From Traces to Transformation: Leveraging ns-3 as a Digital Twin for Next-generation Networks

WNS3 2023 Invited Talk

Helder Fontes – helder.m.fontes@inesctec.pt

Manager of the Wireless Networks Research Area at CTM, INESC TEC Invited Assistant Professor at University of Porto

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• Context and Motivation
• Trace-based Simulation Approach
• ns-3 as a Network Digital Twin: new Data-driven Models
• Example of Ongoing Projects for Next-generation Networks
  • HE CONVERGE - https://converge-project.eu/
  • HE SuperIoT - https://superiot.eu/
CONTEXT AND MOTIVATION
Context
Main research lines and topics

- On-demand Communications for **Extreme Environments**
  - Location, Traffic, QoS, Slicing and Energy-aware
- **Network Simulation, Digital Twins**
- Mesh Networks, Multi-technology Gateways, Overlay Networks
- Wi-Fi, 5G/6G, Satellite, IoT
- Machine Learning for Networking
Context
On-demand Airborne Networks
Context
Maritime Multimodal Long-range Communications
Context

Examples of the platforms
Problem and Objective

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 Experimental conditions in ns-3
Trace-based Simulation Approach

(since 2017)
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 Simulation Approach

### Overview on the TS models

<table>
<thead>
<tr>
<th>Trace Type</th>
<th>Trace files and its variables</th>
<th>Trace-based ns-3 model</th>
</tr>
</thead>
</table>
| Link Quality      | Signal-to-noise ratio (SNR)   | TraceBasedPropagationLoss  
|                   | PHY rate/MCS                  |                         |
|                   | Number of radio streams       |                         |
|                   | Channel occupancy             | TraceBasedWiFiRateAdaptation  
|                   |                               |                         |
|                   |                               | TraceBasedWiFiChannelOccupancy  
|                   |                               | - “Sender” Model  
|                   |                               | - “Receiver” Model  
|                   |                               |                         |
| Position of nodes | Cartesian coordinates         | WaypointMobilityModel     |

- **Real SNR**
- **MIMO and Rate Adaptation**
- **Shared radio spectrum**
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

<table>
<thead>
<tr>
<th>Exp.#</th>
<th>Flow</th>
<th>Real Exp</th>
<th>Trace Sim. HSSR</th>
<th>Trace Sim.</th>
<th>Pure Sim.</th>
<th>Trace Sim. HSSR</th>
<th>Trace Sim.</th>
<th>Pure Sim.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>C-&gt;A</td>
<td>5.4</td>
<td>5.3</td>
<td>8.3</td>
<td>28.2</td>
<td>1.4%</td>
<td>53.9%</td>
<td>426.2%</td>
</tr>
</tbody>
</table>

![Graph showing UDP Throughput (Mbit/s) over time (s) with Real Exp., Trace Sim., and Trace Sim. HSSR lines]

Legend:
- Real Exp.
- Trace Sim.
- Trace Sim. HSSR
Trace-based Wi-Fi Rate Adaptation
Concept

• **SNR trace** alone is **not enough for MIMO scenarios**
  • The **number of radio streams** depends on **CSI**, influenced by **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)
Main Conclusions

- **TS approach** 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** (Reproducibility)

- **Limitation**: only reproduces the same conditions (number of nodes, duration of experiments, trajectories, etc.)
ns-3 as a Network Digital Twin: new Data-driven Models

(Since 2021)
Objectives

• Develop **Data-driven models** for specialized/accurate ns-3 Digital Twins
  • Use traces to train **ML-based models** and create new **stochastic models**
  • Enable accurate simulations with different **number of nodes, mobility and duration**

Digital Twin

Test “What If”/”Why Not” scenarios:

Examples:
- Assess the impact of turning off some APs to save energy
- Assess the capacity of the network to handle new use cases

• Experimental data/real measurements e.g. RSSI per Access Point

• Realistic results to support informed decisions
Recent Data-driven Models

• ML-based **Propagation Loss Model (MLPL)**
  • Composed of **Path Loss** (supervised learning) and **Fast Fading** Models (stochastic)
  • **Specialized** for a specific scenario/environment

• ML-based **Traffic Generation Model**
  • Based on **GANs** and **Time Series**
  • **Specialized** for specific (type of) user, application, etc.
  • Eases the **generation of real-like IP traffic** in **Physical** and **Digital Twins** (ns-3)
  • Allows for **data-augmentation** to train traffic classifier (Anomaly detection, App identification, QoS, Traffic Forensics, etc.)

• Stochastic **Computational Delay Model**
  • Reproduces **computational delays** (e.g., State, Action and Reward) in ns-3
  • **Specialized** for specific **model implementation** and **hardware profile**
  • Tested for **Rate-Adaptation ML-based models**, but applicable to other applications
Main Conclusions

- **Data-driven models** represent a **transformation** leveraging **ns-3** as a Digital Twin
  - Allows **flexible**, but **specialized** and **accurate** Digital Twins
  - **Saves resources** – can be used as a realistic Sandbox for real testbeds
  - **Perpetuates experimental conditions**, even if the original **testbeds cease to exist**
    - Interpolation and extrapolation is possible
    - Reproducibility/Independent Validation is possible
  - Allows **Model Checkpoints** to be referenced in **scientific publications**
    - In complement or in substitution of the original datasets (e.g. because of data privacy)
- **Limitation:** Non-real-time interaction between Digital and Physical Twin
Example of Ongoing Projects for Next-generation Networks

- HE CONVERGE - https://converge-project.eu/
- HE SuperIoT - https://superiot.eu/
CONVERGE (2023–2026)

Telecommunications and Computer Vision Convergence Tools for Research Infrastructures

Goal: develop innovative toolset combining radio and vision-based communications and sensing technologies under motto “view-to-communicate & communicate-to-view”

- Communications solutions that dynamically and in real-time take advantage of vision and sensing information
- Vision solutions that take advantage of networks of cameras, sensing and radio information
- Future integration in European SLICES-RI

3 Research Infrastructures (Porto, Oulu, Sophia-Antipolis)

5 Vertical markets: Telecommunications, Automotive, Health, Media, Industry

8 M€ Funding
Coordinator: INESC TEC

https://converge-project.eu/
CONVERGE (2023–2026)

Telecommunications and Computer Vision
Convergence Tools for Research Infrastructures

Participants from the US
• Edward Knightly (Rice University)
• Ivan Seskar (Rutgers University)
SuperIoT (2023–2026)

Truly Sustainable Printed Electronics-based IoT Combining Optical and Radio Wireless Technologies

**Goal:** developing a truly sustainable and highly flexible IoT system based on the use of optical and radio communications, and the exploitation of printed electronics technology for the implementation of sustainable IoT nodes.

- Energy-autonomous nodes
- Reconfigurable networks
- Use of printed electronics
- Dual-mode energy harvesting and positioning

https://superiot.eu/
Thank you!

Questions?

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