Université de Strasbourg

ICUBE

Seminar Wireless AI Lab
Pusan National University

Title: **Digital Twins for Self-configurable Wireless Networks**

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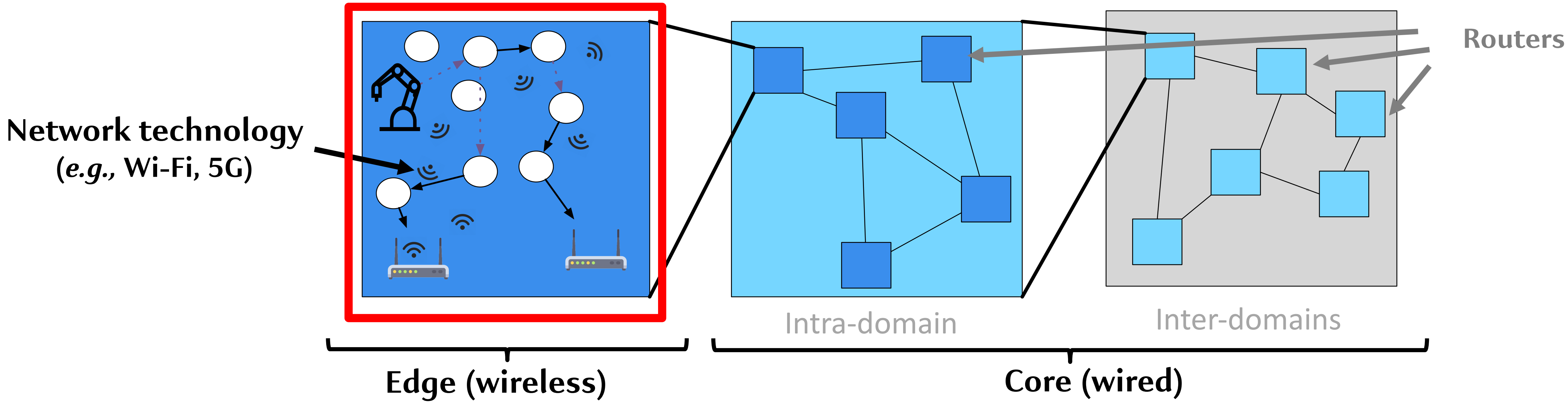
October 22, 2025

Context

❖ Two types of networks: **Edge** networks and **Core** networks



- **Objectives:** More **efficient**, more **reliable** and **less costly** communications
  - Energy, financial cost, radio spectrum, etc.
- **Scientific Challenges:**
  - Shared radio spectrum and not reliable (interferences…)
  - Dynamic environment (nodes' mobility, traffic…)

  ➔ **Constant need for adaptation**
- **Research Question:** How to efficiently configure a network technology according to the environment?

Academic Background + Contributions

2015 – 2020 — **Engineer + Masters in Computer Science** (École Nationale Supérieure d'Informatique)

January – June 2020 — **Research Internship** (EURECOM Sophia Antipolis)
Topic: Deployment of Drones on 5G Networks

2020 – 2023 — **PhD in Computer Science (10/2023)** (ENS de Lyon)
Topics:
- Network Technologies Optimization
- Network Simulators Calibration

June – August 2023 — **Visiting Scholar** (University of Waterloo)
Topic: Localization in 5G

2023 – 2025 — **Postdoc** (Université de Strasbourg)
Topic: Digital Twins for Wireless Networks

September 2025 – — **Associate Professor** (Université de Lorraine)

Network Configuration Optimization

- **Issue:**
  - How to obtain an optimized configuration for a given scenario?
    - Combinatorial explosion of parameters
      - > 20,000 configurations for 802.15.4 technology
    - Considerable impact on performances
      - Example: Spreading Factor in LoRa
        - SF=7 → Lifetime: 10 years / Range: 100 m
        - SF=12 → Lifetime: 1 year / Range: 10,000 m

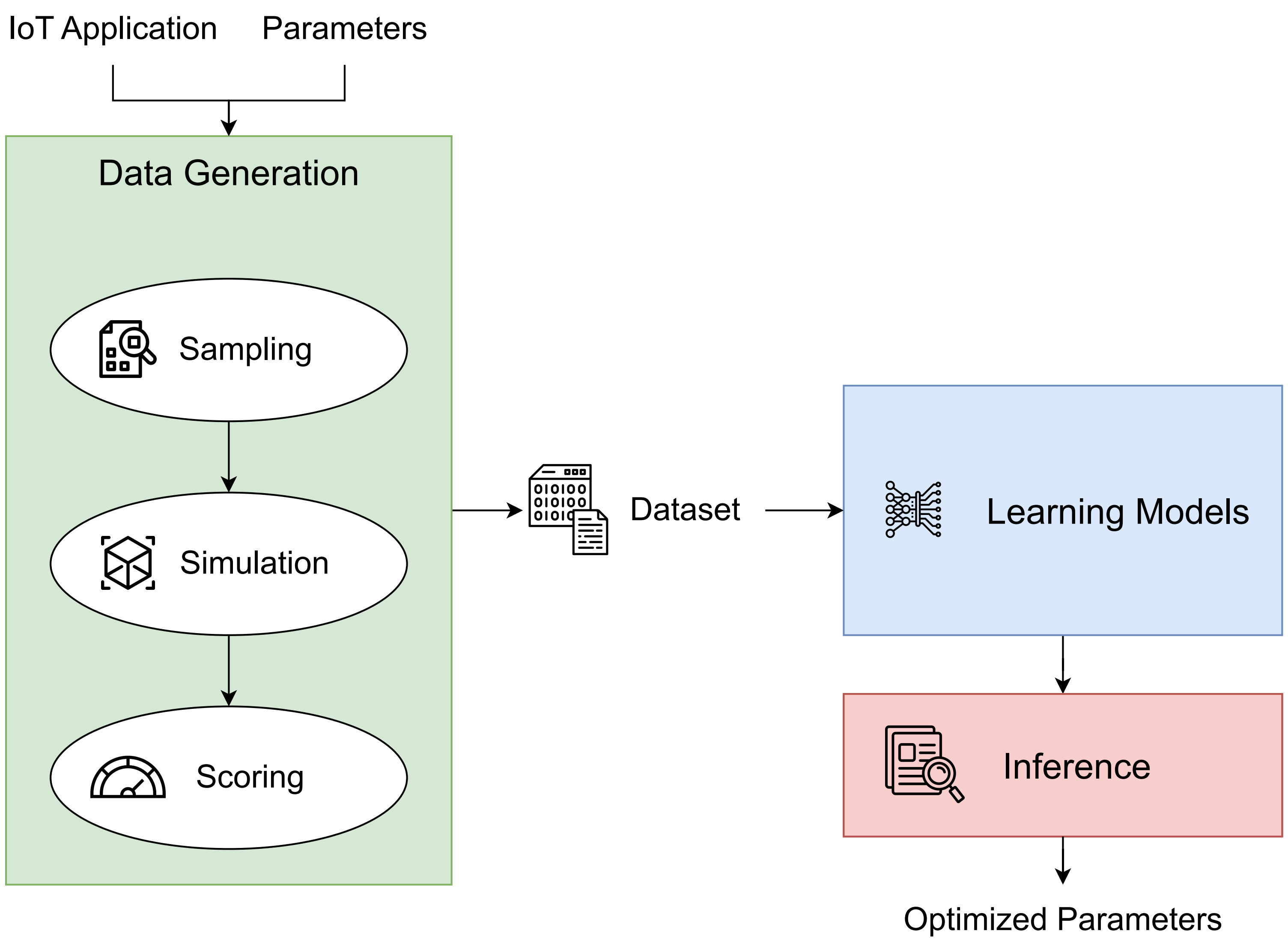
- **Scientific Locks:**
  - Practical impossibility of comprehensive search
  - Dependence to the network technology

Network Configuration Optimization

❖ **Contribution: Surrogate Model**

❖ **Functioning:**

1. Configurations Space Sampling
2. Use of Machine Learning models (Regression)
3. Inference on the comprehensive set of Configurations



Near-optimal configuration for 802.15.4 technology, with a 60-fold reduction in execution time compared to a comprehensive search

- **Si-Mohammed** et al. "NS+NDT: Smart Integration of Network Simulation in Network Digital Twin, Application to IoT Networks", in Elsevier Future Generation Computer Systems, March 2024.

Network Simulators Calibration

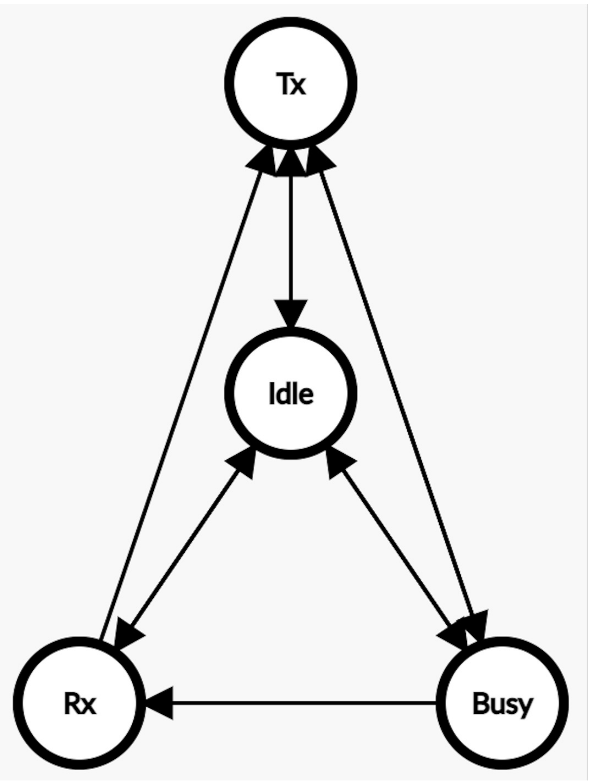
❖ **Issue:**

- Simulation is extremely used in networks
  - Example: Approx. as many IoT articles using ns-3 than FIT IoT-Lab in 2021 [1]

- How to calibrate the energy consumption models?
  - Networks simulator's reliability
  - Example: Energy consumption if crucial in IoT networks

❖ **Scientific Lock:**

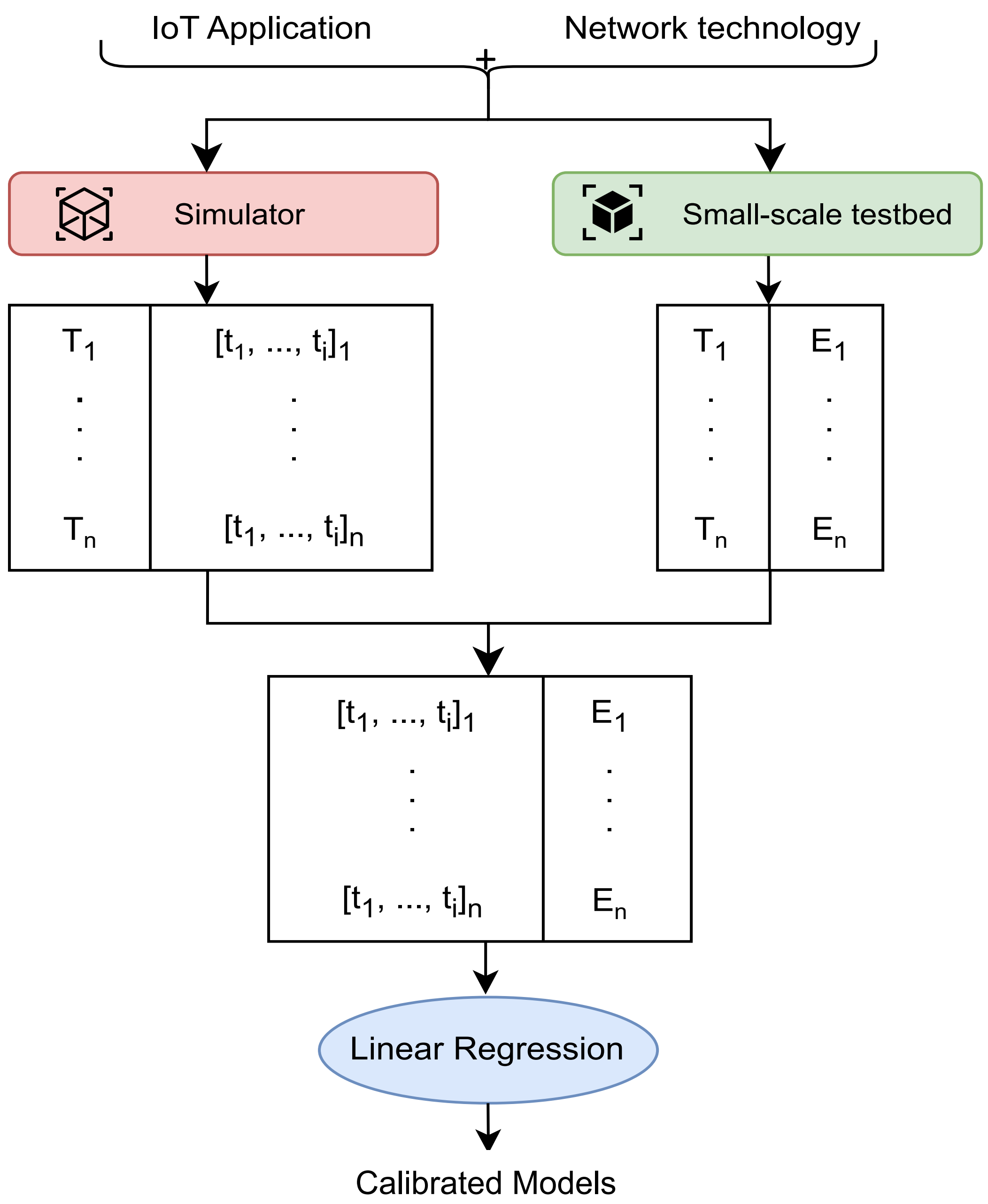
- Discrepancy between experimentation and simulation in terms of time spent in each state



[1] Singh, A., Nandanwar, H., & Chauhan, A. (2022, September). Simulation Tools and Testbeds for Internet of Things (IoT):“Comparative Insight”. In 2022 Second International Conference on Computer Science, Engineering and Applications (ICCSEA) (pp. 1-7). IEEE.

Network Simulators Calibration

❖ **Contribution:** Hybrid method combining **simulation** and **experimentation**



❖ **Functioning :**

1. For identical time windows:
   - Keep track of the times spent in each physical state in the simulator
   - Compute the consumed energy in the experimental platform
2. Merge the two datasets
3. Apply a linear regression to calibrate the energy consumption models

10-fold difference between simulation and experimentation compared with default models

- **Si-Mohammed** et al. "NS+NDT: Smart Integration of Network Simulation in Network Digital Twin, Application to IoT Networks", in Elsevier Future Generation Computer Systems, March 2024.

Research Project

❖ **Digital Twins (DT):** Approach aimed at reproducing the behavior of a system [2] :

- **Physics-based**,
- **Data-driven**.

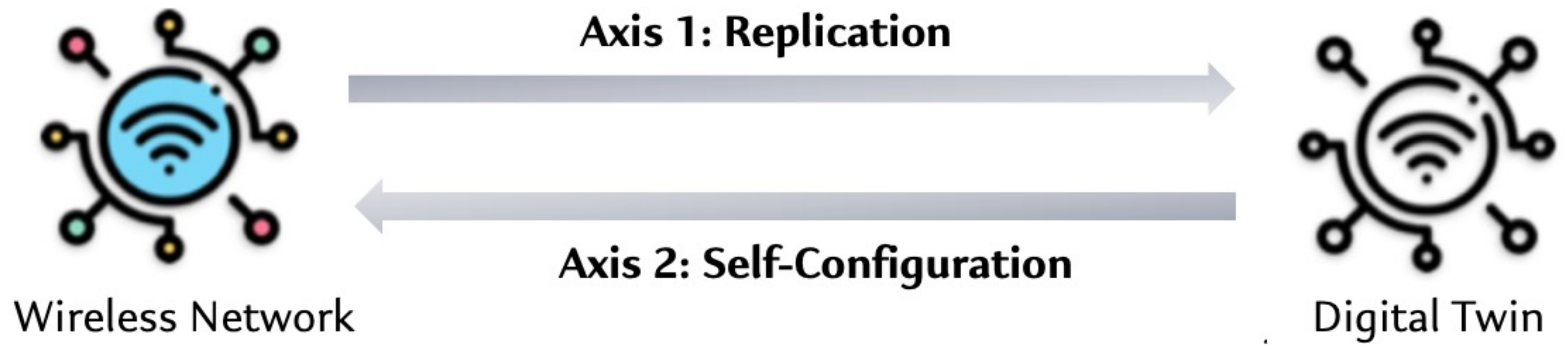
➢ In a networking context (NDT):

- **Detecting** changes in the environment
- **Testing configurations** before the deployment

➔ **Tradeoff between models accuracy and complexity**

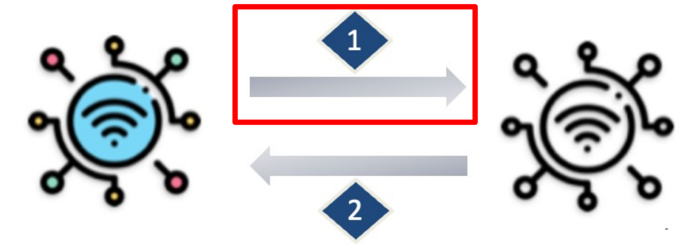
- **Objectives:**
  - Design algorithms/mechanisms to develop an **efficient**, **accurate** and **low-cost** digital twin
  - Allow the **self-configuration** of a wireless network using the digital twin

Approach:



[2] Rasheed, A., San, O., & Kvamsdal, T. Digital twin: Values, challenges and enablers from a modeling perspective. IEEE Access (2020).

Research Project

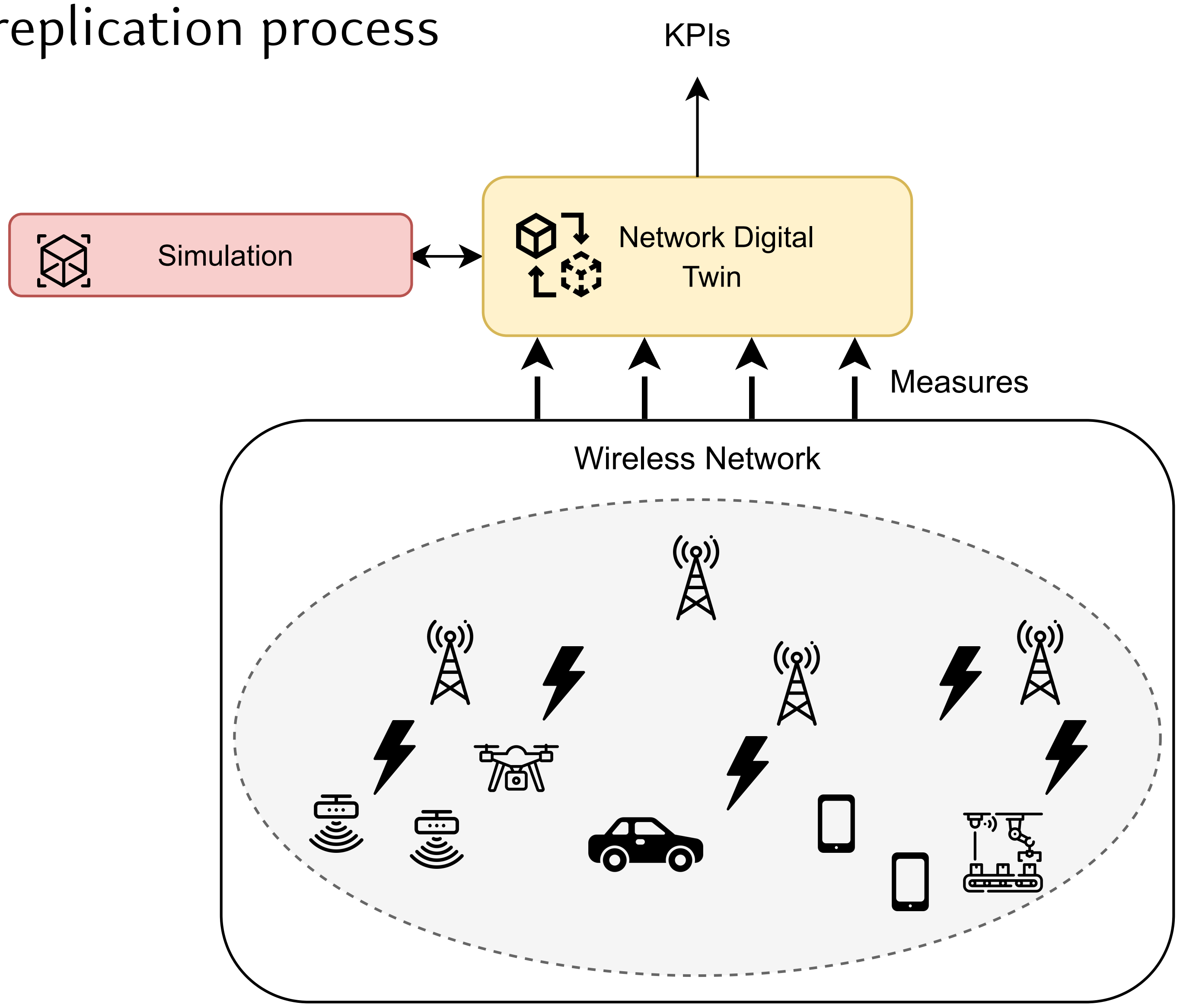


1 Axis 1: Replicating wireless network using digital twins

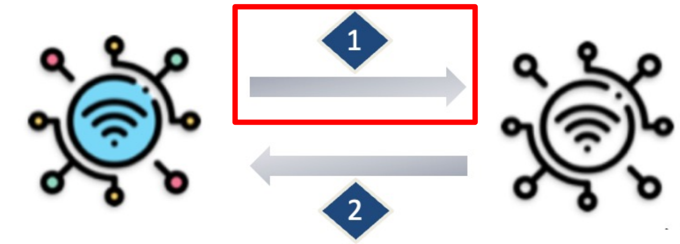
❖ **Objective:** Efficiency and Reliability of the replication process

❖ **Issue:**
- ➢ How to develop in an **inexpensive** way models able to:
  - ➢ **Reproduce** the performances of a wireless network?
  - ➢ **Predict** its future performances?

❖ **Scientific Lock:**
- **Complexity** and **inaccuracy** of physics-based models:
  - Ray-tracing precise but costly
  - Log Distance or Rayleigh too simple

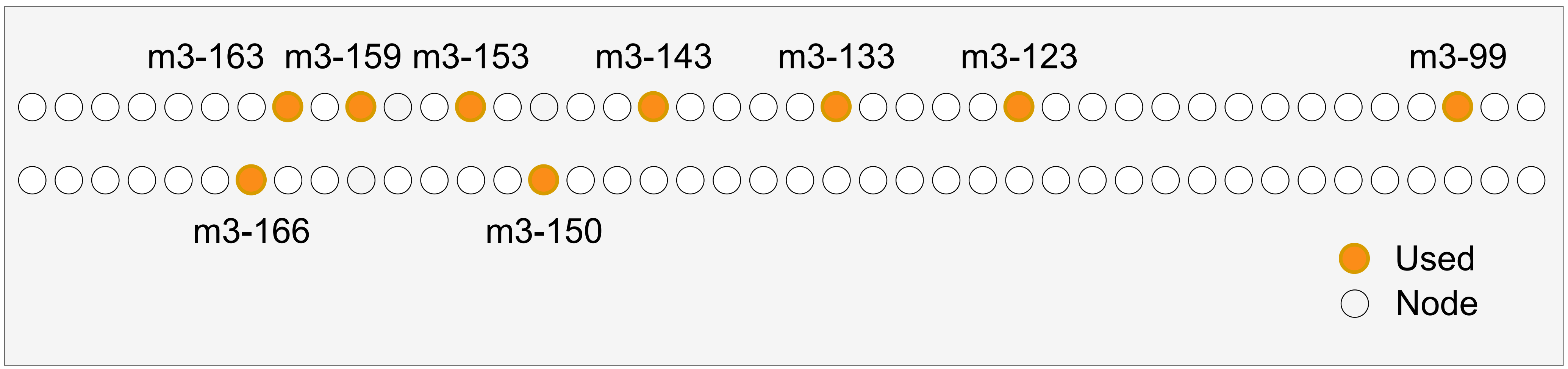


Deployment Example



❖ Case Study:

- Industrial deployment on the experimental platform FIT IoT-Lab [3]
  - **Smart metering in an indoor environment**

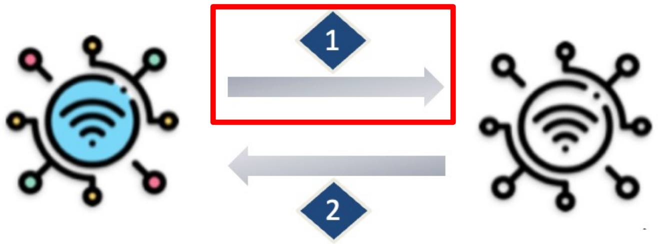


- 9 nodes on the Grenoble site, 24 hours deployment
- Communication technology: 802.15.4 (Zigbee), on Contiki-NG
- Trafic: Broadcast, periodic (1 packet/s)

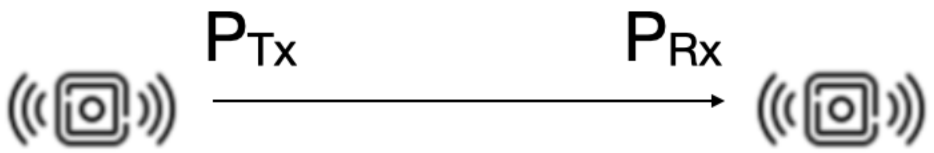
- **Objective: Reproduce and predict the evolution of the PDR (Packet Delivery Ratio)**

[3] Adjih, Cedric, et al. "FIT IoT-LAB: A large scale open experimental IoT testbed." 2015 IEEE 2nd World Forum on Internet of Things (WF-IoT). IEEE, 2015.

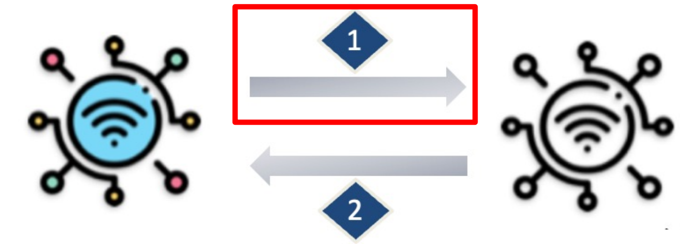
Research Issue



❖ **Compare between the PDR evolution:**
- From real measures
- From the Cooja simulator [4] :
  - Calibrated with an average PDR value per link (fixed)



[4] Osterlind, Fredrik, et al. "Cross-level sensor network simulation with cooja." Proceedings. 2006 31st IEEE conference on local computer networks. IEEE, 2006.



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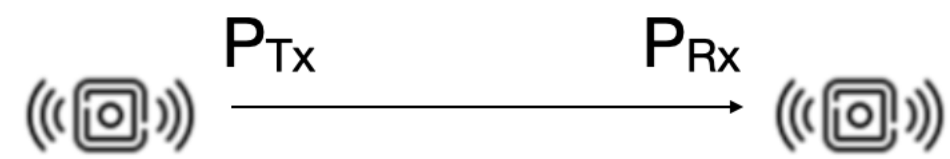
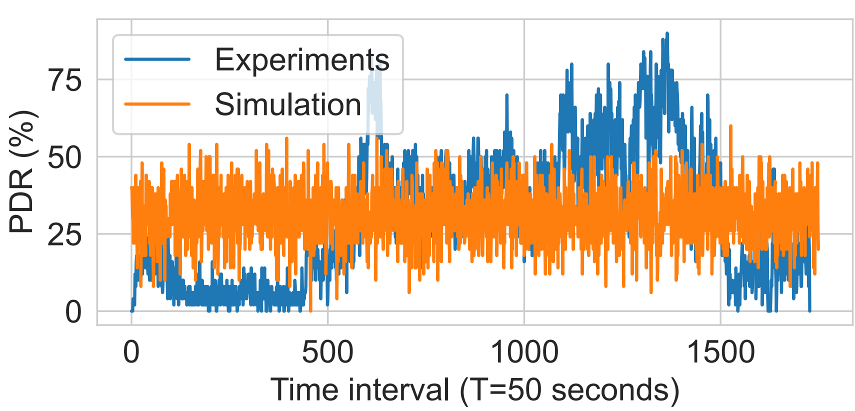


link m3-133_m3-153



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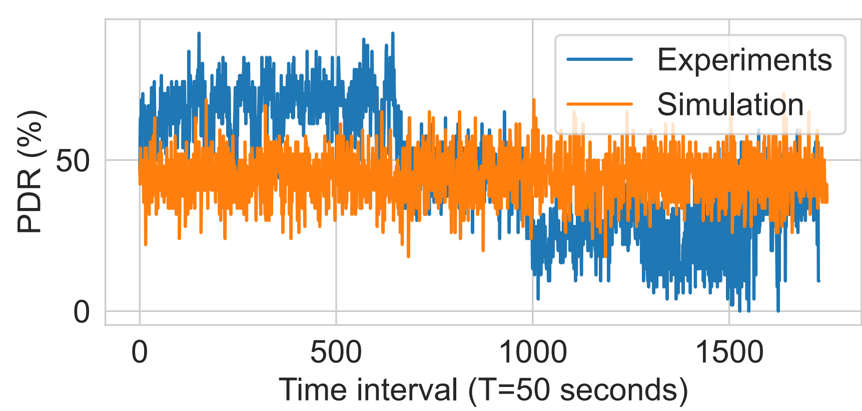
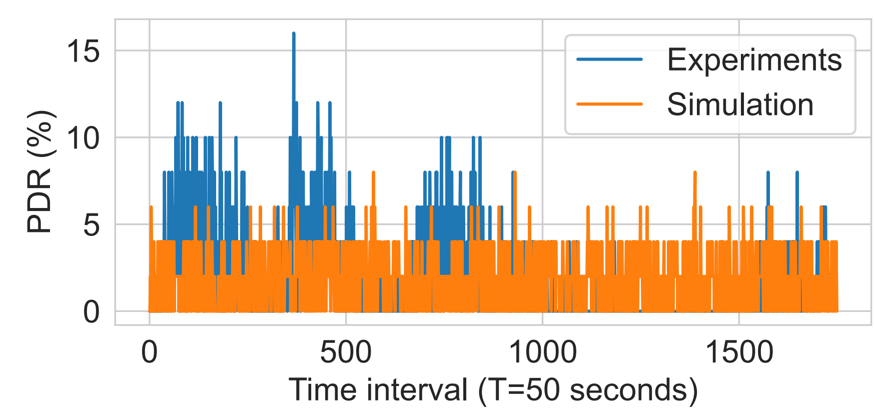
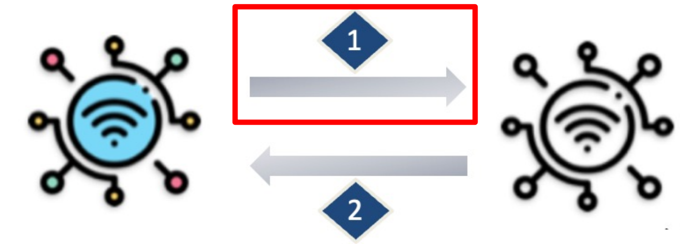


link m3-166_m3-163



[4] Osterlind, Fredrik, et al. "Cross-level sensor network simulation with cooja." Proceedings. 2006 31st IEEE conference on local computer networks. IEEE, 2006.

Research Issue



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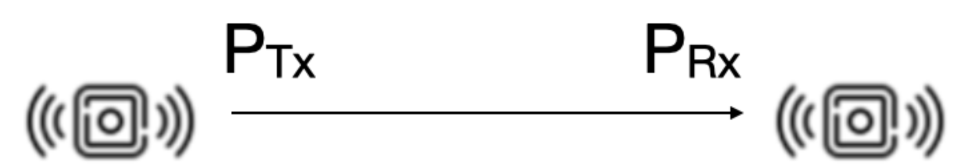
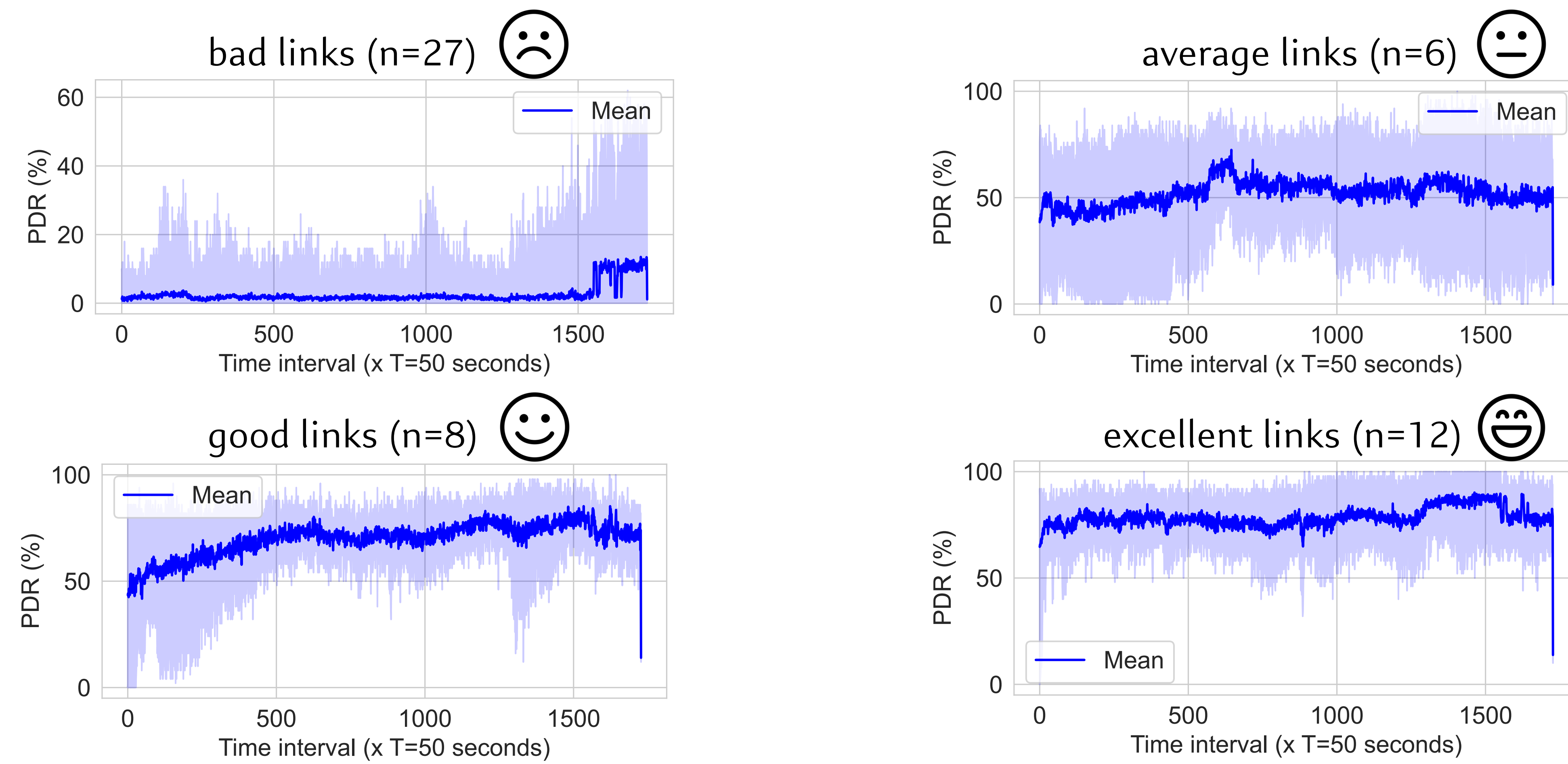
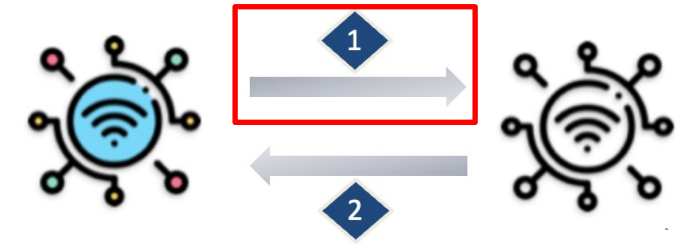


❖ **Classification according to the mean PDR: 0% - 20% - 60% - 75% - 100%**



[4] Osterlind, Fredrik, et al. "Cross-level sensor network simulation with cooja." Proceedings. 2006 31st IEEE conference on local computer networks. IEEE, 2006.

Proposed Solution



1 Axis 1: Replicating wireless network using digital twins

❖ **Approach:**

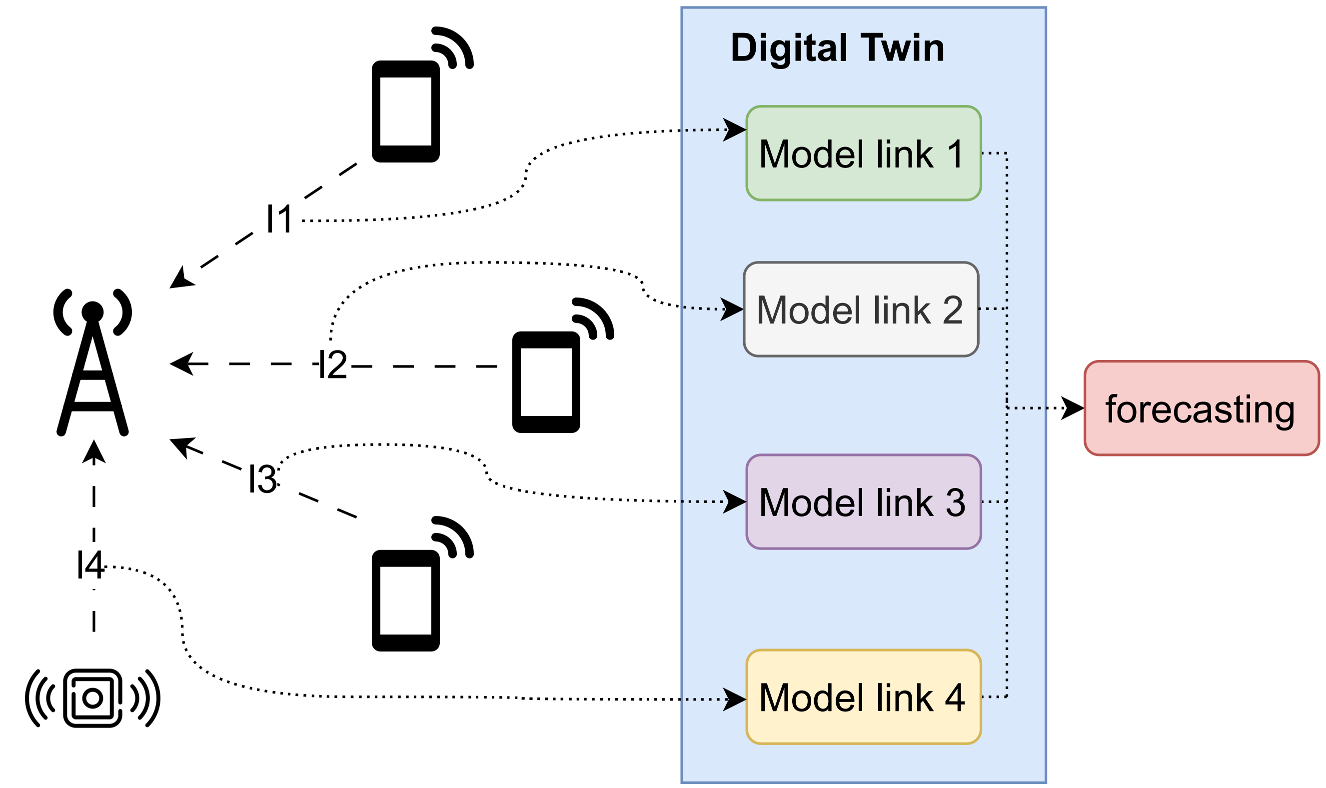
1. Replace the **physical layer** simulation by measures time series
2. **Separately** model each radio link

❖ **Interest:**

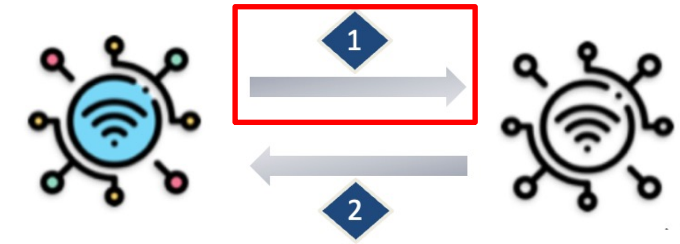
- Flexibility (compared to [5,6])
- Temporality (compared to [7])
  - Anomaly Detection

❖ **Scientific Challenges:**

- Type/Granularity/Cost of measures
- Learning Models
  - LSTM, ARIMA, etc.

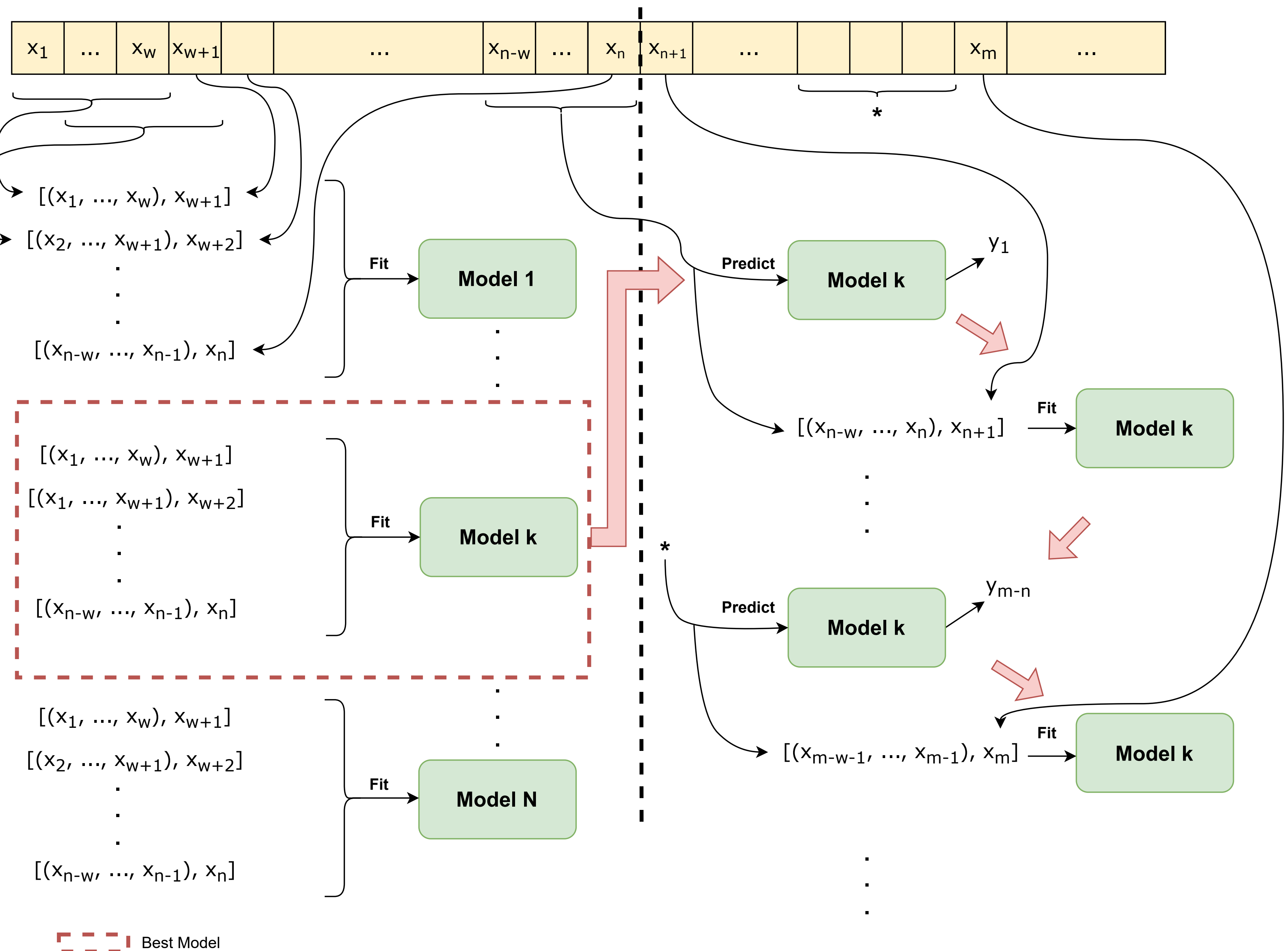


[5] Benadji, H., Zitoune, L., & Vèque, V. (2023). Predictive Modeling of Loss Ratio for Congestion Control in IoT Networks Using Deep Learning. In the IEEE GLOBECOM 2023.
[6] Rusek, K., et al., A. (2020). Routenet: Leveraging graph neural networks for network modeling and optimization in sdn. IEEE Journal on Selected Areas in Communications.
[7] Almeida, E. N., Rushad et al., M. P. (2022, June). Machine Learning Based Propagation Loss Module for Enabling Digital Twins of Wireless Networks in ns-3. In 2022 Workshop on ns-3.



Proposed Solution – One step

- **Fixed Model:** For each model:
  - Split between Training and Testing data
  - Create sliding windows for the regression
  - Select the best model to use for predictions



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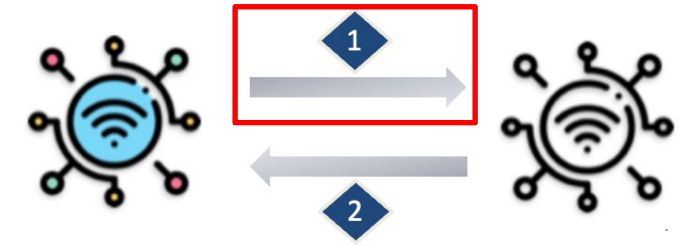
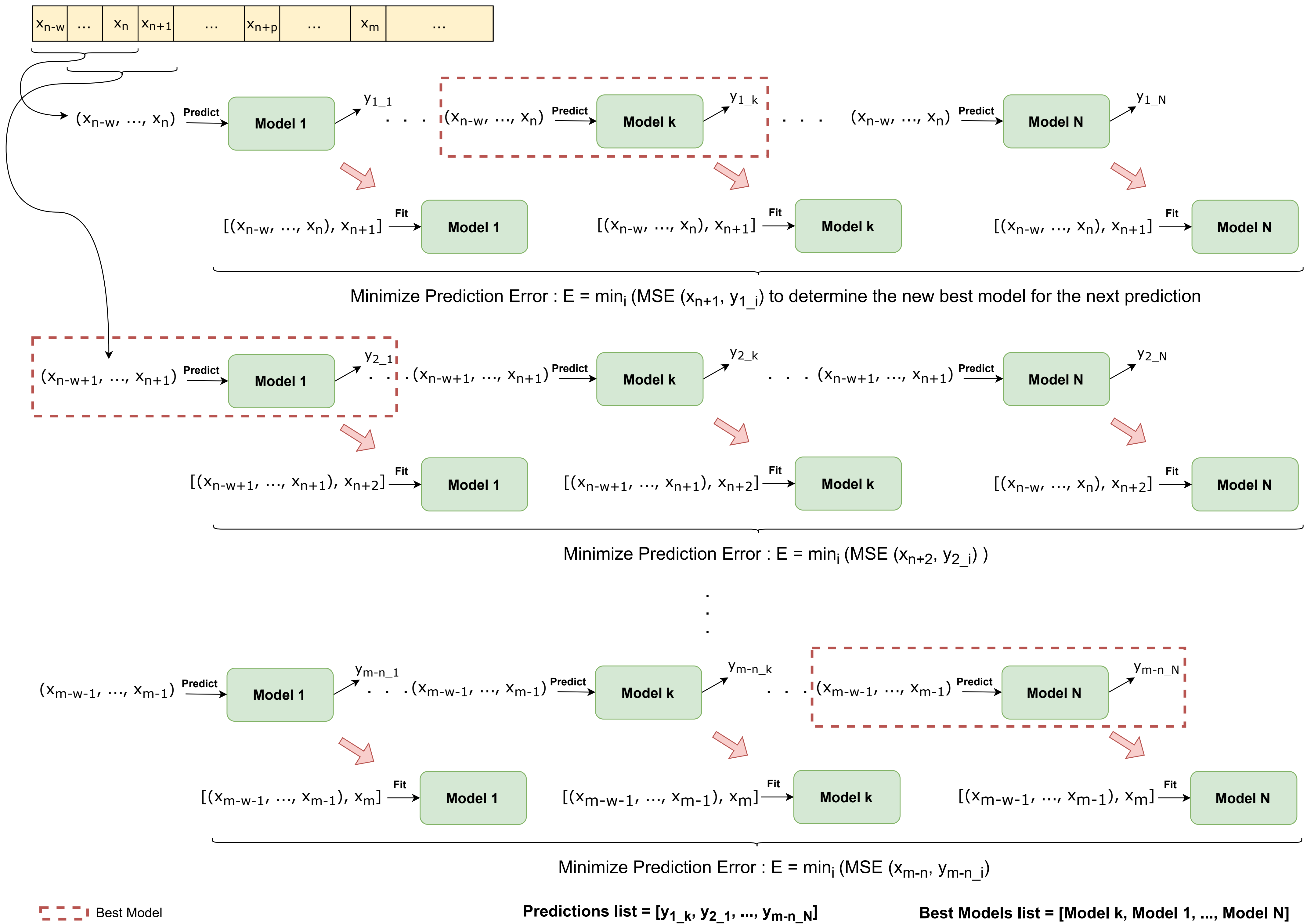
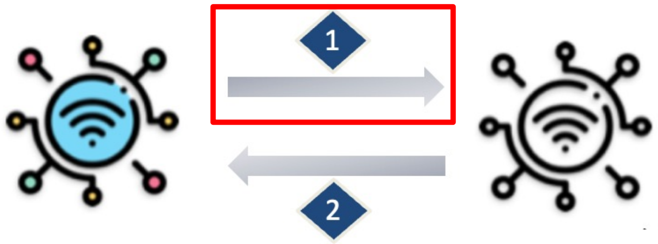


❖ Adaptive Approach

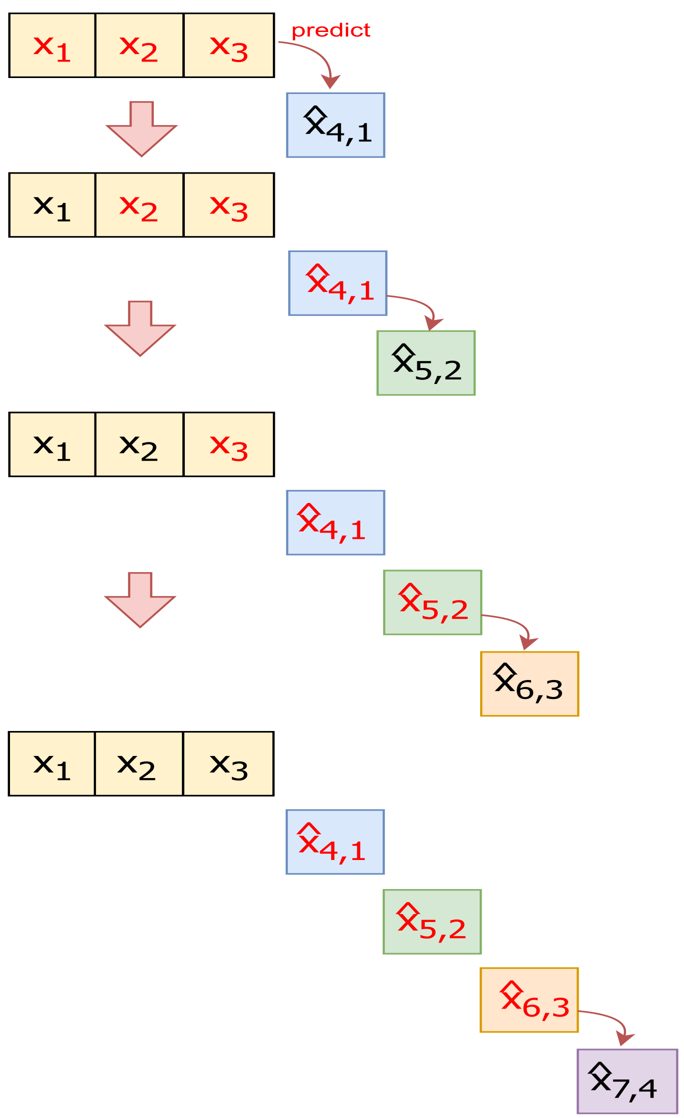


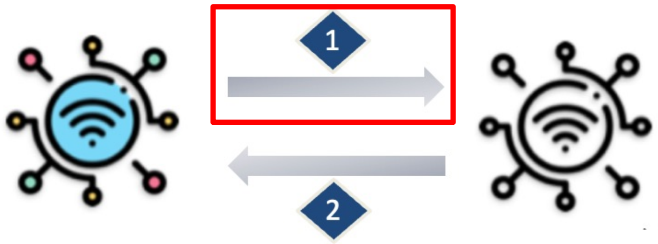


Proposed Solution – Multi-step

❖ **Multi-step prediction:**

- Distinguish between the steps predictions for the evaluation





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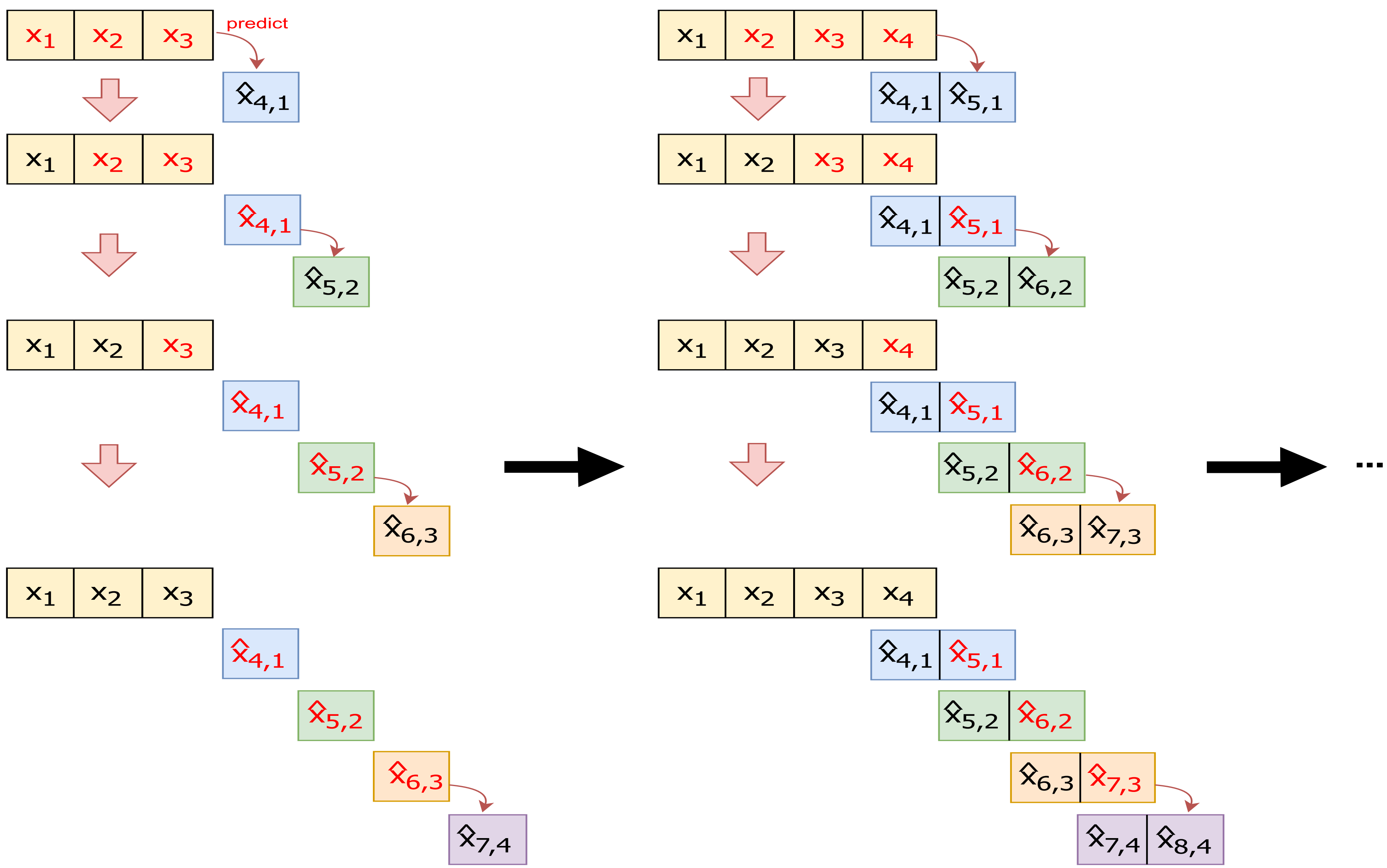
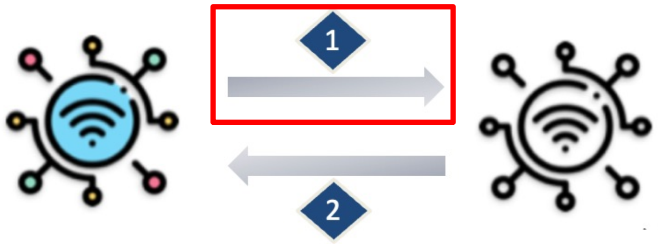
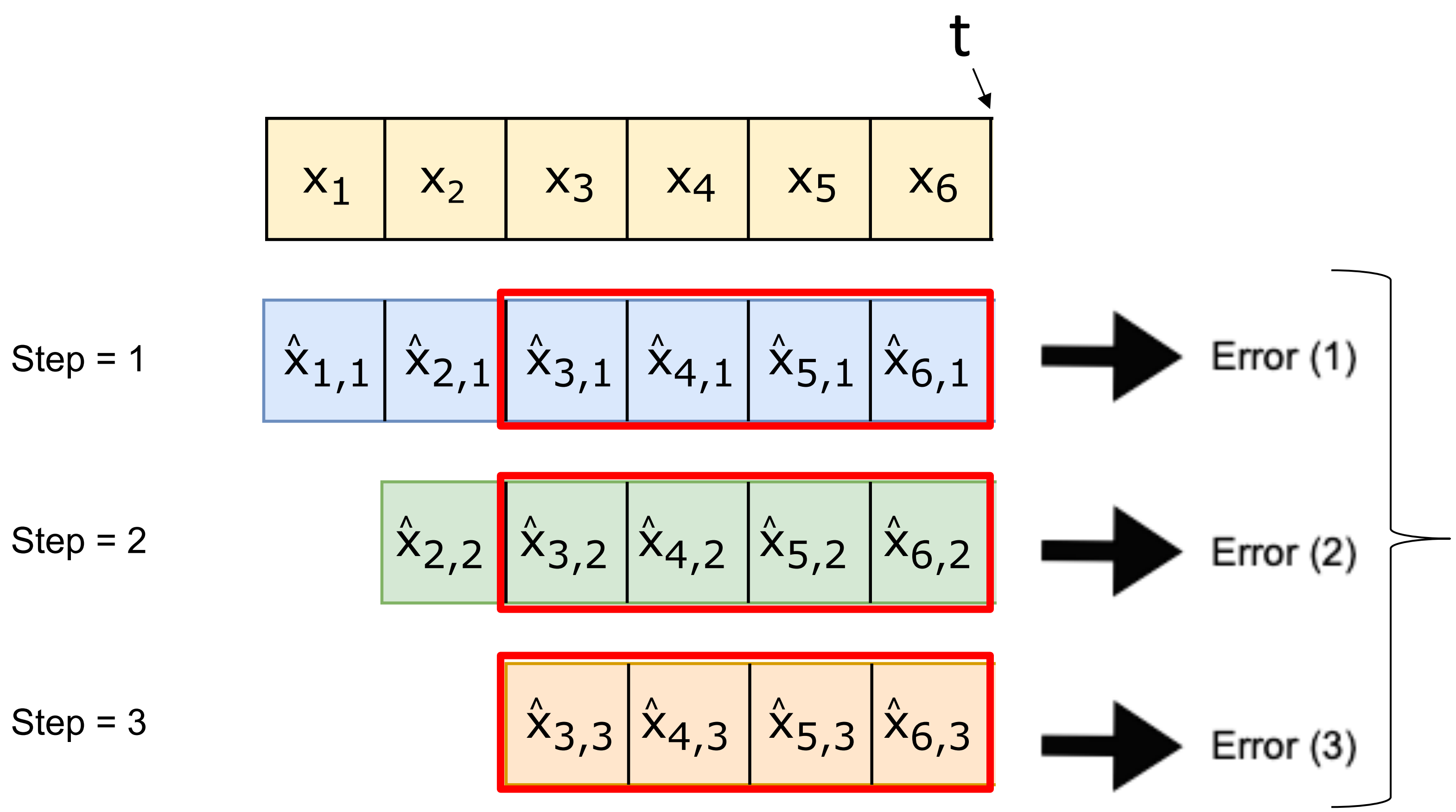




Proposed Solution – Multi-step

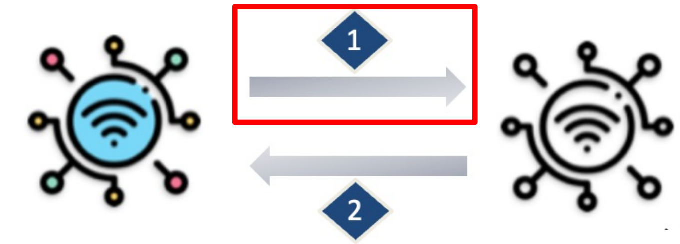
❖ **Error computing for the Adaptive approach:**

- At each interval, compute the error for the last *q (e.g., q*=4) predictions, according to the different steps errors of each model:



$\text{Error}_{\text{model}} = \sum_{i=1}^{i=p} Error^2\ (i)$

❖ **Choose Best Model** = $\boldsymbol{argmin\ (Error_{model})}$ for the next prediction



Results

❖ **Adaptive approach with one step ahead (p=1)**

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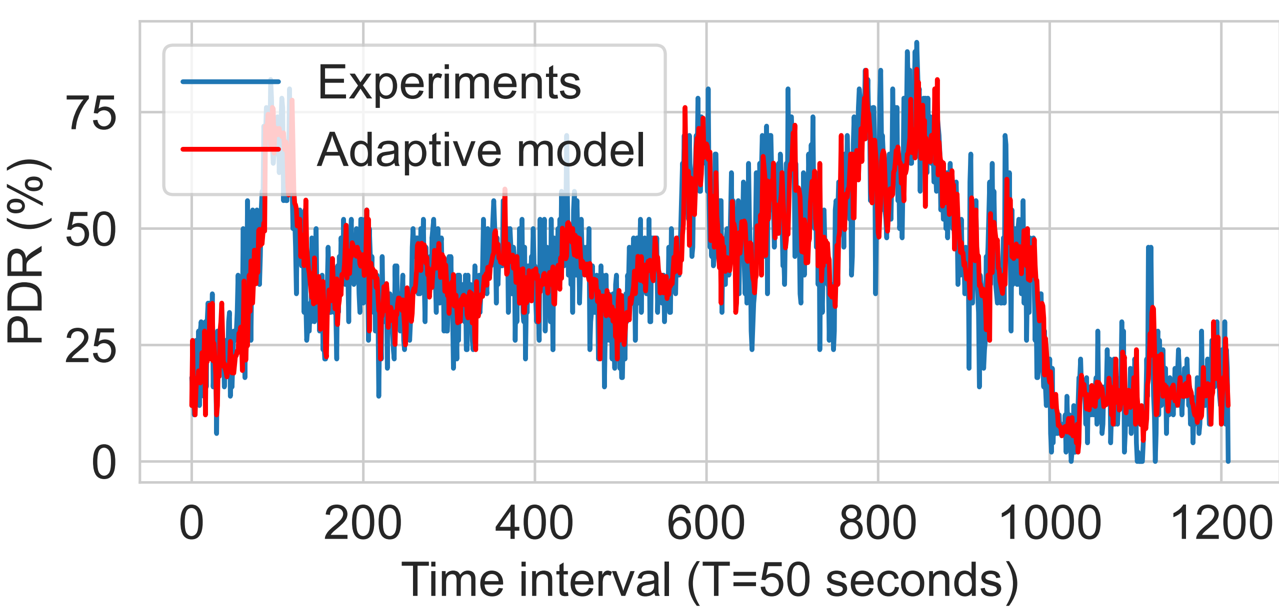

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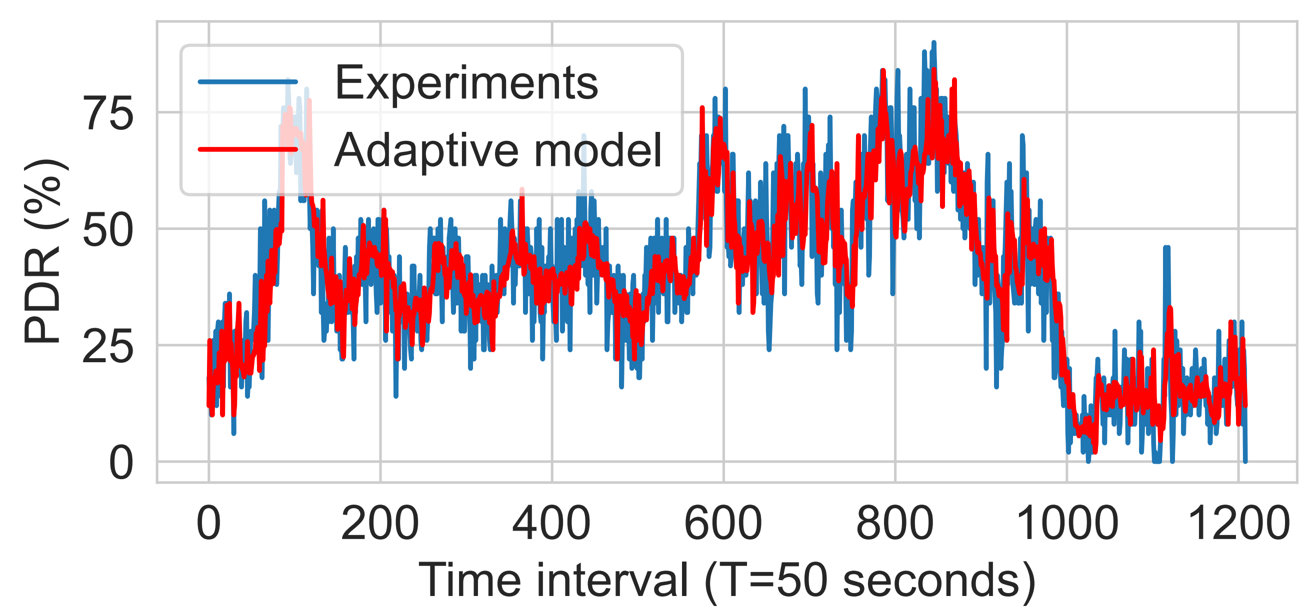

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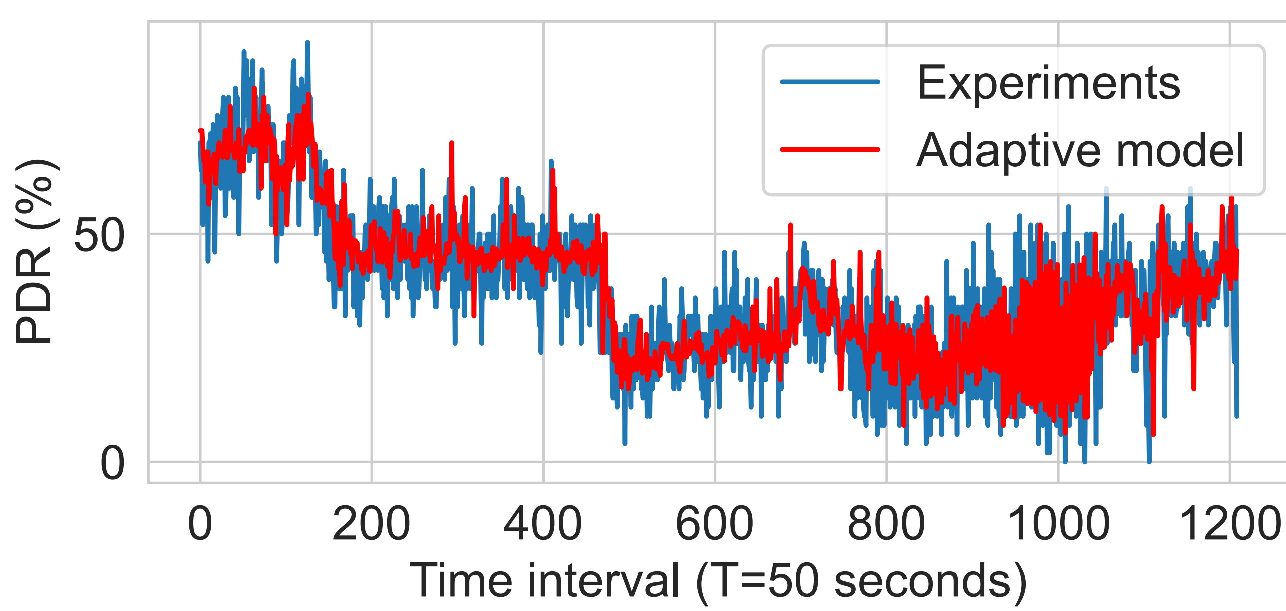
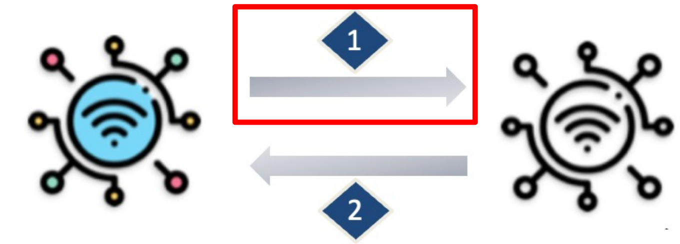
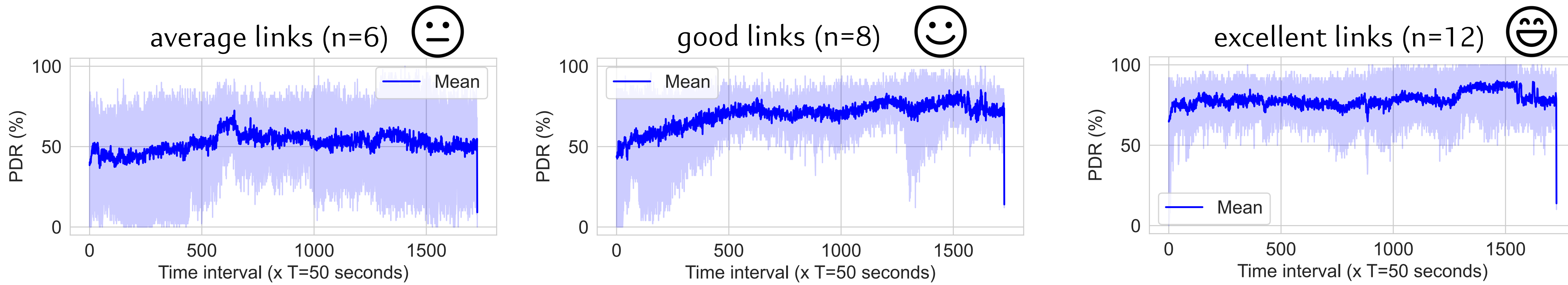
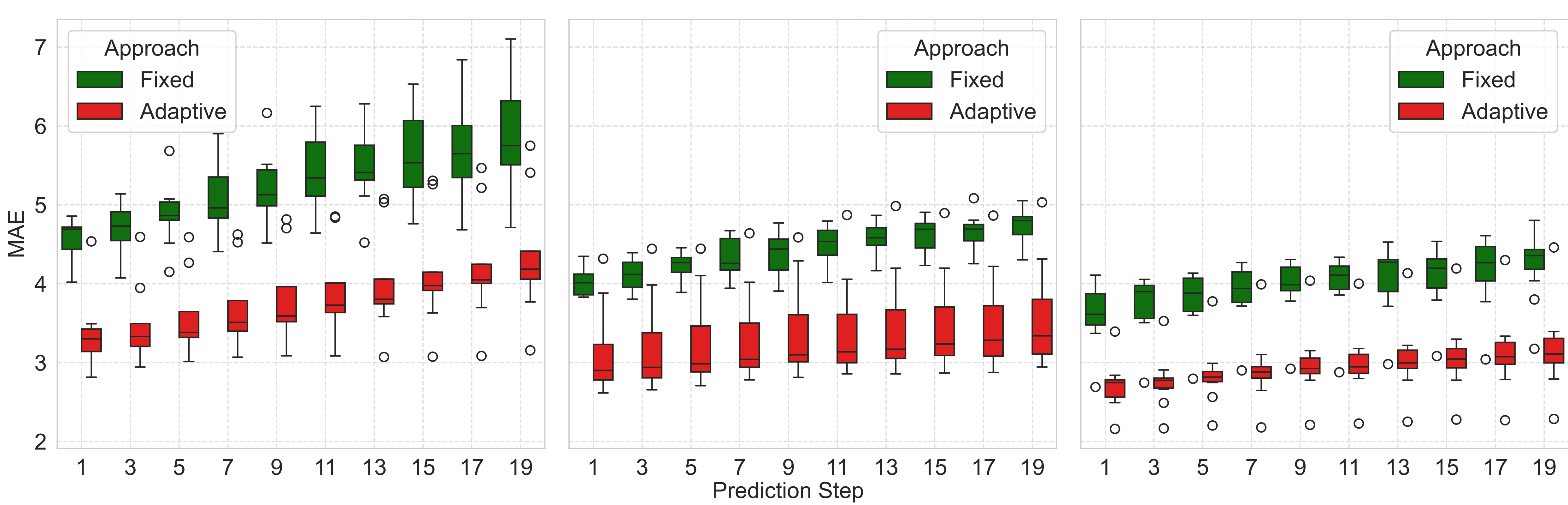


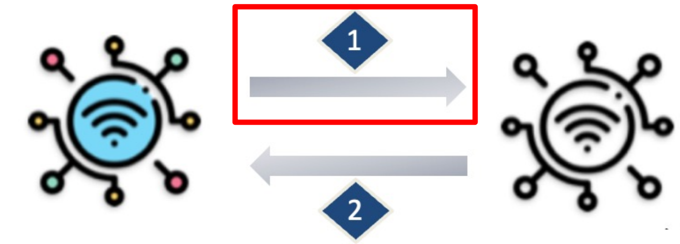
Results

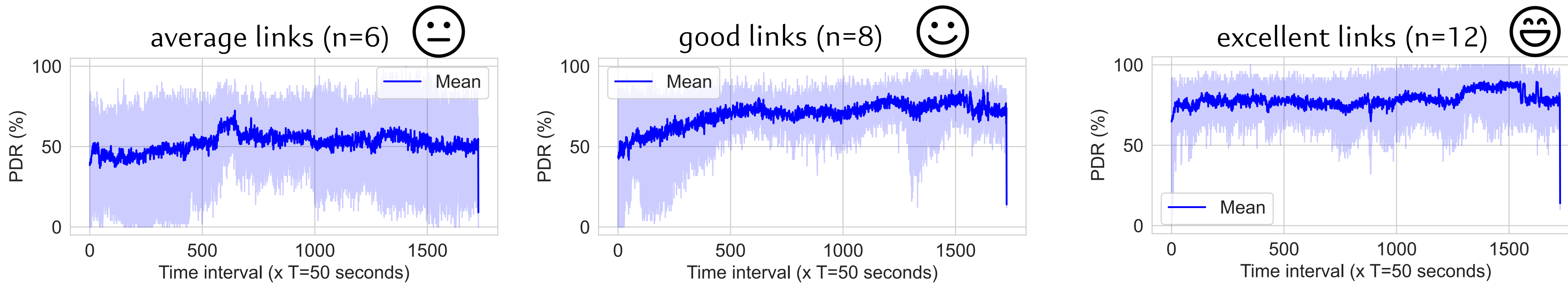

1
2

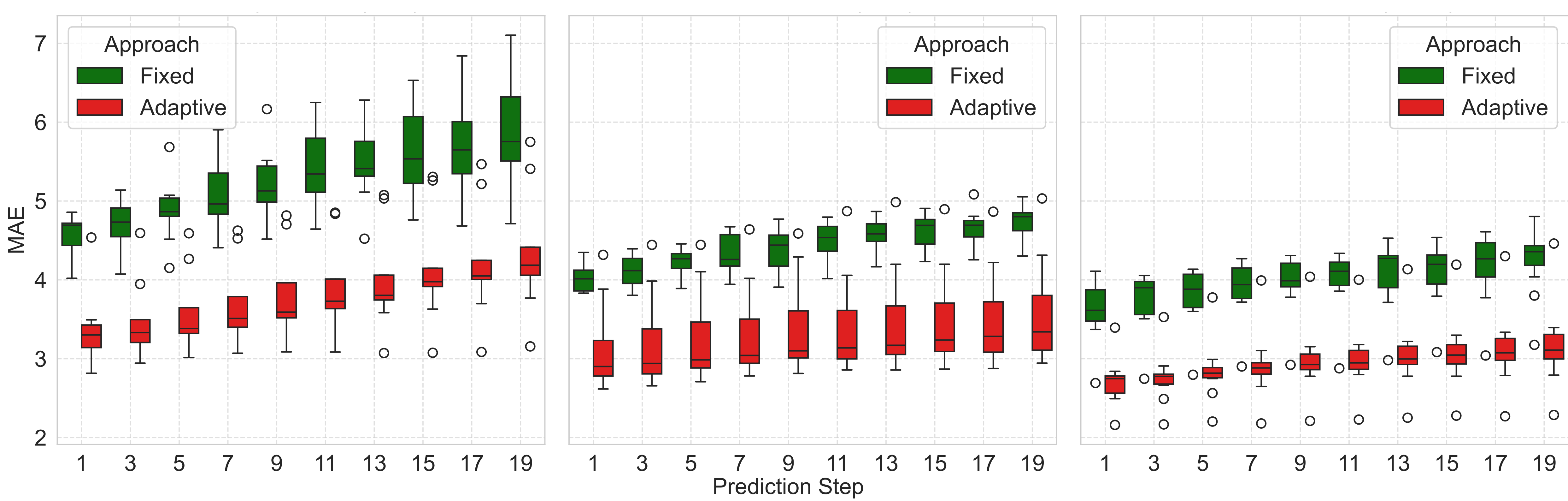

average links (n=6)
good links (n=8)
excellent links (n=12)
PDR (%)
Mean
Time interval (x T=50 seconds)


MAE
Approach
Fixed
Adaptive
Prediction Step

Results

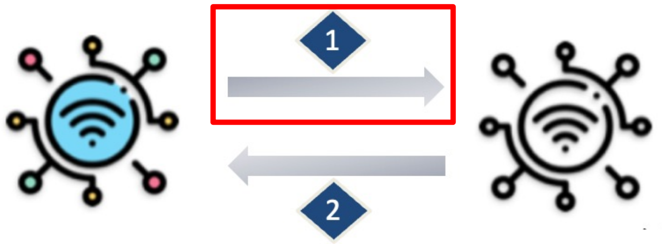


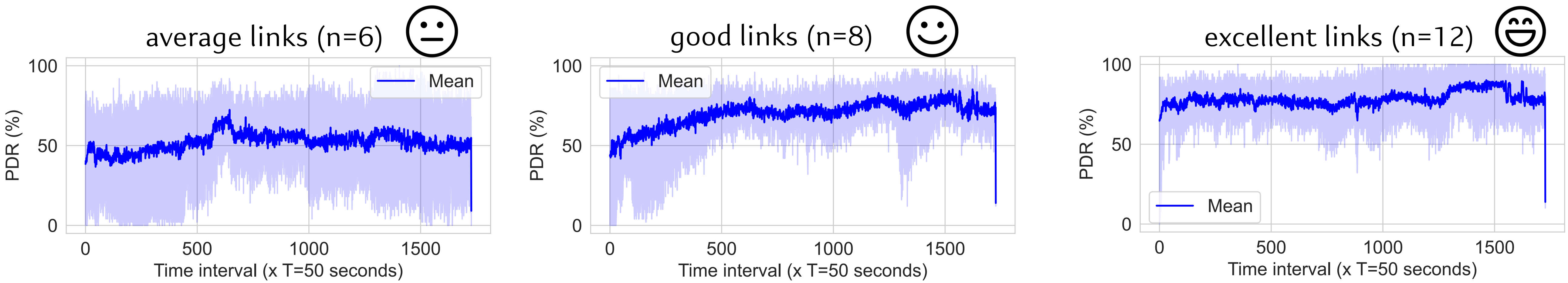


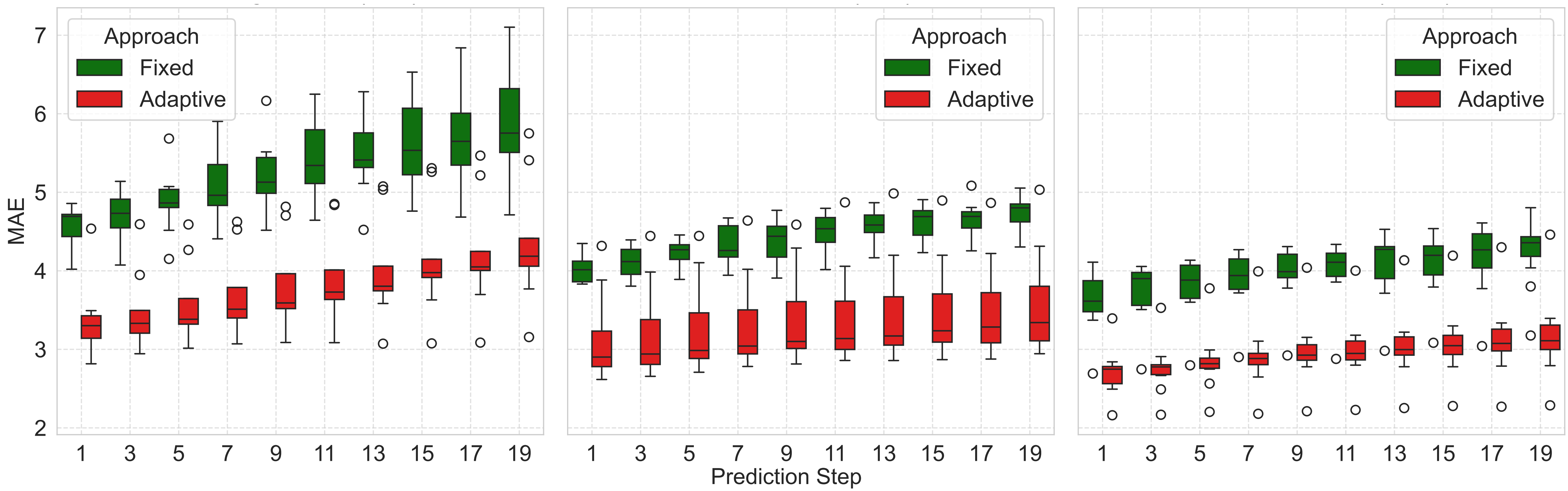


➔ **The adaptive approach always outperforms the fixed one**

Results

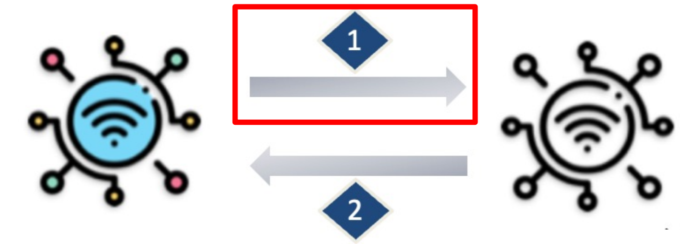


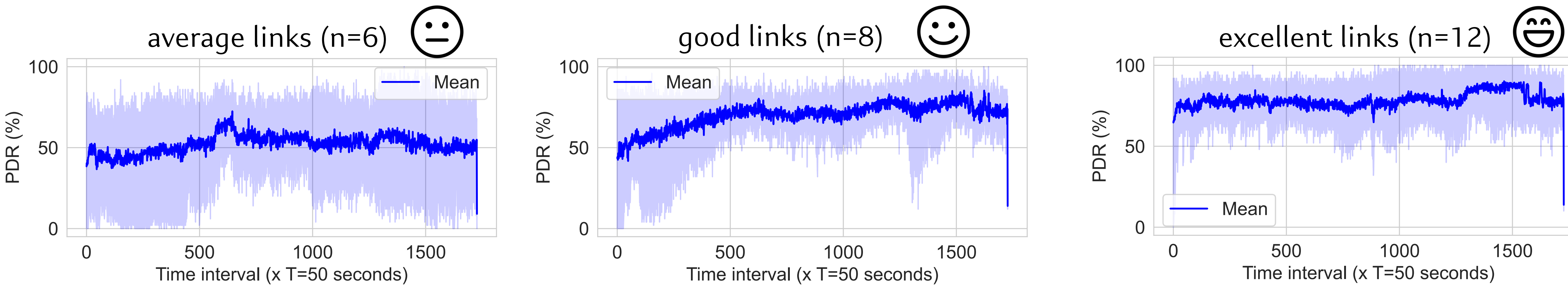


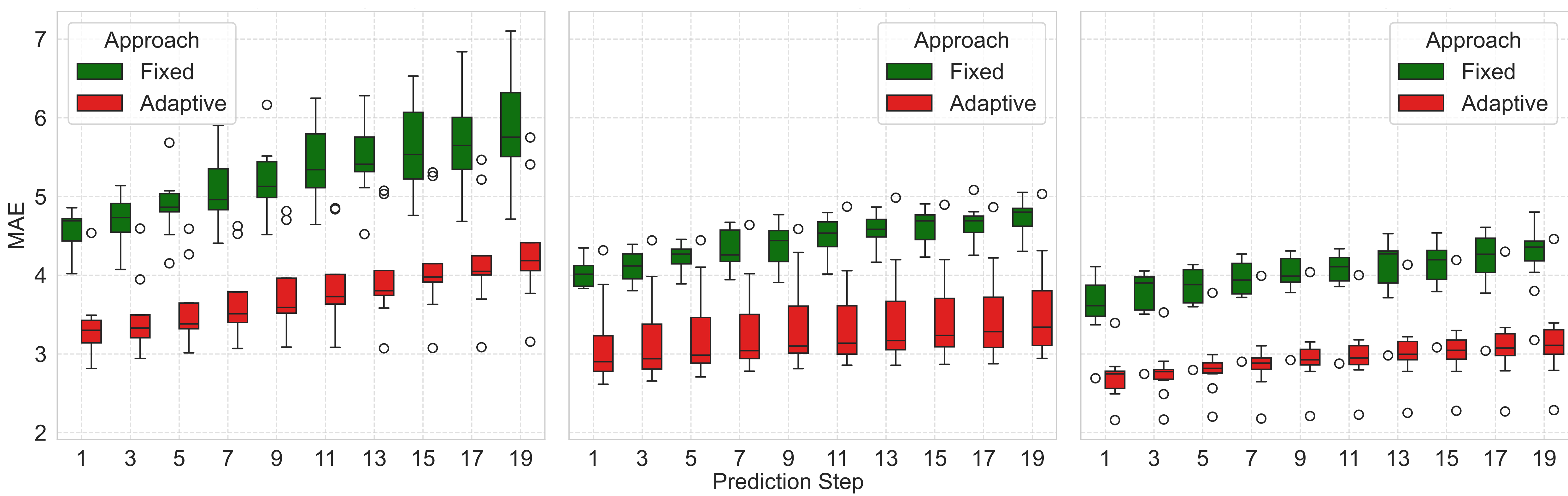


- ➔ **The adaptive approach always outperforms the fixed one**
- ➔ **Low prediction errors for short/mid term, with a linear increasing**

Results

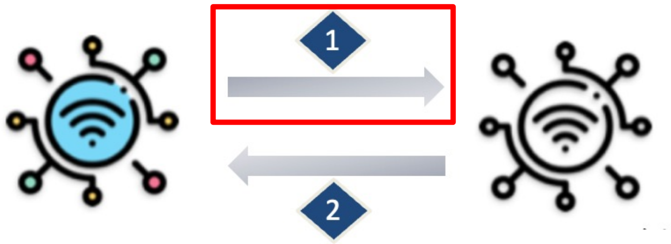






- ➔ **The adaptive approach always outperforms the fixed one**
- ➔ **Low prediction errors for short/mid term, with a linear increasing**
- ➔ **Better predictions for stable links**

Limits and Perspectives



- **Scalability Study**
  - Example: Deployment with more than 100 nodes

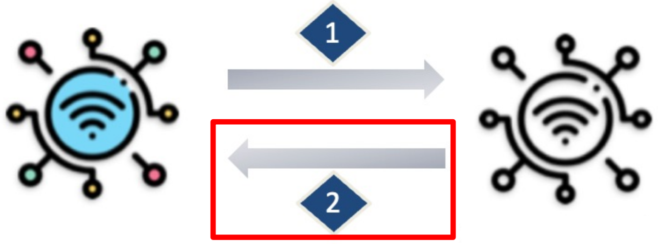
  ➔ Solution: Clusterize the links, one model per cluster

- **Metrology with a dynamic traffic**
  - Active vs. passive measures, frequency...

- **Implementation of the physical & digital twins link**
  - Reliability? Latency? Security?

- **Generalization Capabilities?**
  - Example: Adding a link to the network

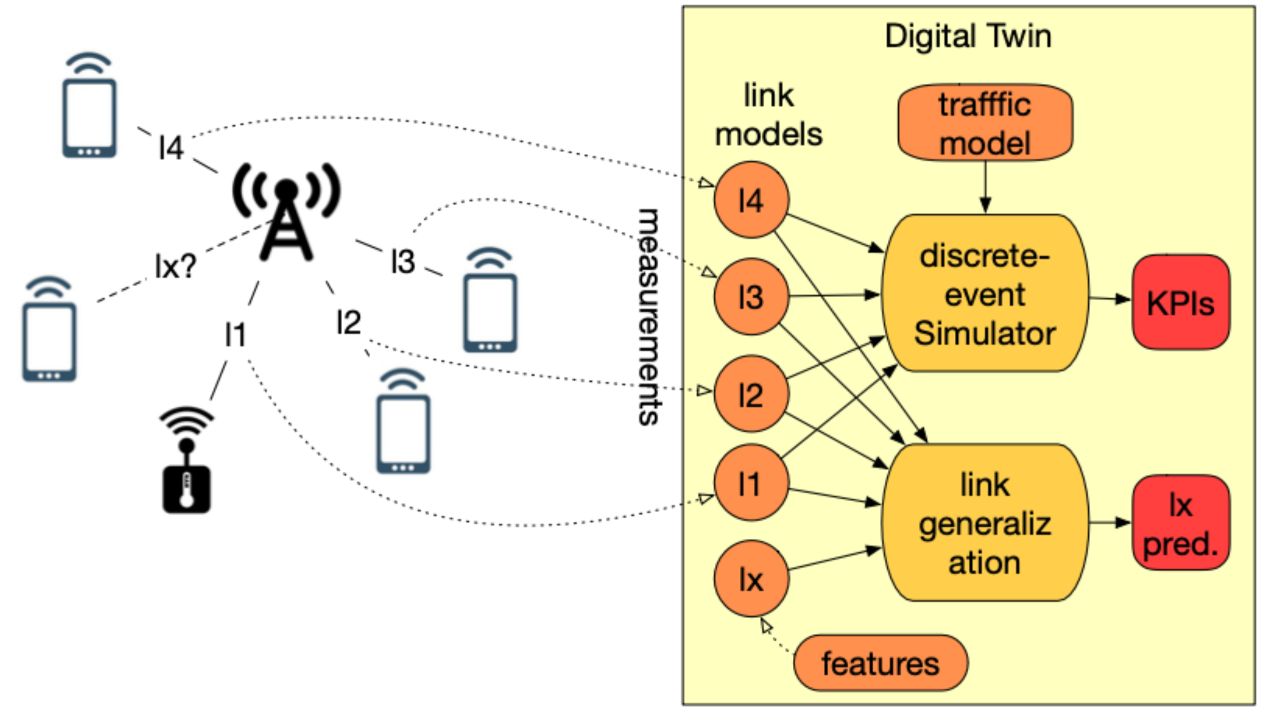
Research Project



2

Axis 2: Self-configurable wireless networks using digital twins

❖ **Objective:** Automatic reconfiguration according to the environment evolution

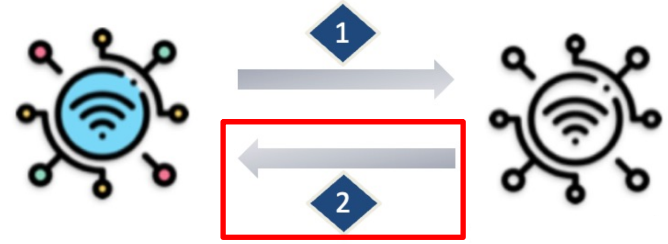


❖ **Issue:**

- How to ensure the reliability of the NDT for unexplored scenarios?
  - Different topology/protocol, etc.

❖ **Scientific Lock:**

- **Complexity of generalization** of current NDT and simulation models:
  - Heterogeneous radio environments
  - Complex relations between topology, routing,, traffic, etc.



Research Project

2 Axis 2: Self-configurable wireless networks using digital twins

❖ **Approach :**

- Creating **agnostic** models through measurements campaigns

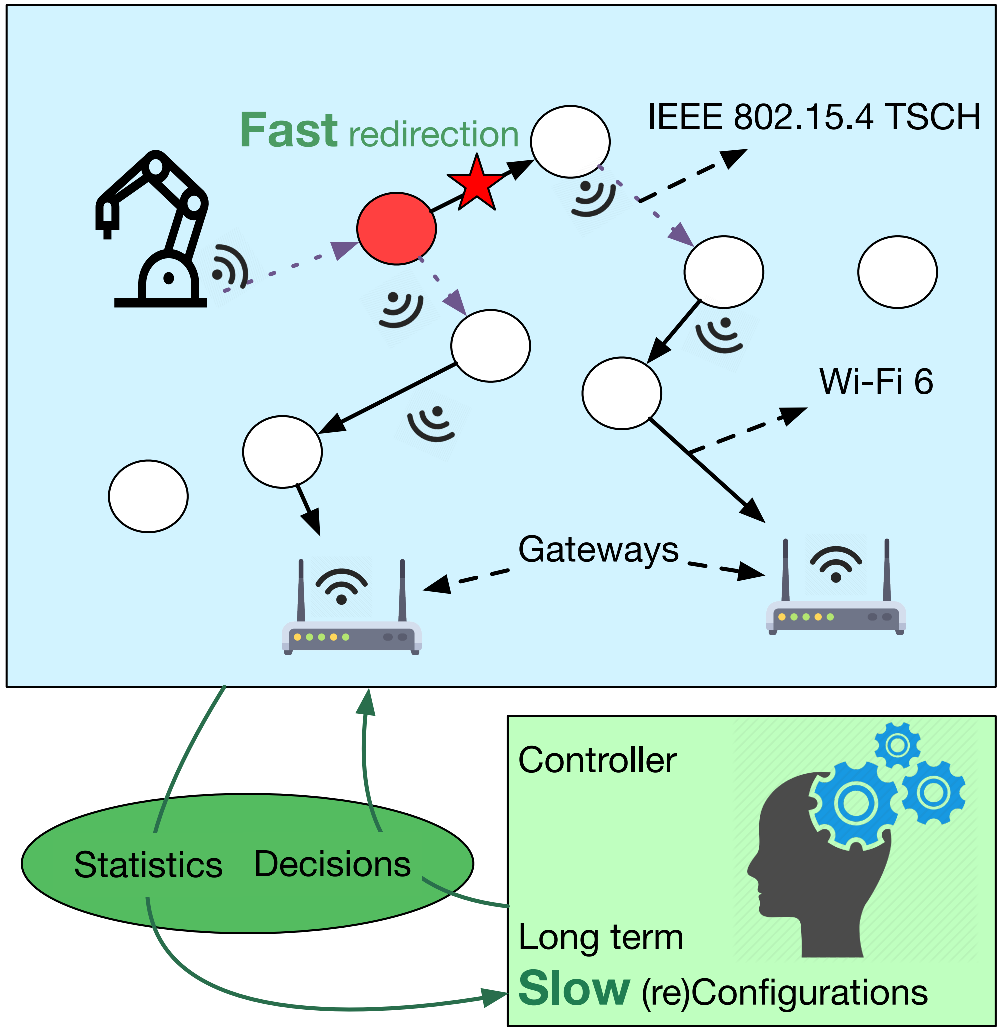
❖ **Interest:**

- **Automatic reconfiguration** on the whole stack

❖ **Scientific challenges:**

- Reliability/complexity of the prediction models
  ➔ **Domain Generalization/Transfer Learning** [8,9]

- Reconfigurations triggering
  ➔ Instability detection, rewards/cost, etc.



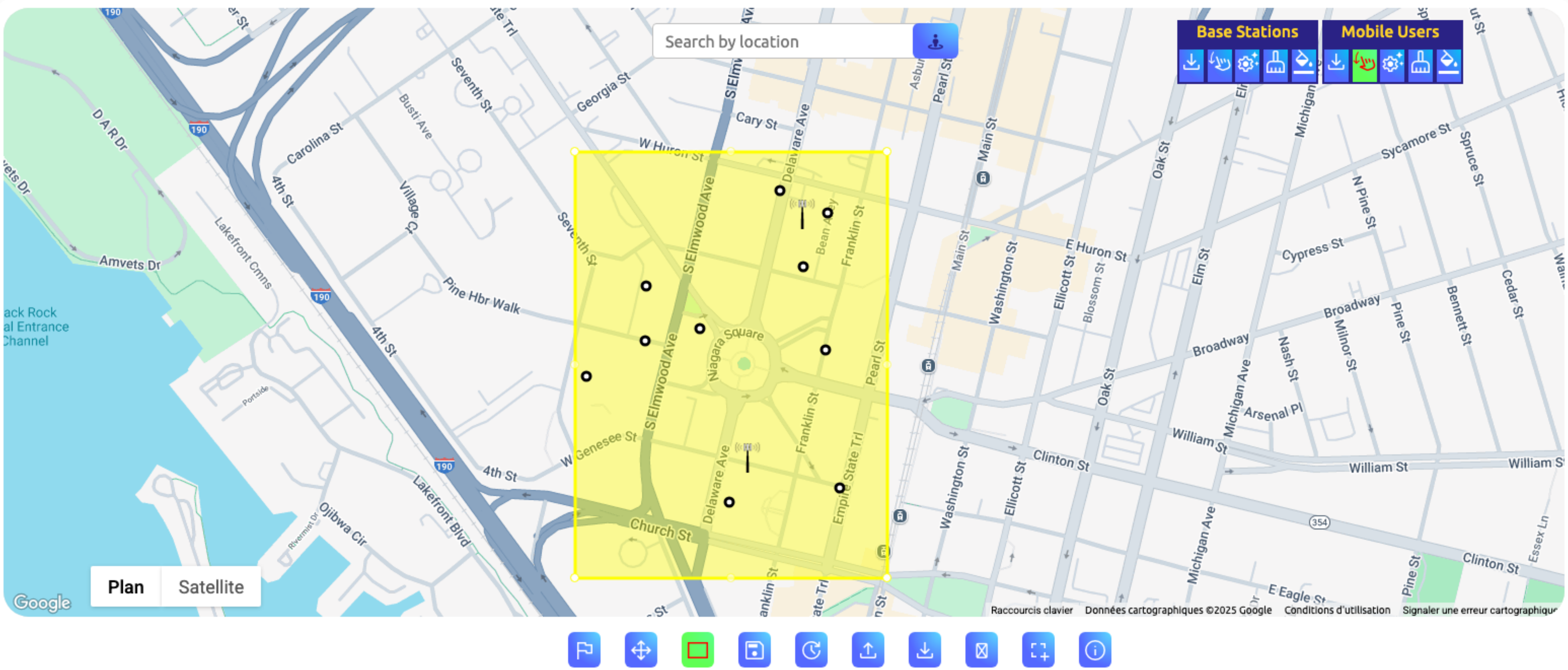
[8] G. Blanchard et al., Generalizing from several related classification tasks to a new unlabeled sample. Advances in neural information processing systems. 2011.
[9] M. Akrout et al., Domain Generalization in Machine Learning Models for Wireless Communications: Concepts, State-of-the-Art, and Open Issues. IEEE Comm. Surveys & Tutorials. . 2023.

Ongoing Projects

University at Buffalo
The State University of New York

❖ No-Code simulation of wireless networks (WTTool)

- Dr. Filippo Malandra
  - Nicholas Accurso, **Samir Si-Mohammed,** Diptangshu De, and Filippo Malandra. « WTTool: A Visual Web-based Topology Generator and 5G Network Simulator with ns-3 (demo) », in 2024 CIoT - Conference on Cloud and Internet of Things.



Ongoing Projects

❖ Digital Twins for Efficient 5G networks

- Ghinwa Ismail, PhD student (co-supervised with F. Théoleyre)
  - Use of the Colloseum platform [10] (https://colosseum.sites.northeastern.edu/)

❖ Data-driven optimization for RPL in mesh networks

- Prof. Georgios Z. Papadopoulos
  - Use of FIT IoT-Lab

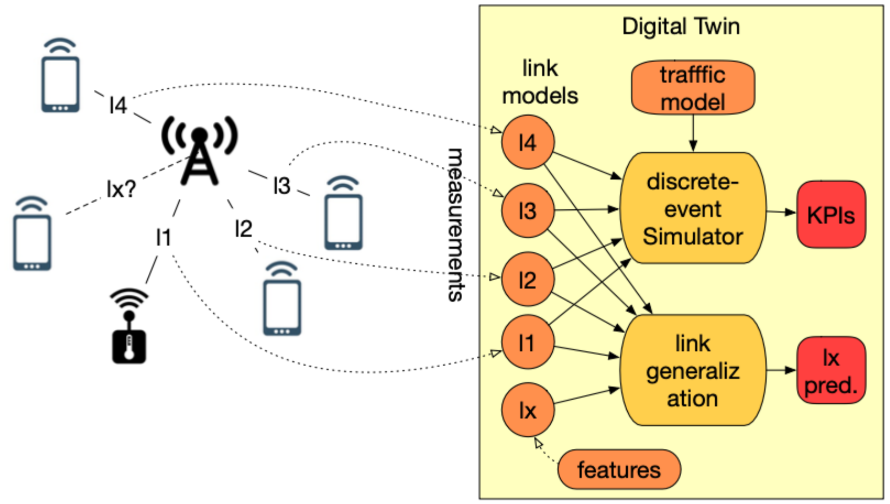
❖ Wi-Fi/5G co-existence optimization using Quantum Annealing

- Prof. Won-Joo Hwang
  - Research visit planned for the end of July (Pusan, South Korea)

[10] Villa, D., Tehrani-Moayyed, M., Robinson, C. P., Bonati, L., Johari, P., Polese, M., & Melodia, T. (2024). Colosseum as a digital twin: Bridging real-world experimentation and wireless network emulation. IEEE Transactions on Mobile Computing.

Future Collaborations

- **Generalization in network performance prediction**
  - **Predict in advance the impact of changing the network scenario (topology, traffic, etc.)**
  - **Expertise on simulation (ns-3) and experimentation (SLICES) for validation**



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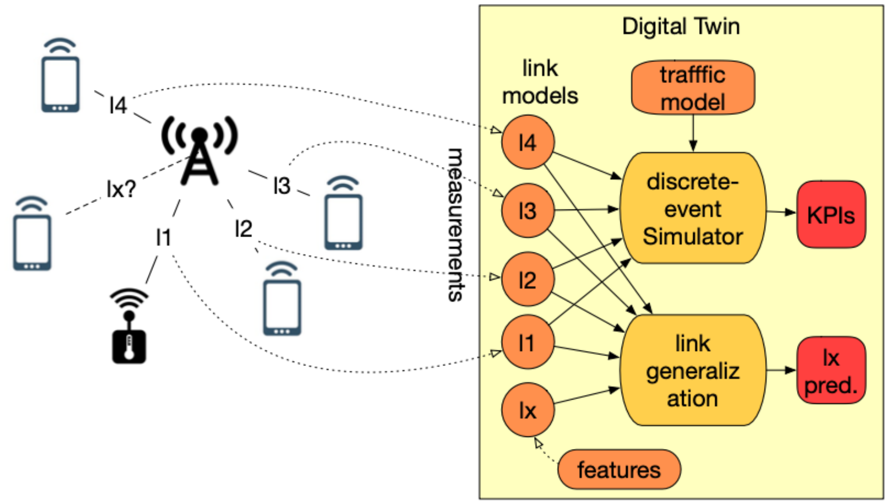

➔ **Definition of source/target domains**
➔ **Usage of Transfer Learning techniques**

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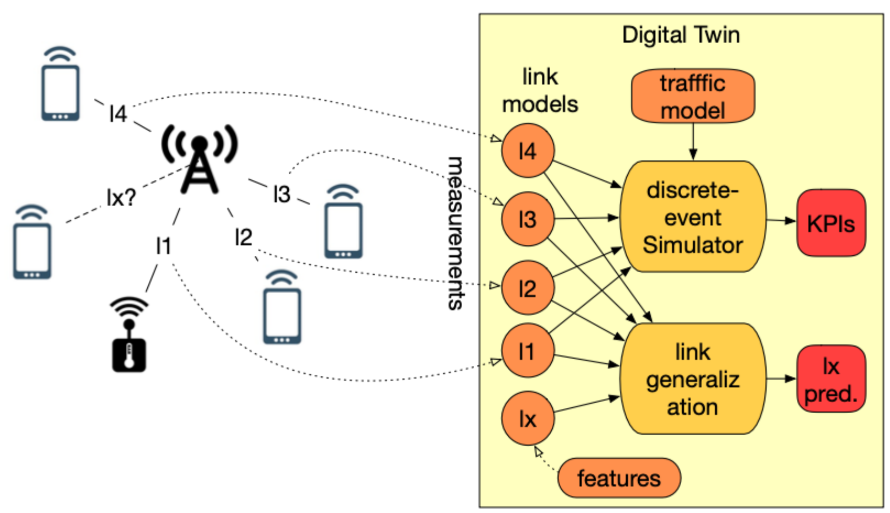
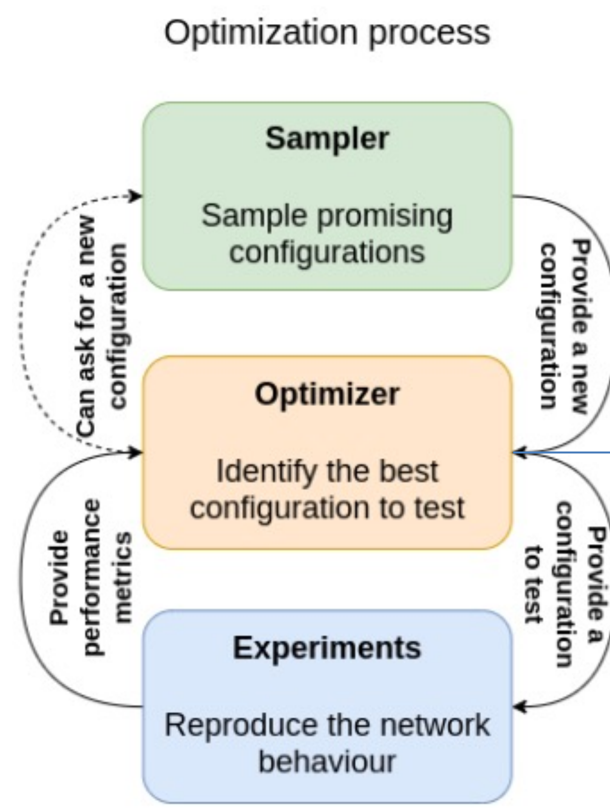


➔ **Definition of source/target domains**
➔ **Usage of Transfer Learning techniques**

❖ **Black-box optimization of network configurations**



Gaussian Processes

- Time consuming

simulation (black-box)

Future Collaborations

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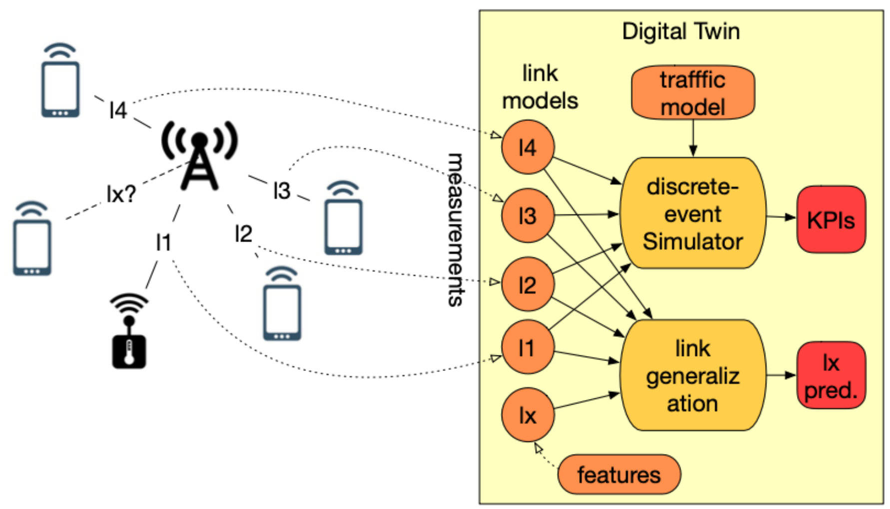

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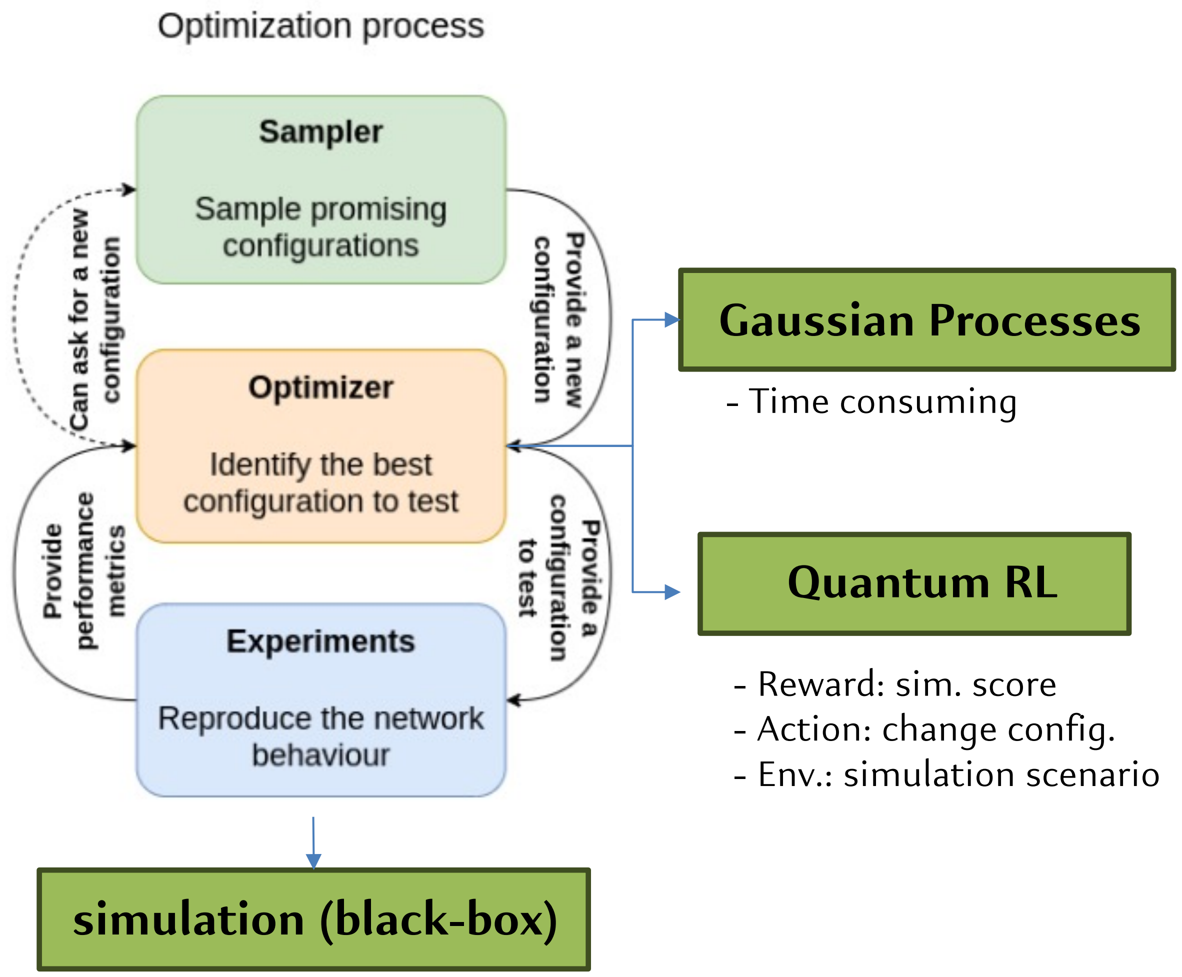

➔ **Definition of source/target domains**
➔ **Usage of Transfer Learning techniques**

➔ **Per-link optimization**
➔ **Using QRL for time reduction**