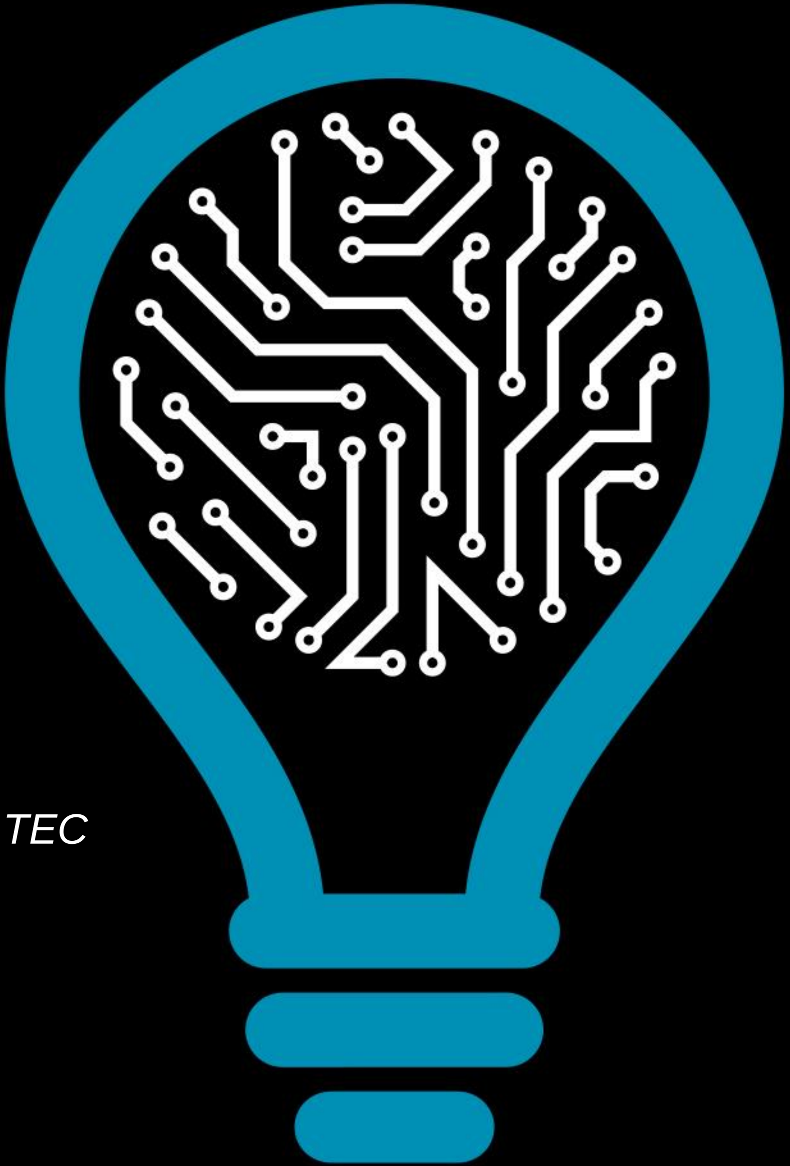
From Traces to Transformation: Leveraging ns-3 as a Digital Twin for Next-generation Networks

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

June 28th, 2023



INESCTEC INSTITUTE FOR SYSTEMS AND COMPUTER ENGINEERING, TECHNOLOGY AND SCIENCE

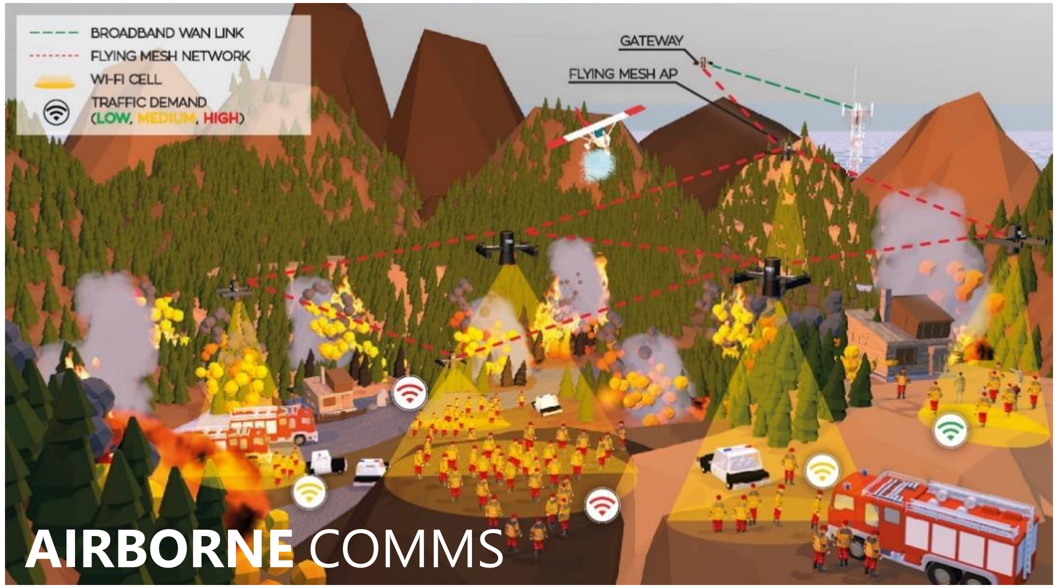
U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

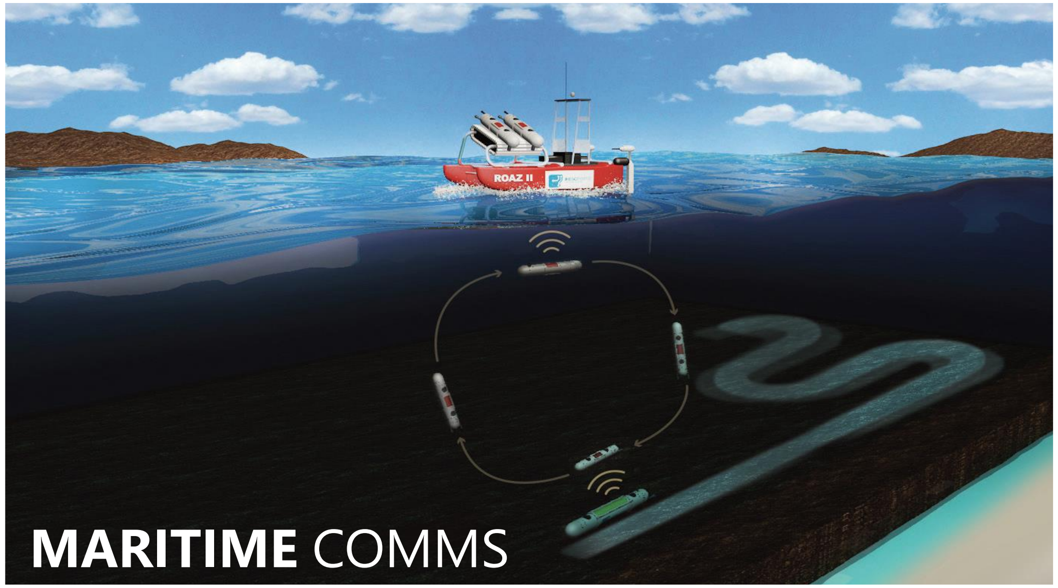
- **Context and Motivation**
- **Trace-based Simulation Approach**
- **ns-3 as a Network Digital Twin: new Data-driven Models**
- **Example of Ongoing Projects for Next-generation Networks**
  - **HE CONVERGE -** https://converge-project.eu/
  - **HE SuperIoT -** https://superiot.eu/

CONTEXT AND MOTIVATION

Context

Main research lines and topics

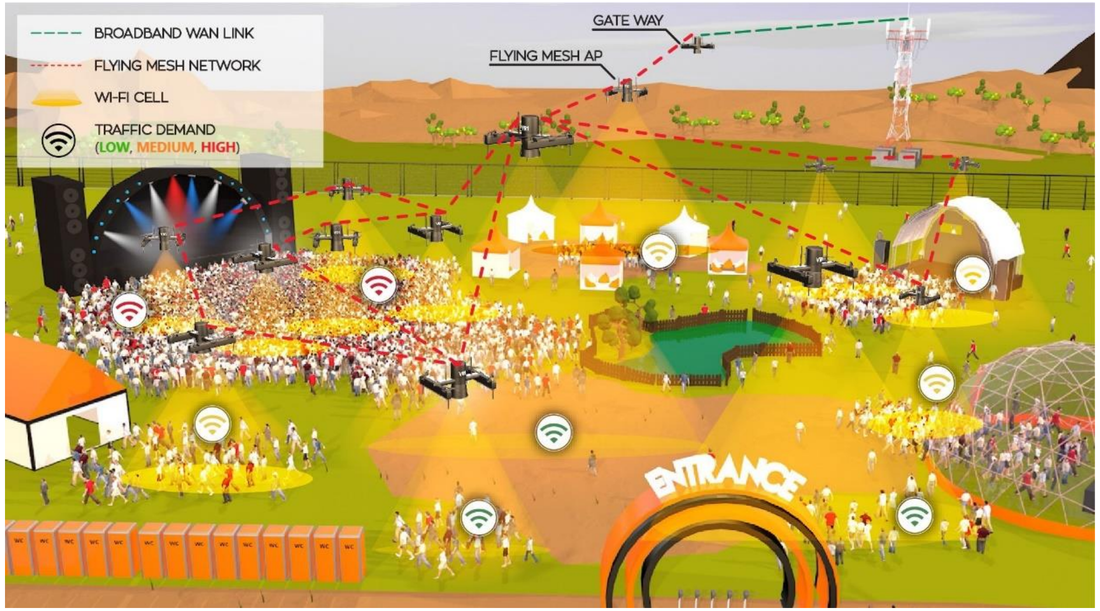


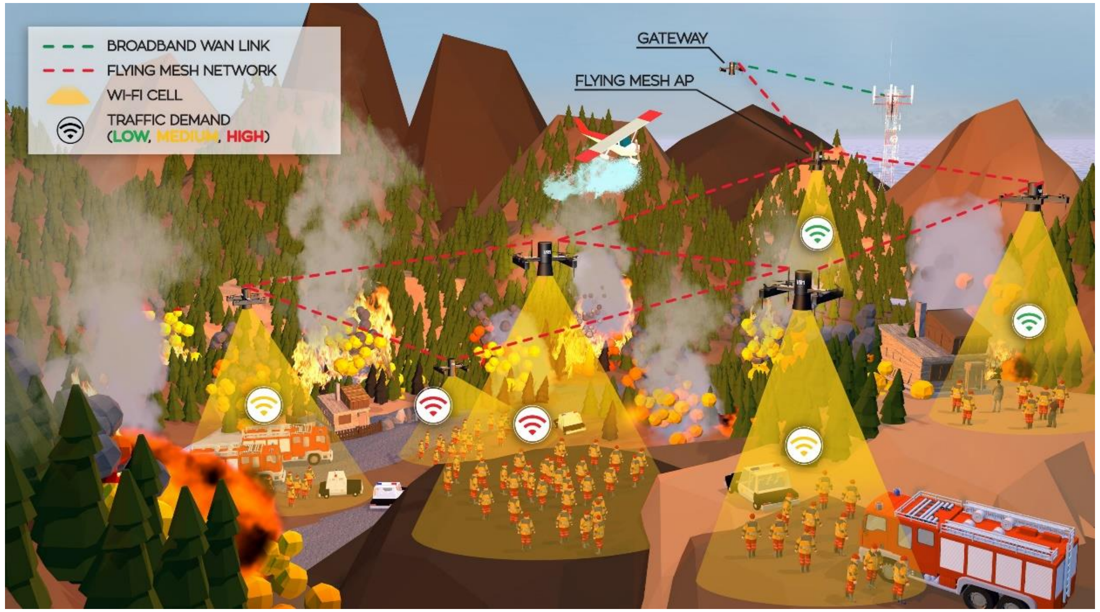


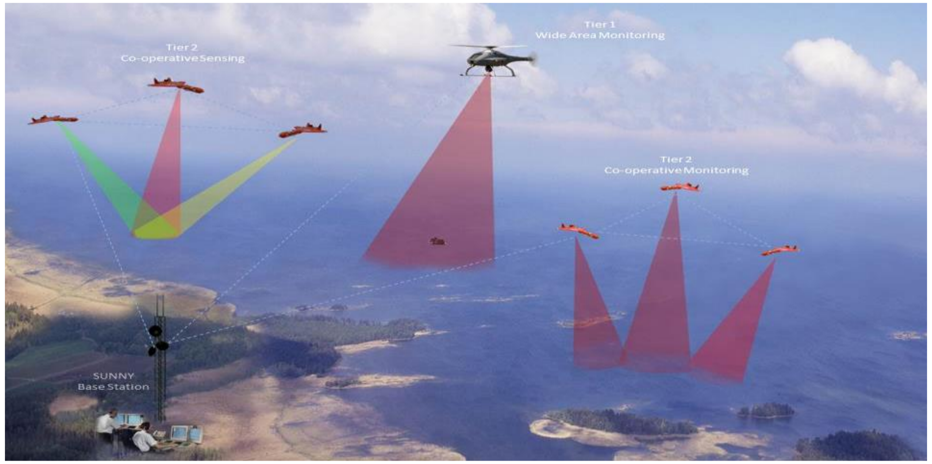
- On-demand Communications for **Extreme Environments**
  - Location, Traffic, QoS, Slicing and Energy-aware
- **Network Simulation, Digital Twins**
- Mesh Networks, Multi-technology Gateways, Overlay Networks
- Wi-Fi, 5G/6G, Satellite, IoT
- Machine Learning for Networking

Context

On-demand Airborne Networks

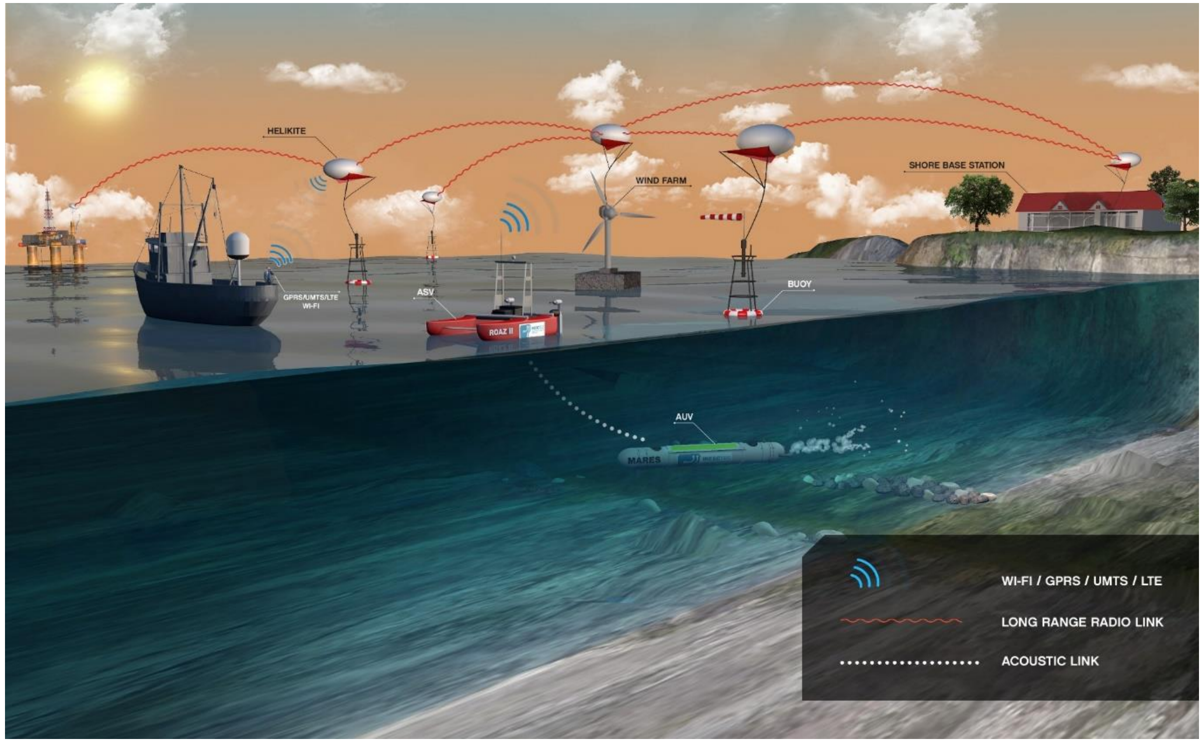


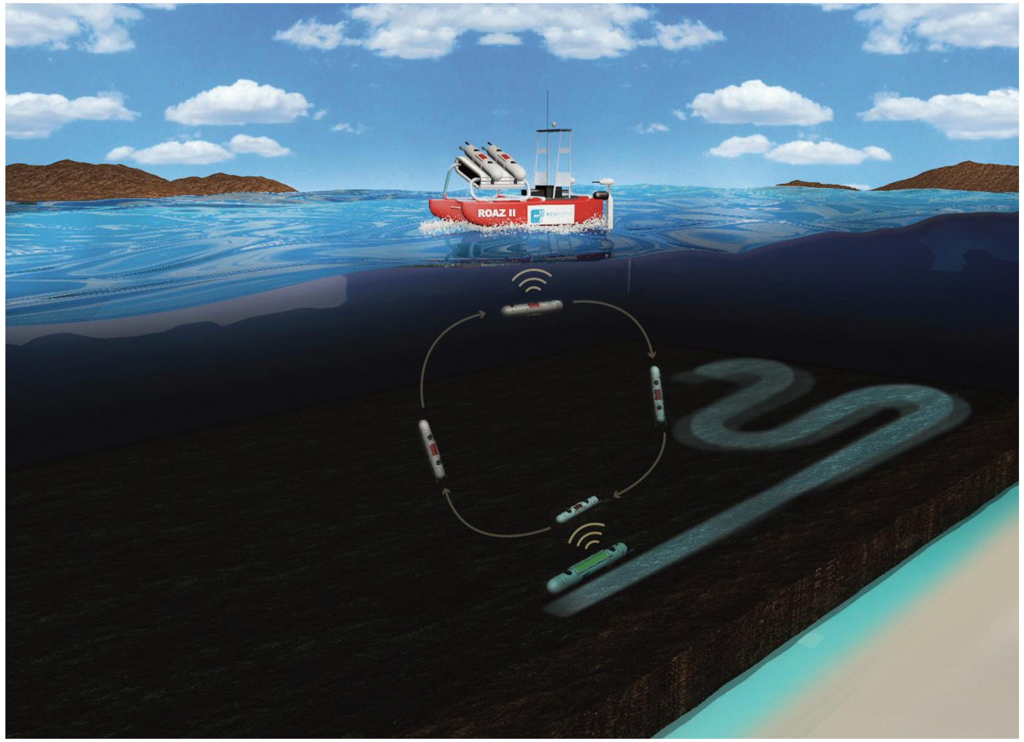




Context

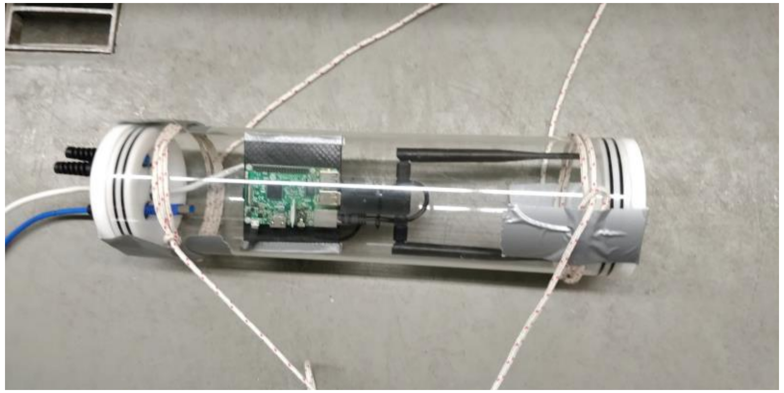
Maritime Multimodal Long-range Communications





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**

→ Limited Performance Evaluation and Validation

Objective

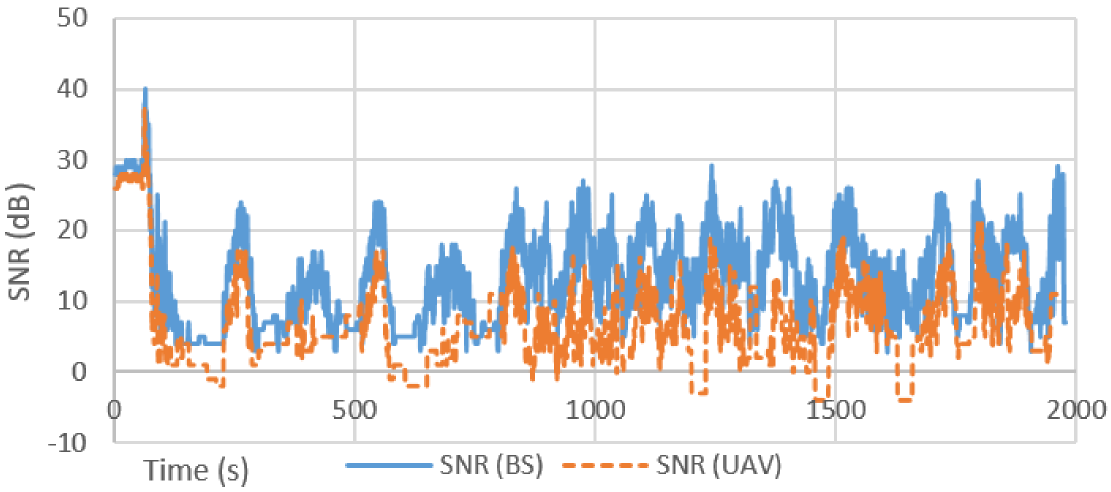
- Enable **repeatable** and **reproducible experiments without access to the testbed**
    - Accurately reproduce Real-World Experimental conditions in ns-3

Trace-based Simulation Approach

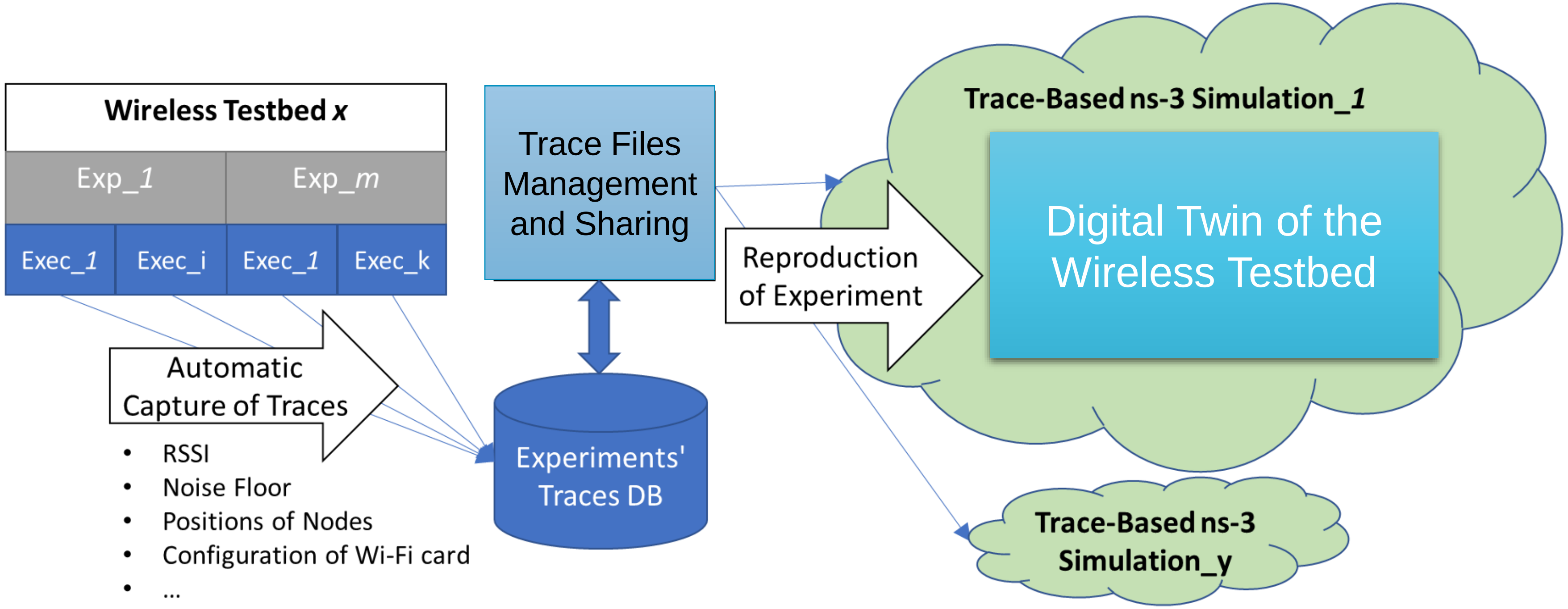
(since 2017)

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

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**

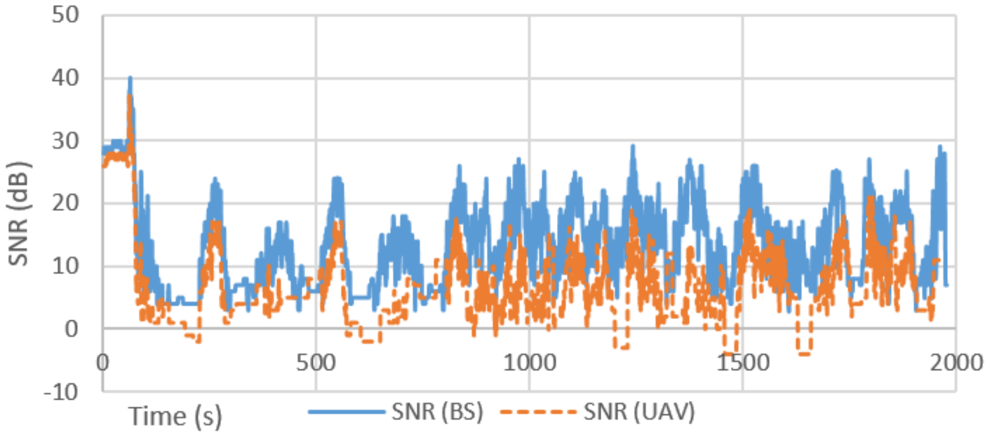
Real SNR

MIMO 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

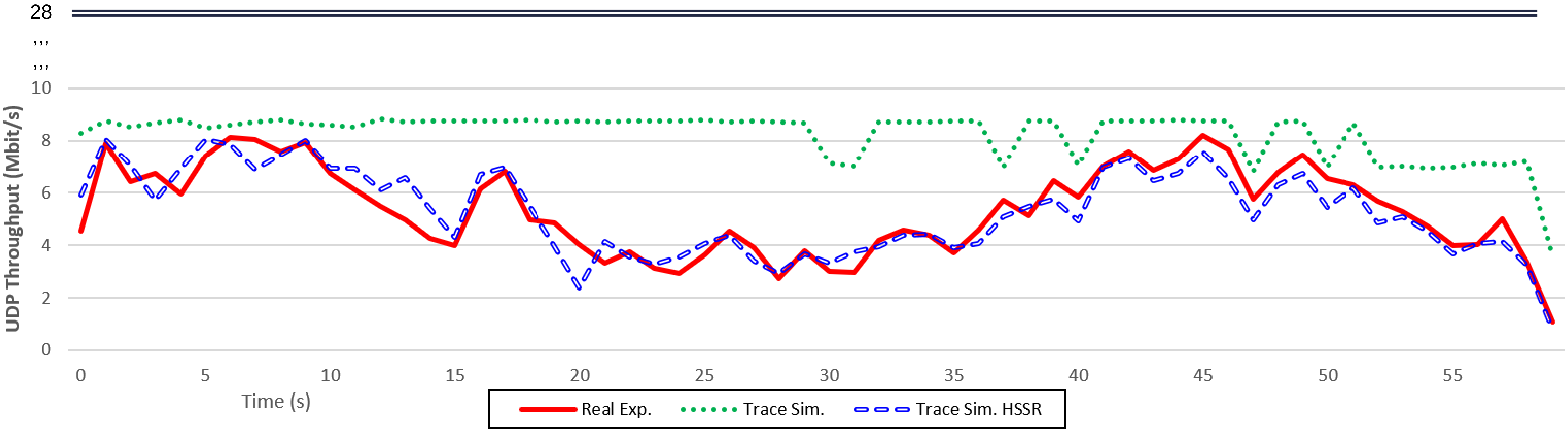
- ErrorRateModel
  - *Input:* PHY rate, Frame size, SNR (from real node)
  - *Output:* FER

- FER causes frame retransmissions → closer to real **throughput and delay**
  - ns-3 Minstrel **auto-rate** adaptation is used

Trace-based Propagation Loss

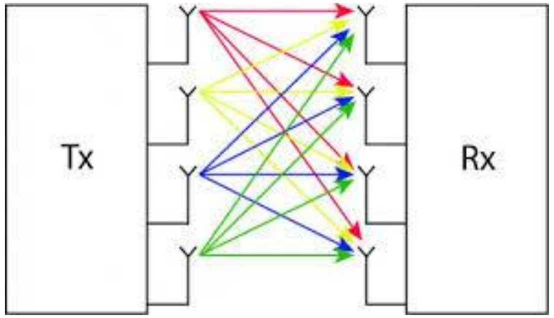
Low *vs.* High SNR Sampling Rate

		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 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**

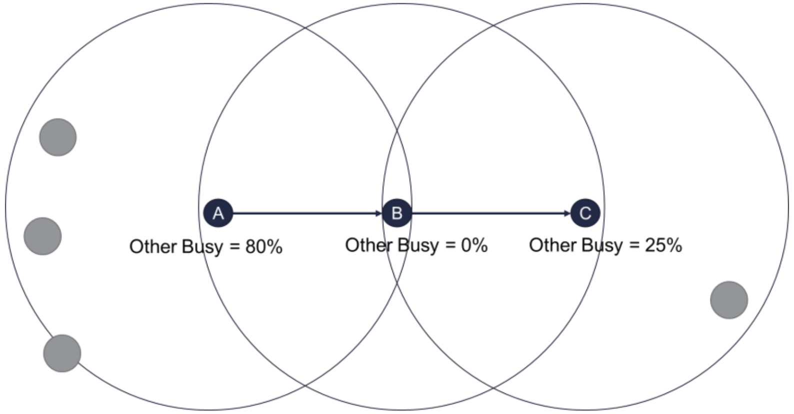
- Captures and Reproduces the **MCS** and **number of radio streams** used to transmit frames to each of the neighboring nodes
  - Each successfully received frame is a valid sample
  - A modified **Wi-Fi Station Manager** is used to reproduce the traces

- 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)**

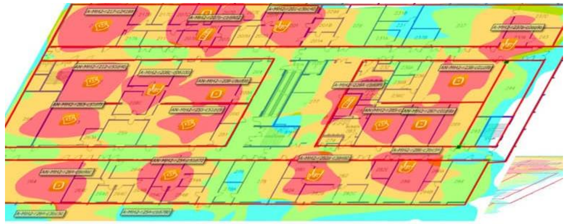
- **Limitation:** only reproduces the same conditions (number of nodes, duration of experiments, trajectories, etc.)

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**



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

Digital Twin

ns-3 NETWORK SIMULATOR

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

- 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.)

Patent app. submitted

- 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/

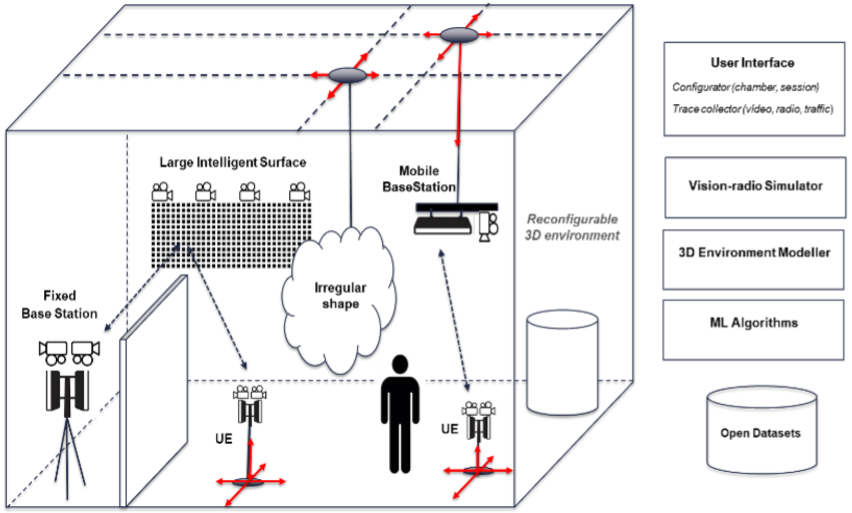
CONVERGE (2023–2026)

CONVERGE
view-to-communicate and communicate-to-view

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



8 M€
Funding

Coordinator:
INESC TEC

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

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

INESCTEC · UNIVERSITY OF OULU · EURECOM · SORBONNE UNIVERSITÉ · Inria · allbesmart · Greener wave. · adapttech · FINWE · FinCloud.tv LIVE · RICE · RUTGERS · QUEEN'S UNIVERSITY BELFAST · interdigital

https://converge-project.eu/

Funded by the European Union

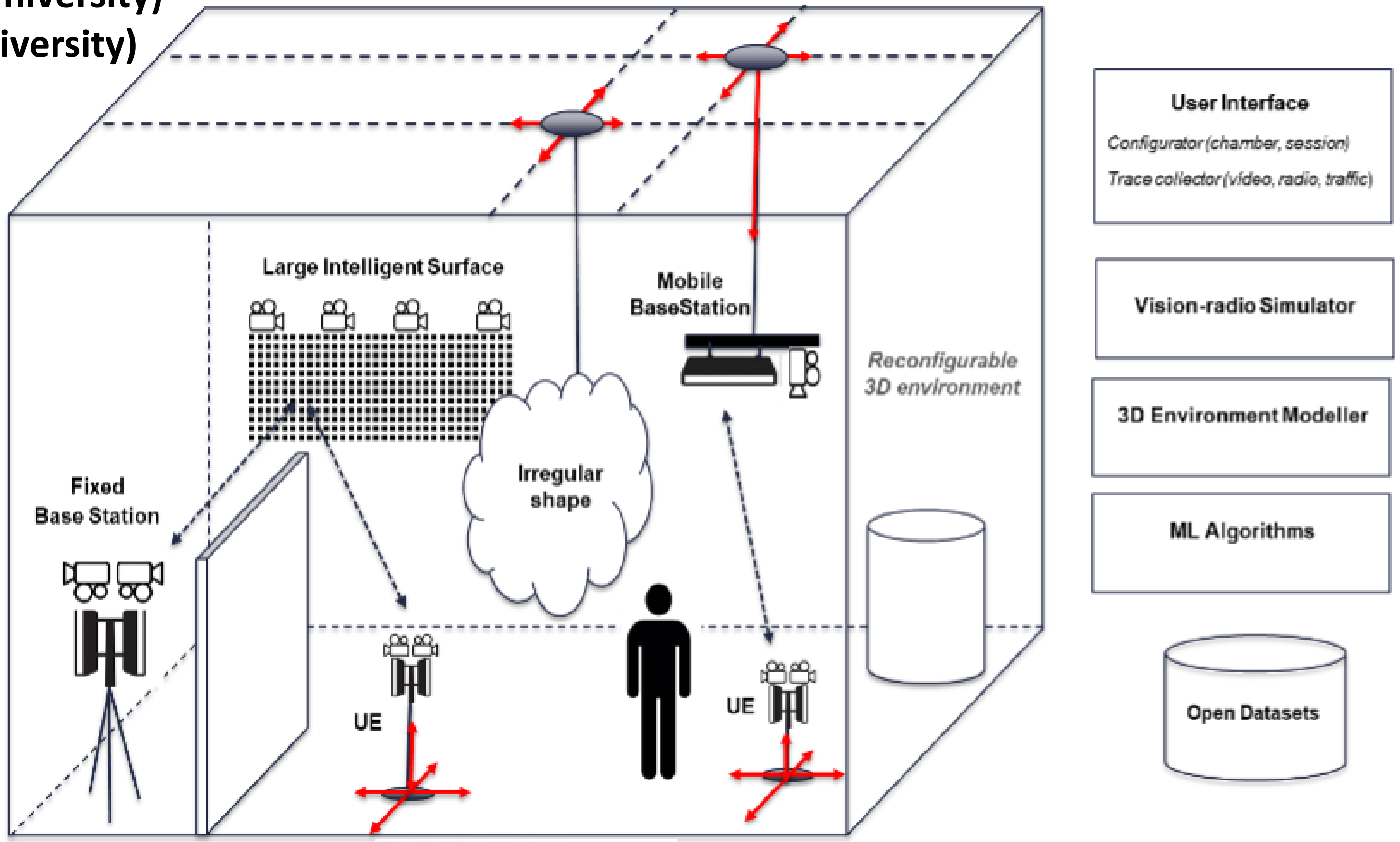
CONVERGE (2023–2026)

view-to-communicate and communicate-to-view

Telecommunications and Computer Vision Convergence Tools for Research Infrastructures

Participants from the US

- **Edward Knightly (Rice University)**
- **Ivan Seskar (Rutgers University)**



User Interface
Configurator (chamber, session)
Trace collector (video, radio, traffic)

Vision-radio Simulator

3D Environment Modeller

ML Algorithms

Open Datasets

Funded by the European Union

SuperIoT (2023–2026)

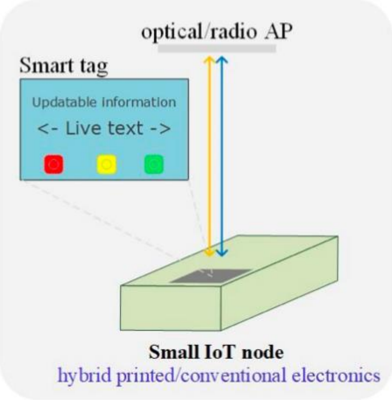
SUPERIOT

6GSNS

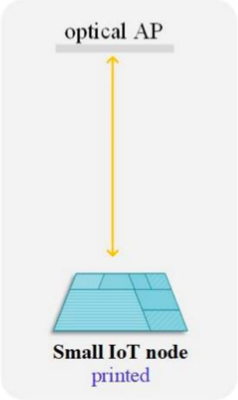
Truly Sustainable Printed Electronics-based IoT Combining Optical and Radio Wireless Technologies

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

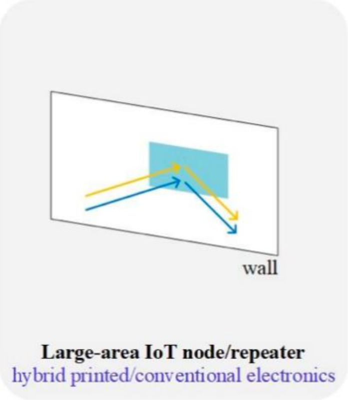
- Energy-autonomous nodes
- Reconfigurable networks
- Use of printed electronics
- Dual-mode energy harvesting and positioning



Small IoT node
hybrid printed/conventional electronics



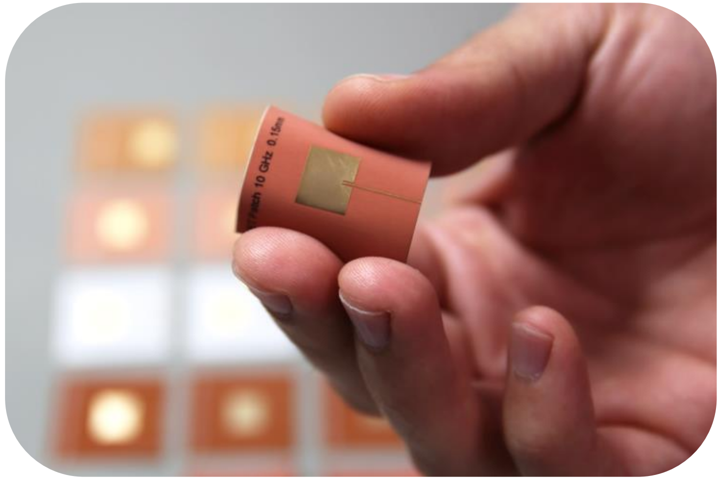
Small IoT node
printed



Large-area IoT node/repeater
hybrid printed/conventional electronics

5 M€
Funding

Coordinator:
Univ. Oulu



UNIVERSITY OF OULU
VTT
Lightbee
MPICOSYS LOW POWER INNOVATORS
wavecom
KU LEUVEN
imec
INESCTEC
NOVA SCHOOL OF SCIENCE & TECHNOLOGY
WWWD COMPONENTS
University of BRISTOL

https://superiot.eu/

Co-funded by the European Union
6GSNS

Thank you!

Questions?

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