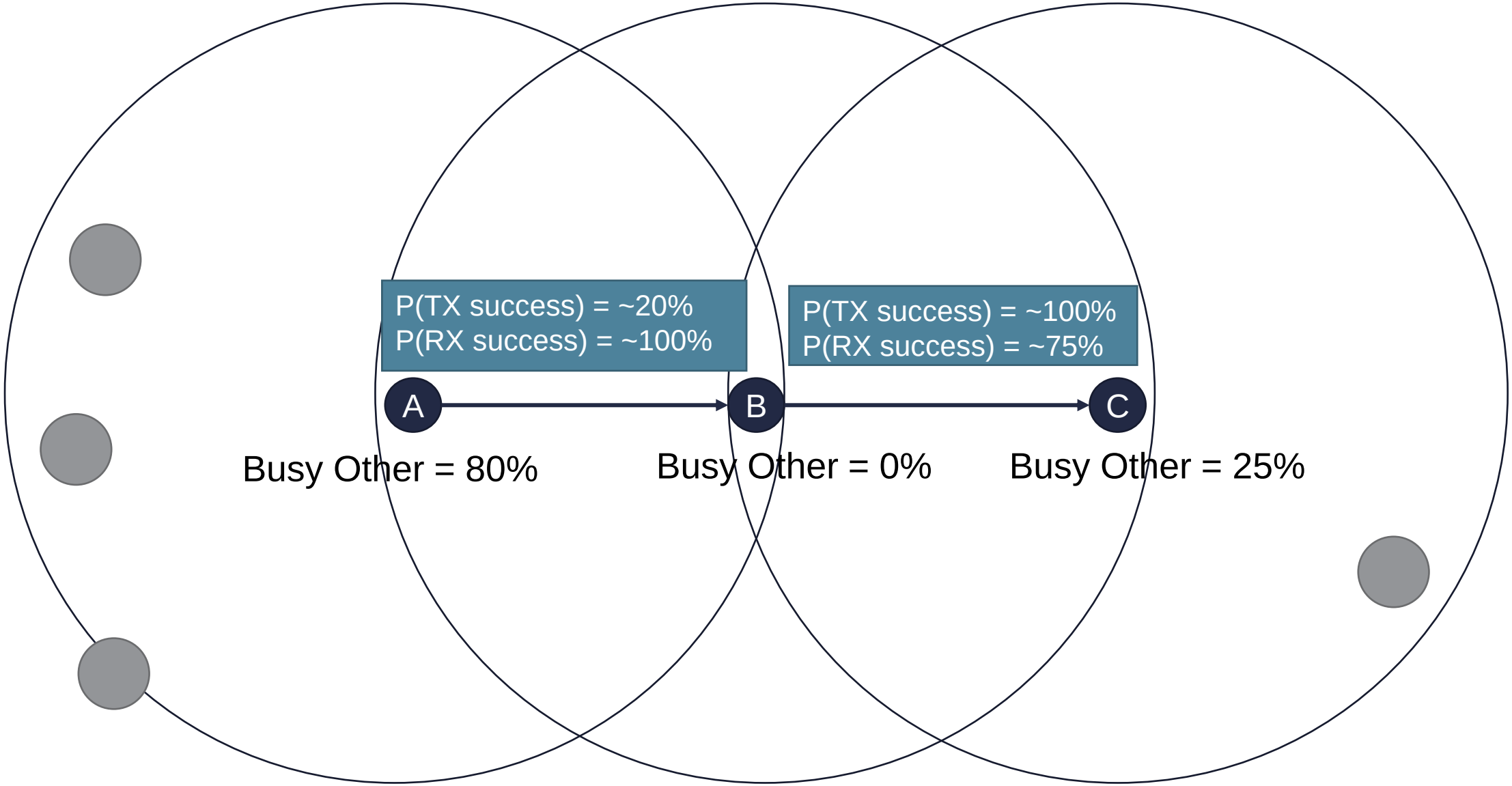
Concept



- **Channel occupancy** traces
  - Wi-Fi interfaces report **TX-time**, **RX-time** and **total busy time** in *ms*
  - **Busy time** caused by **other nodes** from concurrent networks can be calculated
- Sender Model
  - If channel is “sensed” busy, frame is not transmitted
- Receiver Model
  - Causes **frame losses** on purpose, acting as **collisions from hidden nodes**
  - Only used if “busy other” at RX node is higher than the TX node (simplification)

Trace-based Wi-Fi Channel Occupancy

Concept

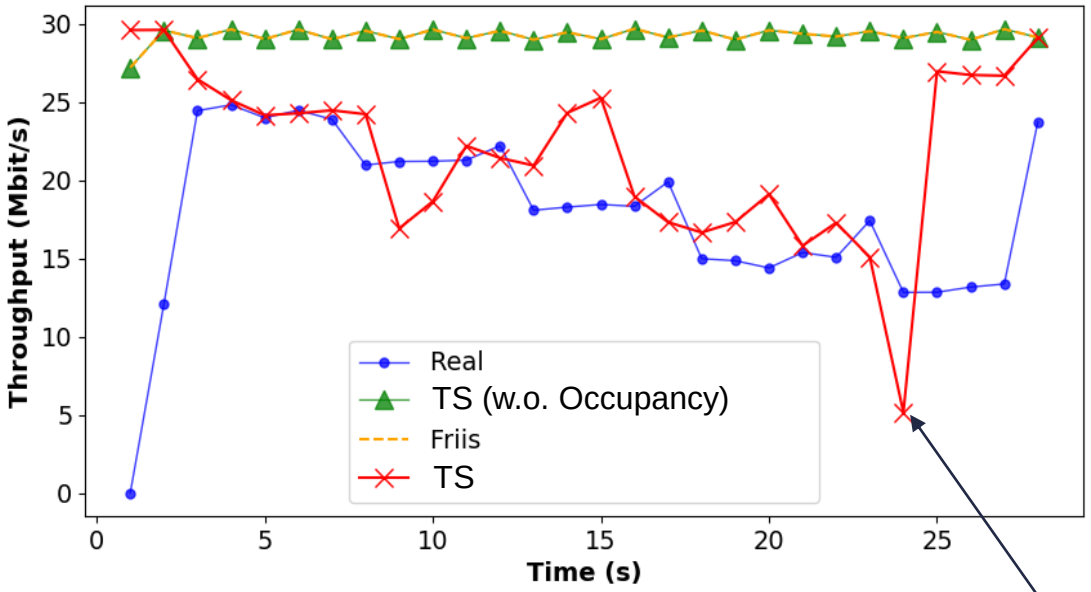


Trace-based Wi-Fi Channel Occupancy

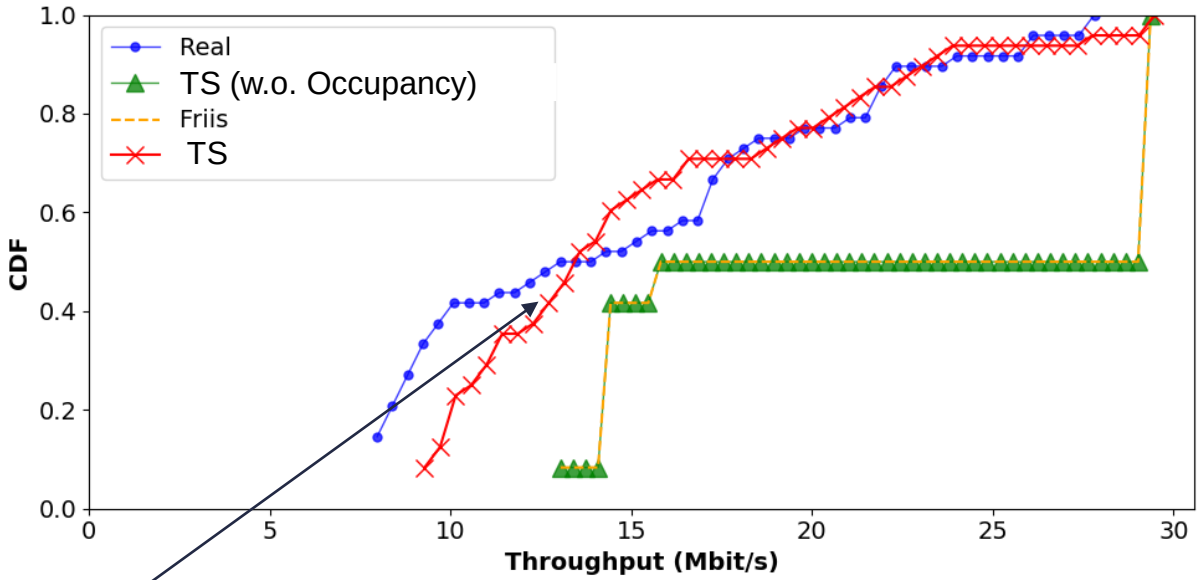
Evaluation – Static Scenario @ Wi-Lab.2 (SIMBED+ Project)

802.11a, 20 MHz (Sender Model)

Example of an experiment



CDF of the throughput samples



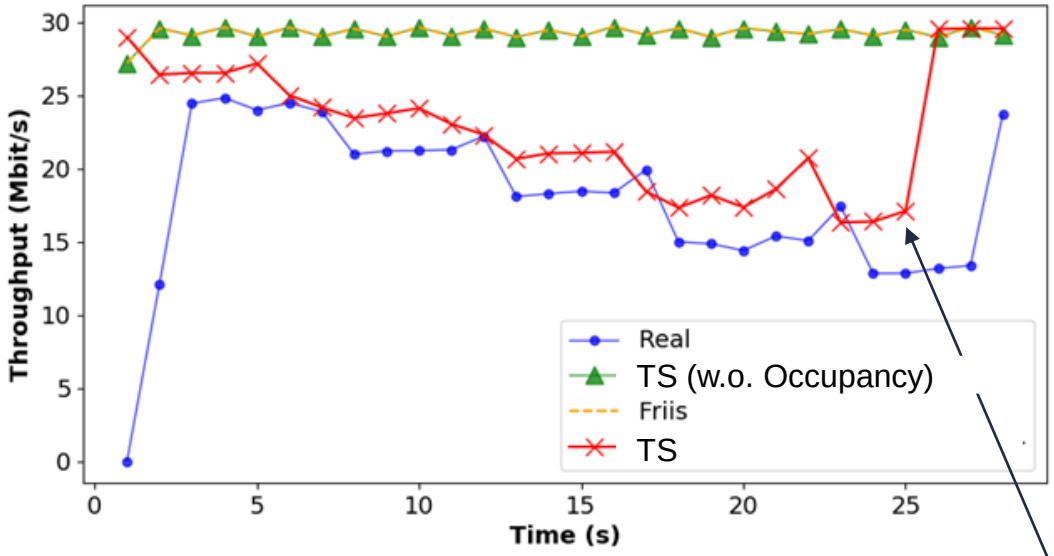
TS results close to Real

Trace-based Wi-Fi Channel Occupancy

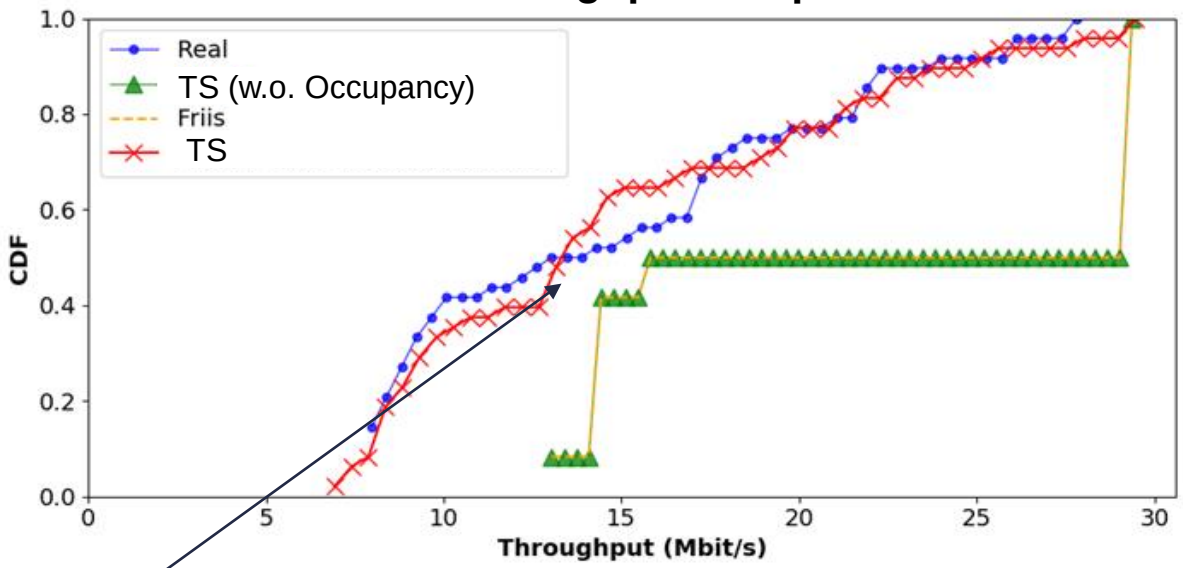
Evaluation – Static Scenario @ Wi-Lab.2 (SIMBED+ Project)

802.11a, 20 MHz (Receiver Model)

Example of an experiment



CDF of the throughput samples



TS results close to Real

Trace-based Simulation Approach

Summary and upcoming ns-3 apps

Trace Type	Trace files and its variables	Trace-based ns-3 model
Link Quality	Signal-to-noise ratio (SNR)	**TraceBasedPropagationLoss** → Validated in SIMBED
	PHY rate/MCS Number of radio streams	**TraceBasedWiFiRateAdaptation** → Validated in SIMBED+
	Channel occupancy	**TraceBasedWiFiChannelOccupancy** **- "Sender" Model** **- "Receiver" Model** → Validated in SIMBED+
Position of nodes	Cartesian coordinates	**WaypointMobilityModel**

Real SNR

MIMO

Shared radio spectrum

Main Conclusions

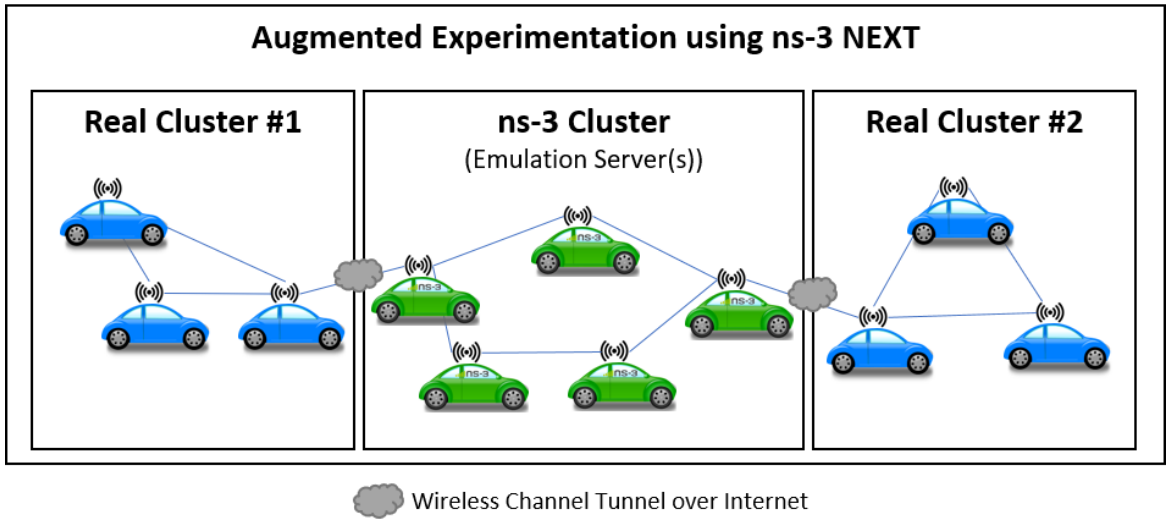
- The **TS approach** with its **three models** supports realistic reproduction of
  - **SNR** (Asymmetric)
  - **MIMO** operation (MCS and number of radio streams)
  - **Shared radio spectrum** (influencing, both, TX and RX operations)
- These models enable **ns-3** to be used as a **Digital Twin for Wireless Testbeds**
  - **Saves resources**
  - **Perpetuates experiments**, even if the original **testbeds cease to exist**
  - Allows Traces to be referenced in **scientific publications**

Future work

- Keep improving the TS approach/Digital Twin
  - Detection of **link failure**
  - Dynamically **adjust traces resolution** to the scenario
  - Add support for **beamforming**
- Assess TS approach applicability to other wireless technologies
  - E.g., Cellular, IEEE 802.15.4
- Software platform to assist the processes of traces **capturing**, **managing** and **sharing**
  - **Share past or real time execution of experiments**
- Fine-tune and learn new **path loss** and **mobility** models
  - Accurate simulations with different **number of nodes**, **mobility** and **duration**

Future work

- **Augmented Experimentation**
  - **Scale real testbeds** with accurately emulated resources
  - **Seamless interaction** between real and emulated resources



Thank you!

Questions?

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