Per-Link Modeling Towards Self-Adaptive Network Digital Twins

MSWiM 2025

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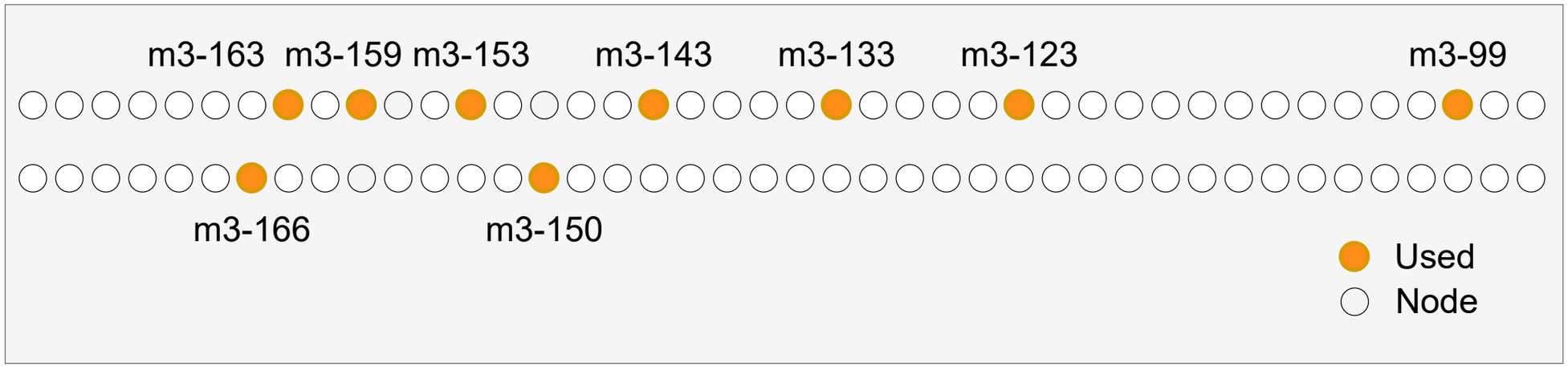
Problem Statement

❖ Case Study:

- Network architect deploying IoT solutions
- Industrial deployment on the experimental platform *FIT IoT-Lab* [1]
  - **Smart metering in an indoor environment**



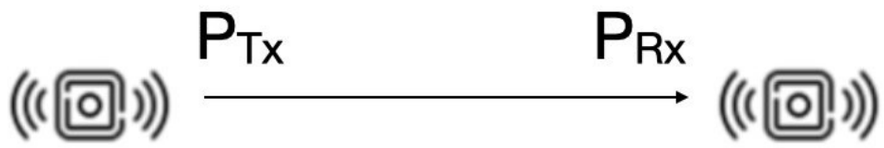
- 9 nodes on the Grenoble site, 24 hours deployment
- Communication technology: 802.15.4, on *Contiki-NG*
- Trafic: Broadcast, periodic (1 packet/s)

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

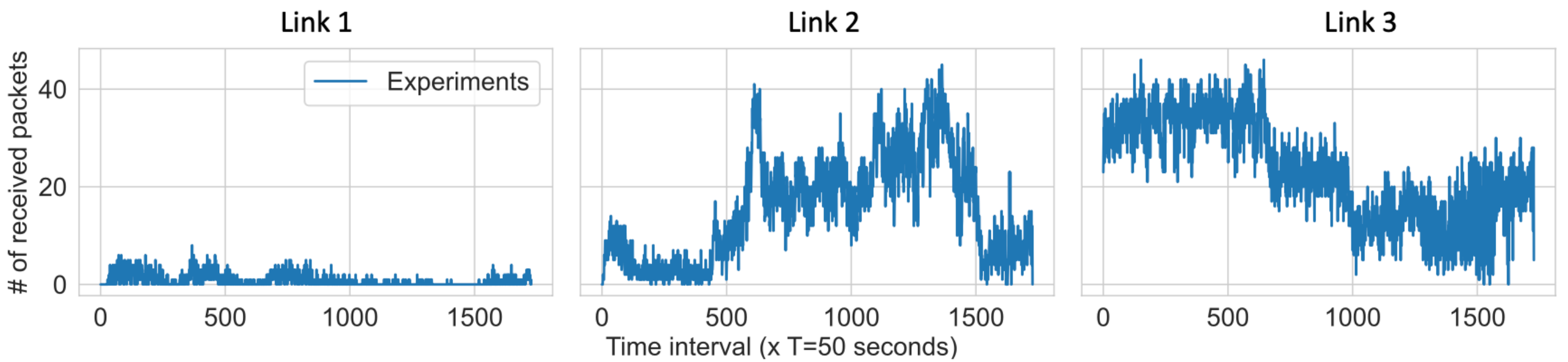
[1] Adjih, Cedric, et al. "FIT IoT-LAB: A large scale open experimental IoT testbed." 2015 IEEE 2nd World Forum on Internet of Things (WF-IoT). IEEE, 2015.

Problem Statement

❖ Compare between the PDR evolution:



- From real measures
- From the Cooja simulator [2] :
  - Calibrated with an average PDR value per link (fixed)



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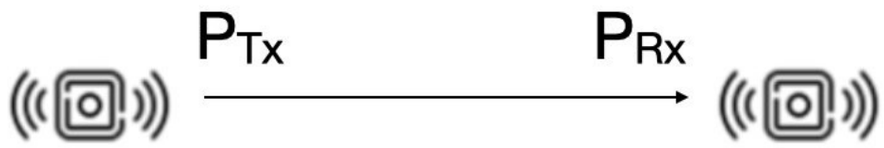

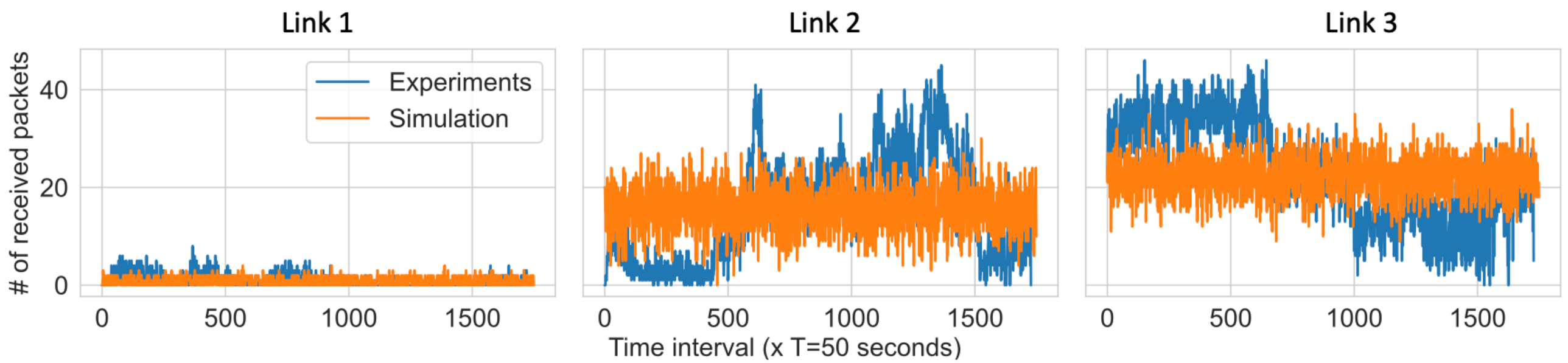

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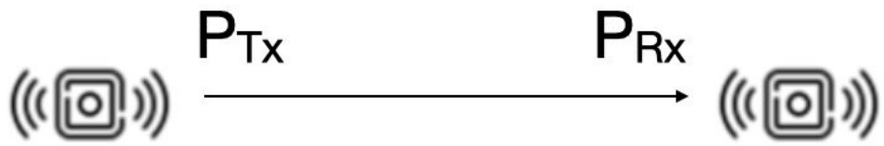
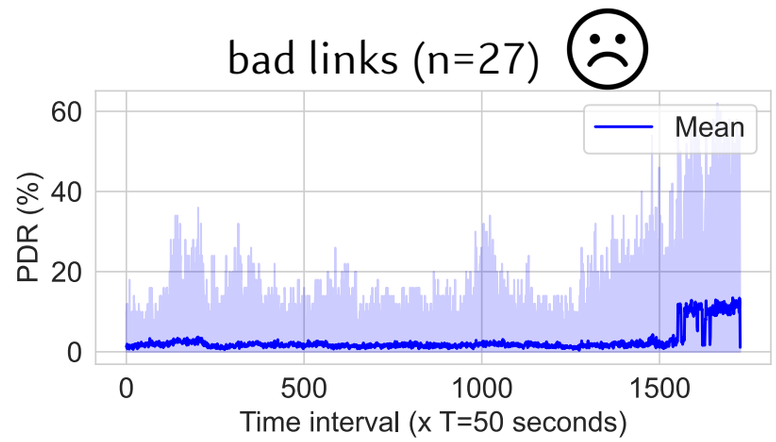
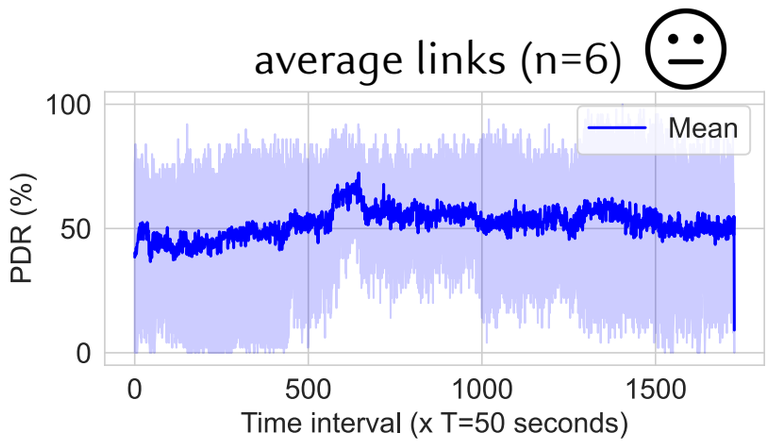
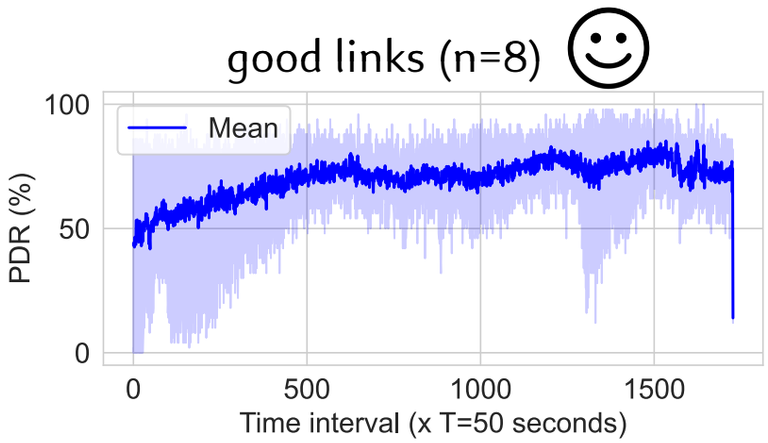
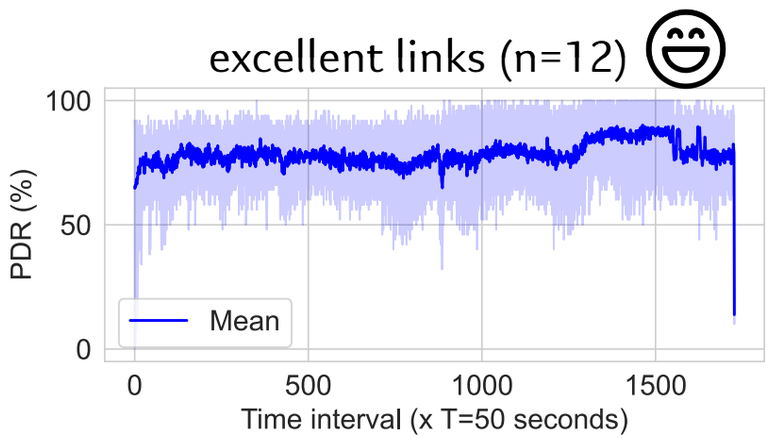


➢ **Classification according to the mean PDR: 0% - 20% - 60% - 75% - 100%**









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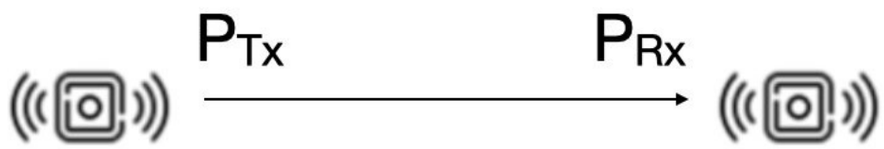

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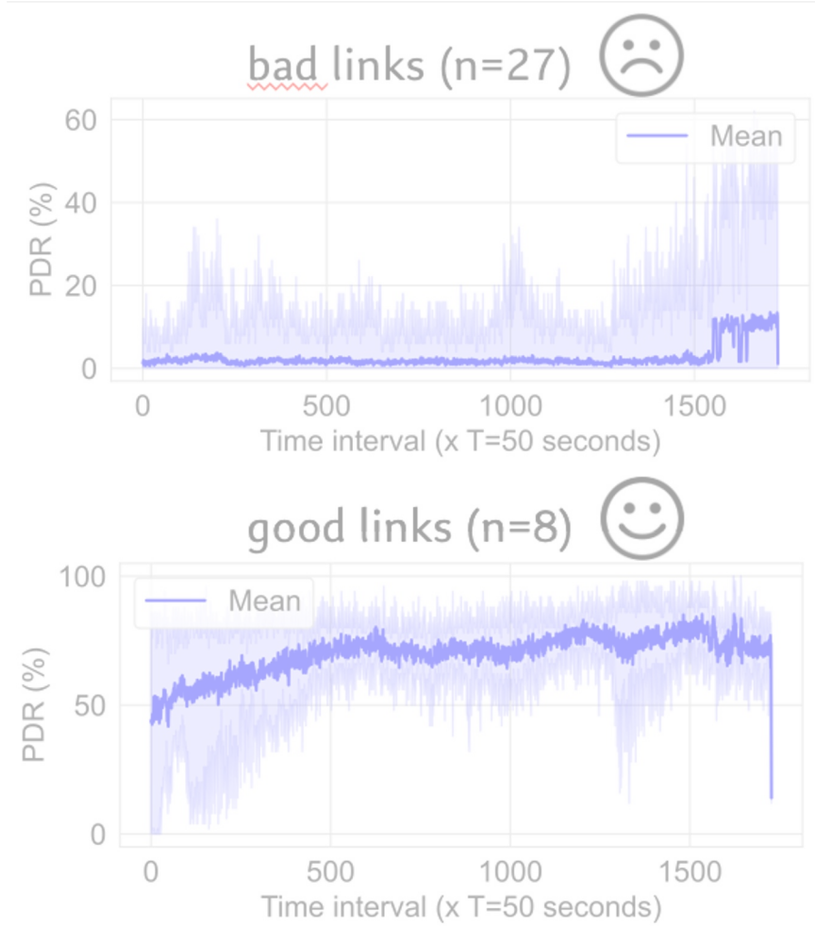

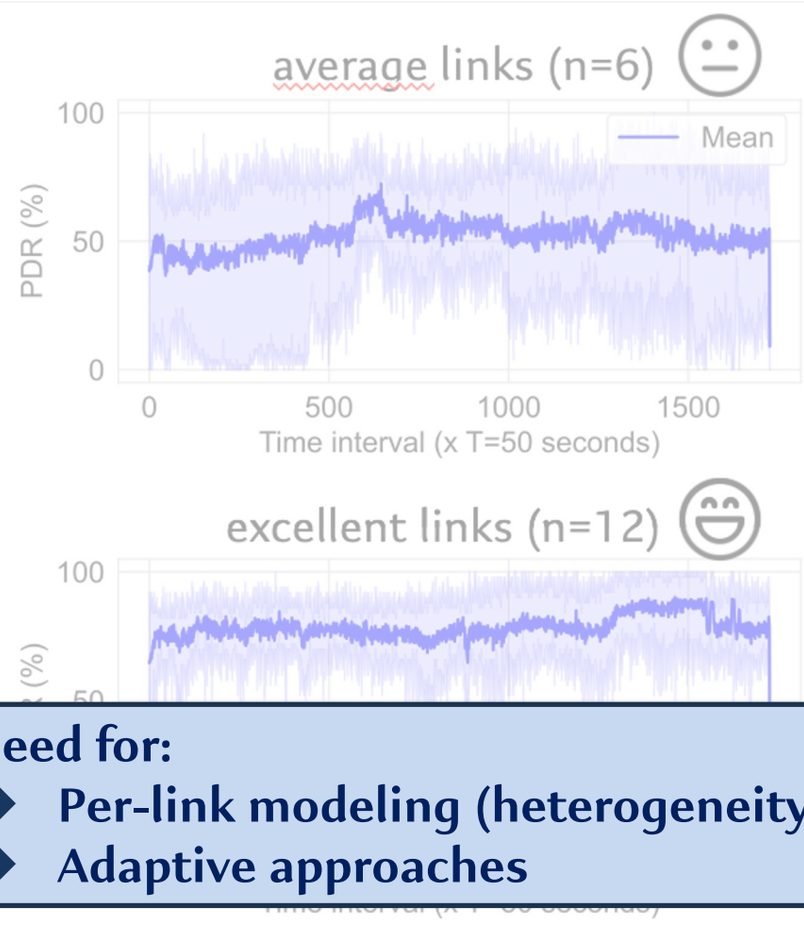

Need for:
- ➔ **Per-link modeling (heterogeneity)**
- ➔ **Adaptive approaches**

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

Problem Statement

❖ **How to accurately predict the evolution of a KPI (PDR) in a network?**

❖ **State of the Art:**

- **Ray-tracing** approaches [3];
- **Empirical studies** [4, 5] to generate propagation models;
- **ML-based heuristics** [6, 7] for predicting performances.

❖ **Limits:**

- Ignoring the links heterogeneity – **Modeling the network as a whole**
- Absence of adaptivity in the modeling.

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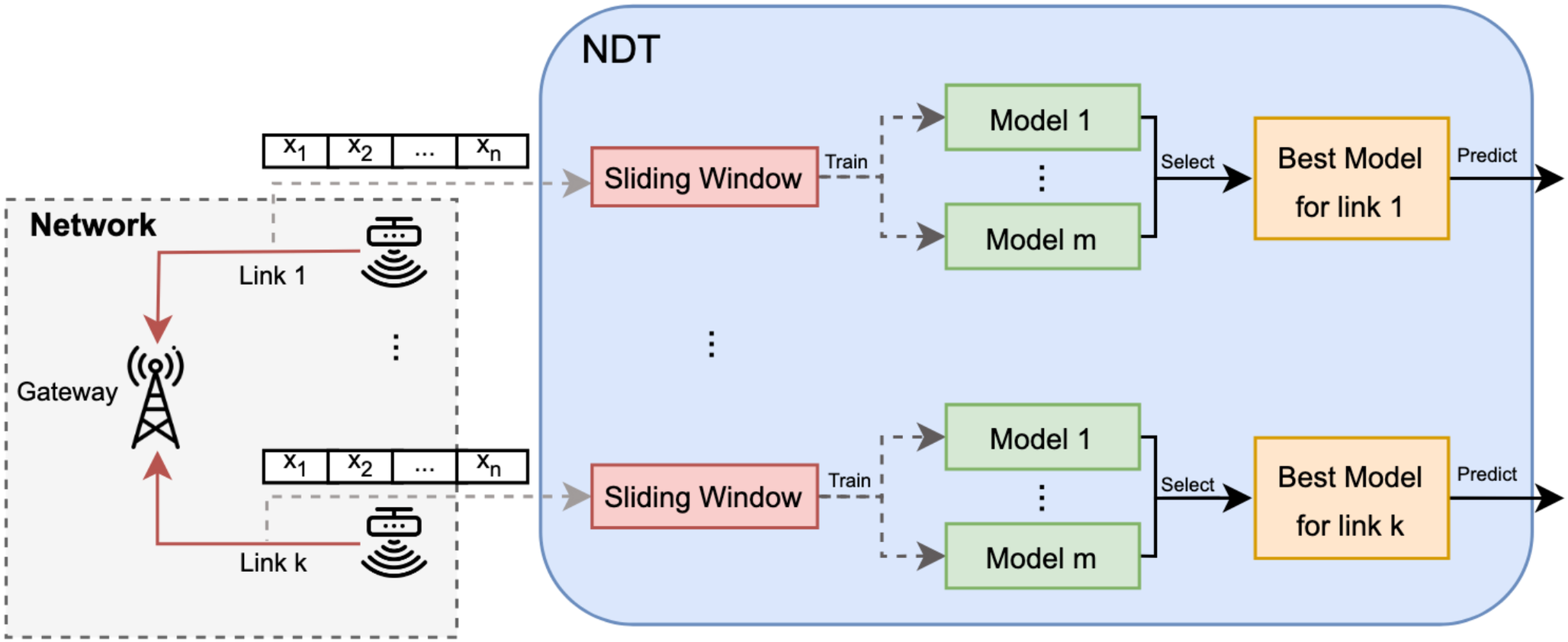
[3] Ruah, C. et al., (2024). Calibrating wireless ray tracing for digital twinning using local phase error estimates. *IEEE Transactions on Machine Learning in Communications and Networking*.
[4] Brun-Laguna, K., Minet, P., Watteyne, T., & Gomes, P. H. (2019). Moving beyond testbeds? Lessons (we) learned about connectivity. IEEE Pervasive Computing, 17(4), 15-27.
[5] Baccour, N. et al., (2012). Radio link quality estimation in wireless sensor networks: A survey. ACM Transactions on Sensor Networks (TOSN), 8(4), 1-33.
[6] Sindjoung, M. L. F., & Minet, P. (2019, November). Wireless link quality prediction in iot networks. In 2019 PEMWN (pp. 1-6). IEEE.
[7] Benadji, H., Zitoune, L., & Vèque, V. (2023, December). Predictive modeling of loss ratio for congestion control in IoT networks using deep learning. In GLOBECOM 2023. IEEE.

Proposed Solution

- **Contribution: Data-driven approach**
  1. Replace the **physical layer** simulation by measurements
  2. **Separately** model each radio link
  3. **Continuously** select the best model for each link

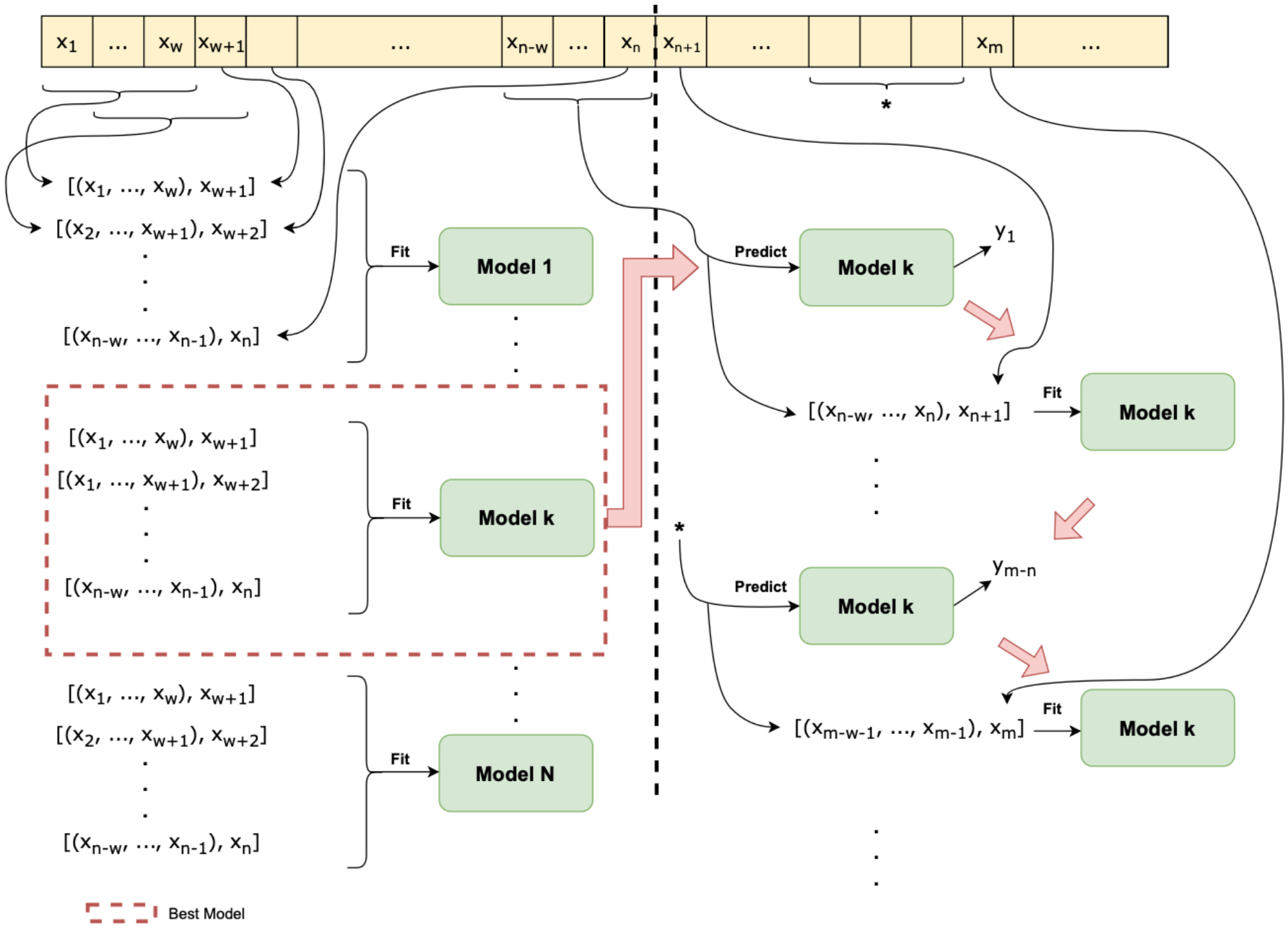
- **Interest:**
  - Flexibility
  - Temporality (anomaly Detection, etc.)



Proposed Solution – One Step

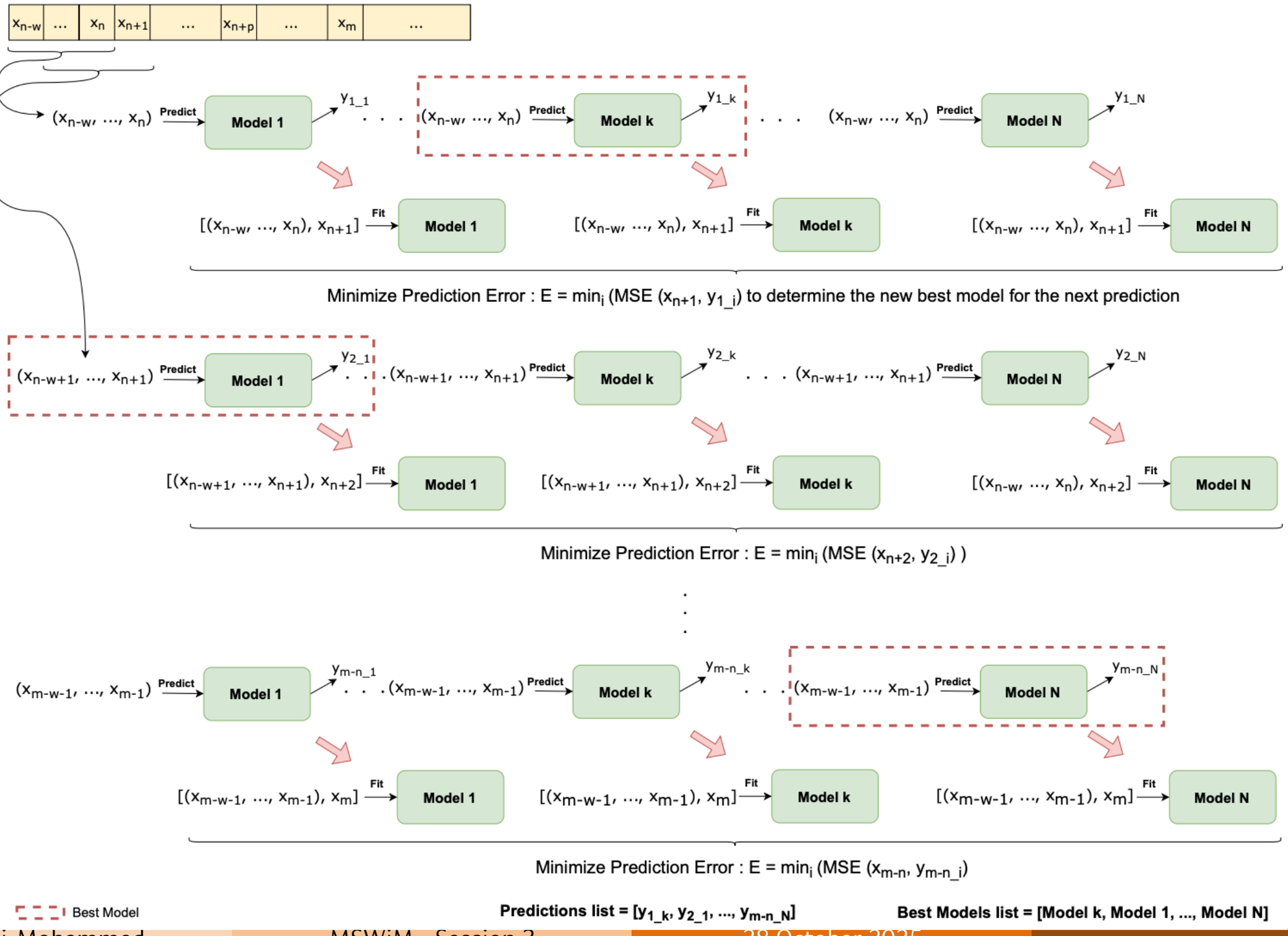
❖ **Fixed Model:** For each model:

- Split between Training and Testing data
- Create sliding windows for the regression
- Select the best model to use for predictions



Proposed Solution – One Step

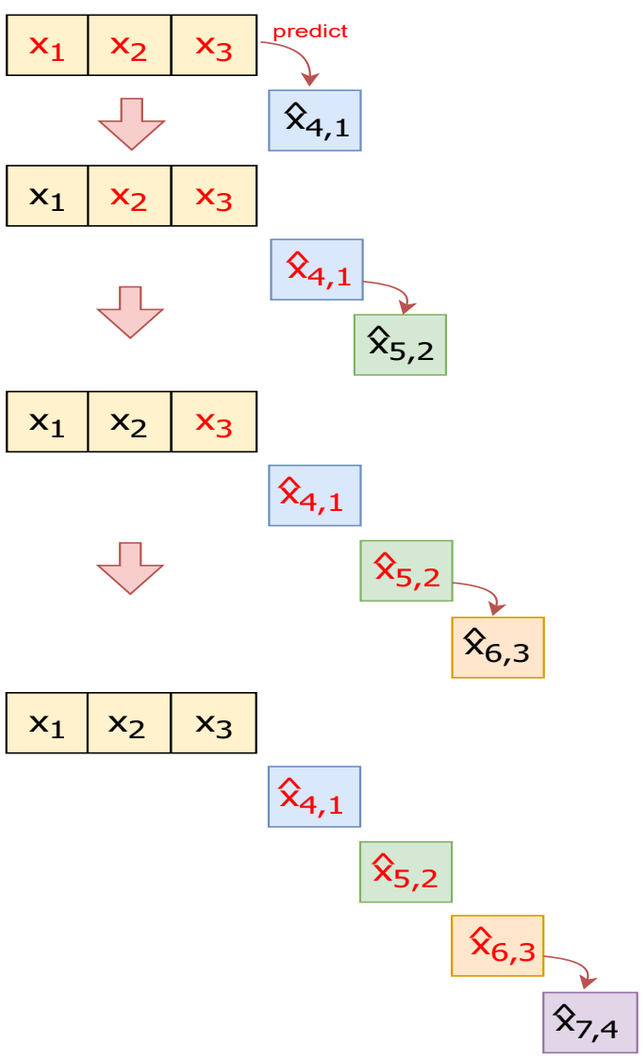
❖ Adaptive Model:



Proposed Solution – Multi-Step

❖ Multi-step prediction:

- Distinguish between the steps predictions for the evaluation



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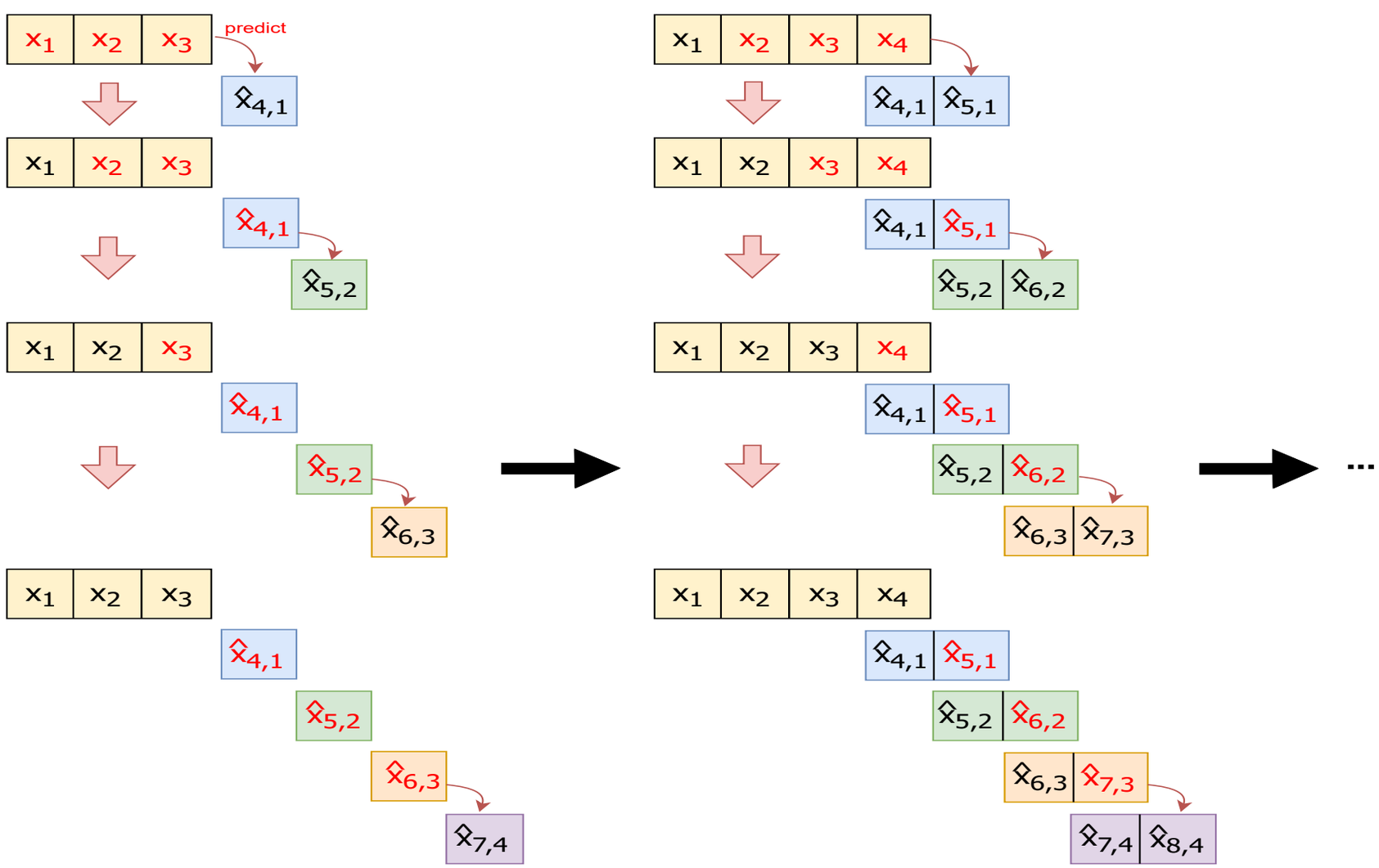
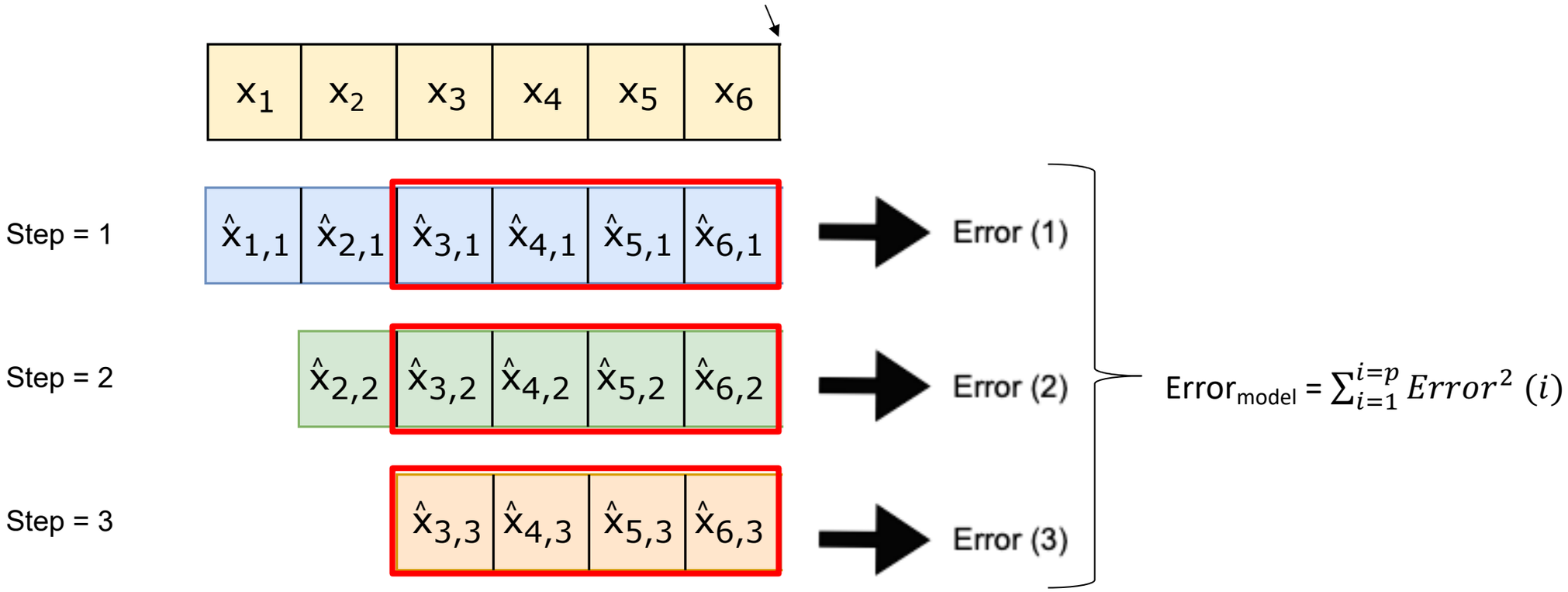


Proposed Solution – Multi-Step

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

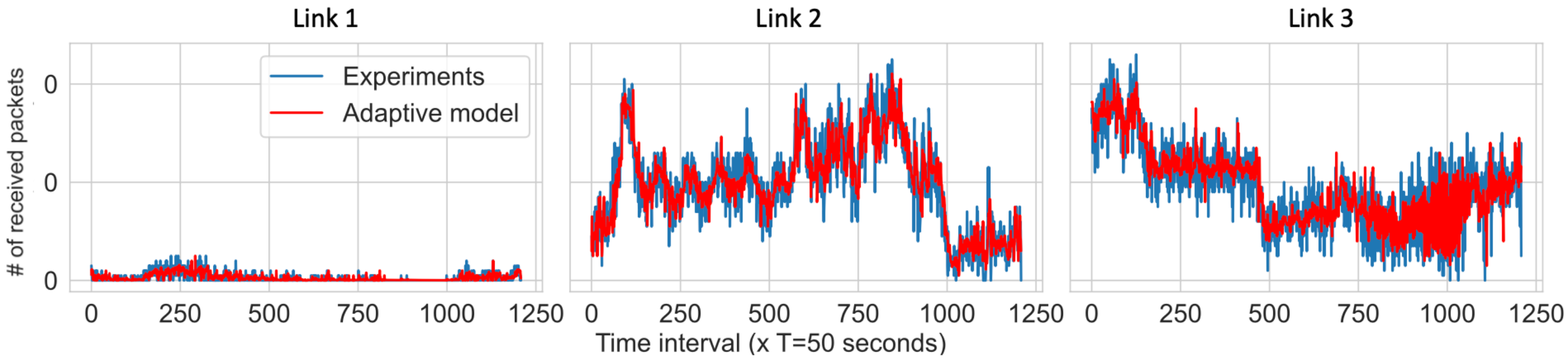
- At each interval, compute the error for the last *q (e.g., q*=4) predictions, according to the different steps errors of each model:



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

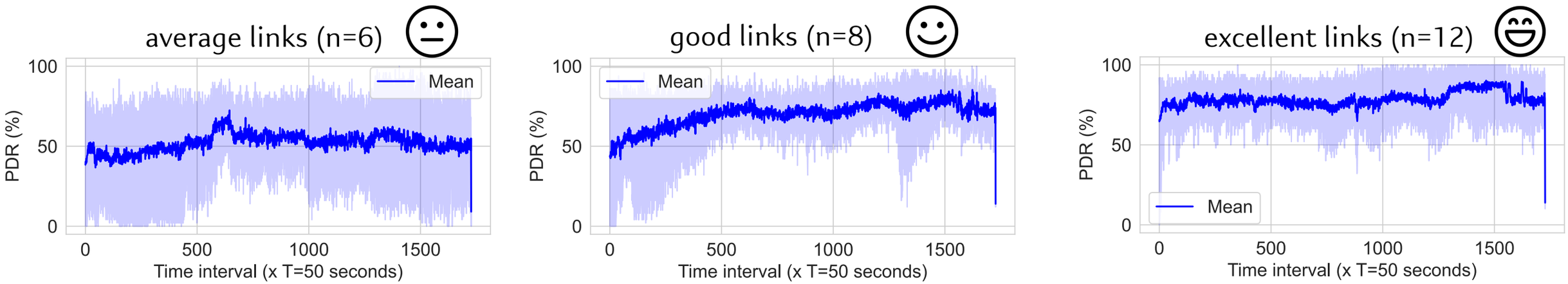
Results

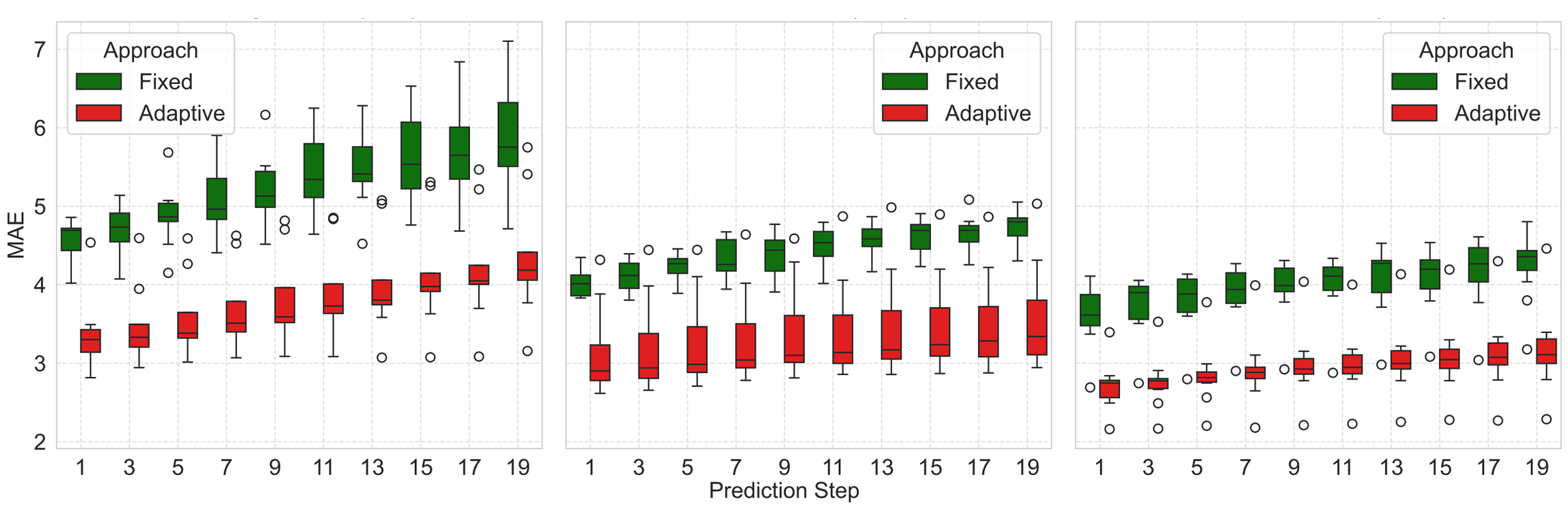
- **Short-term predictions (p=1):**



Results

❖ Mid-term predictions (p>1):





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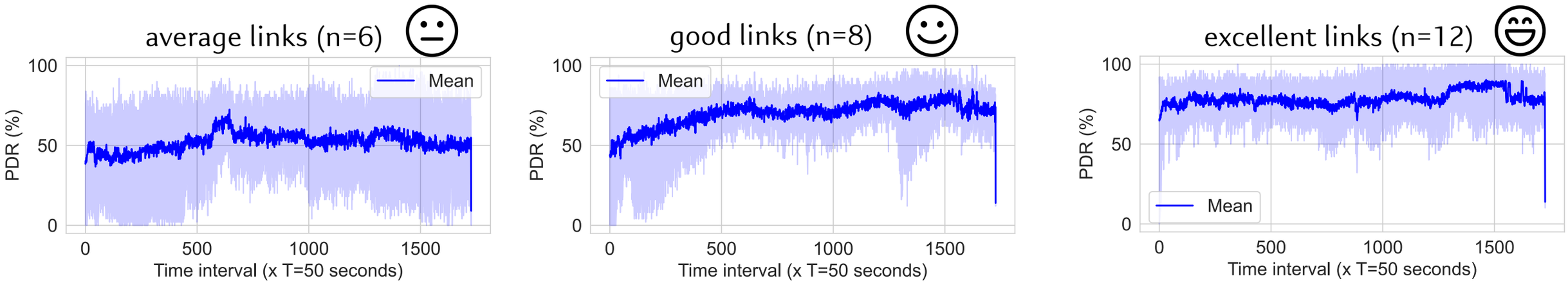

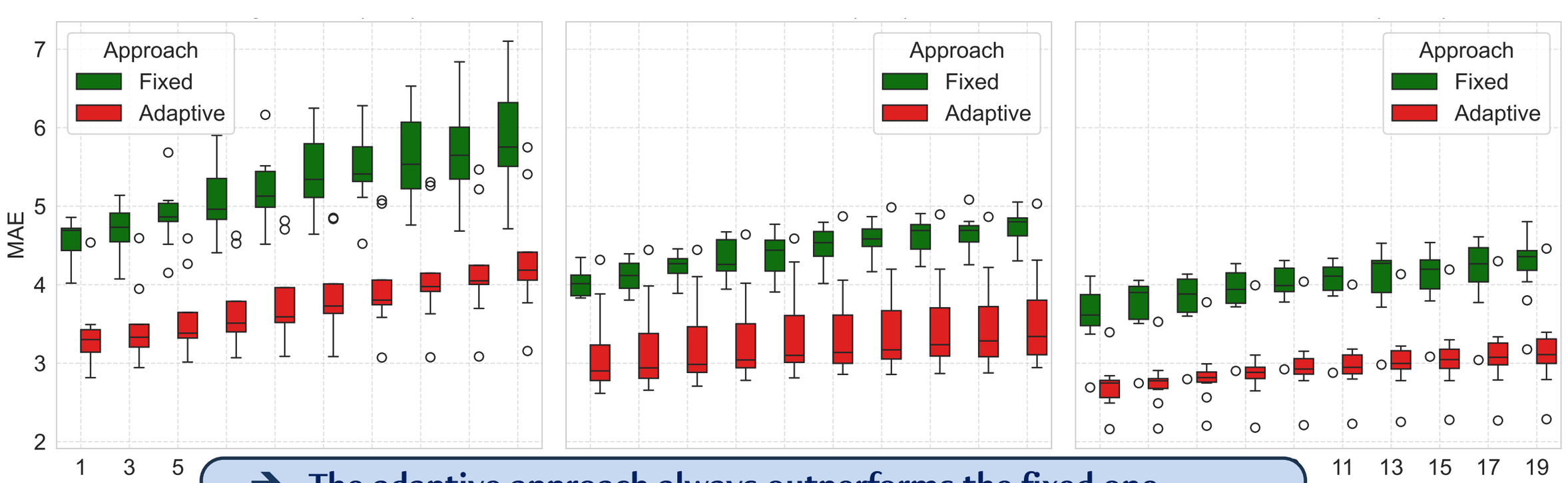

➔ **The adaptive approach always outperforms the fixed one**

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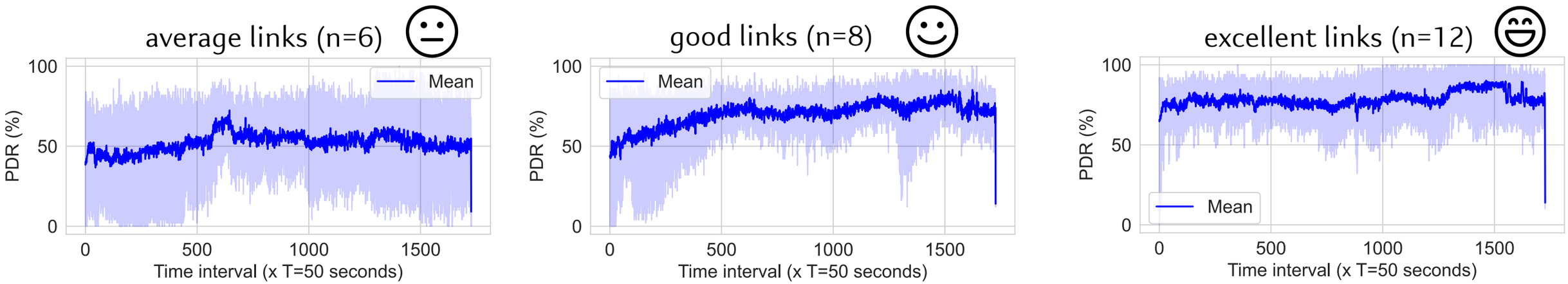

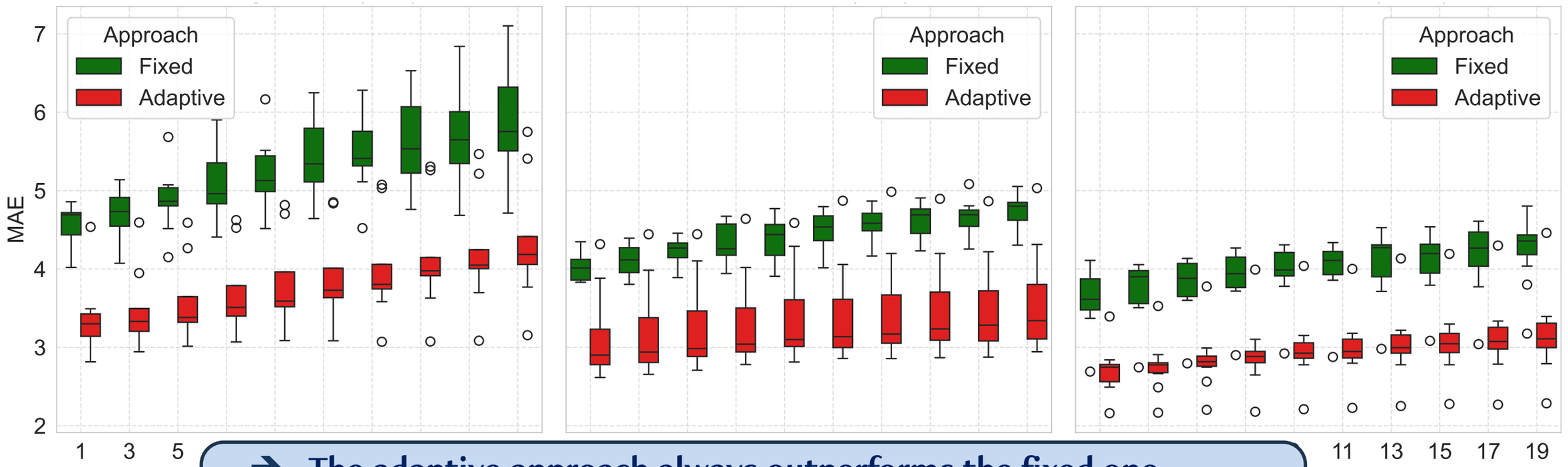

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➔ **Low prediction errors for short/mid term, with a linear increasing**

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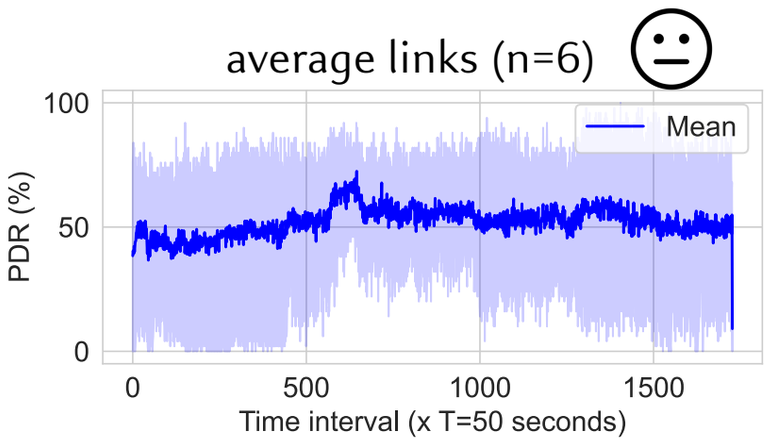

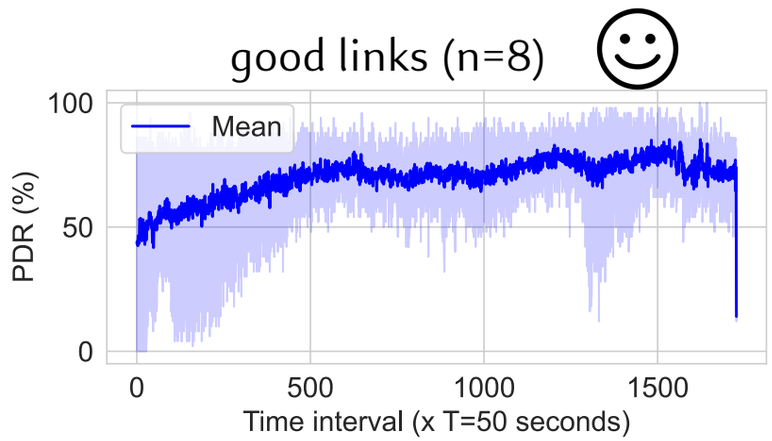

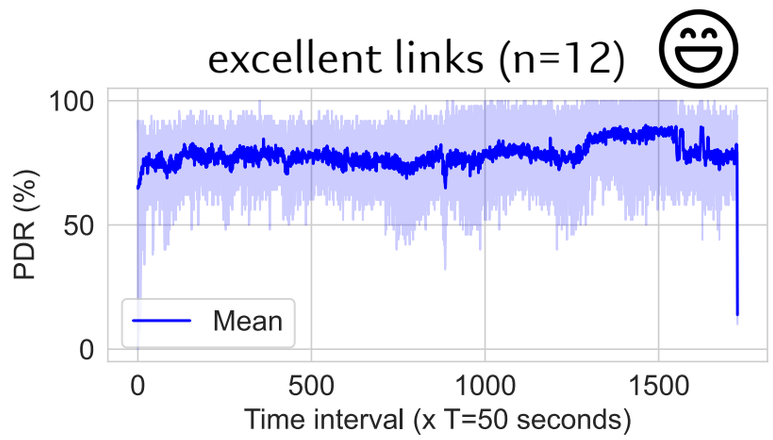

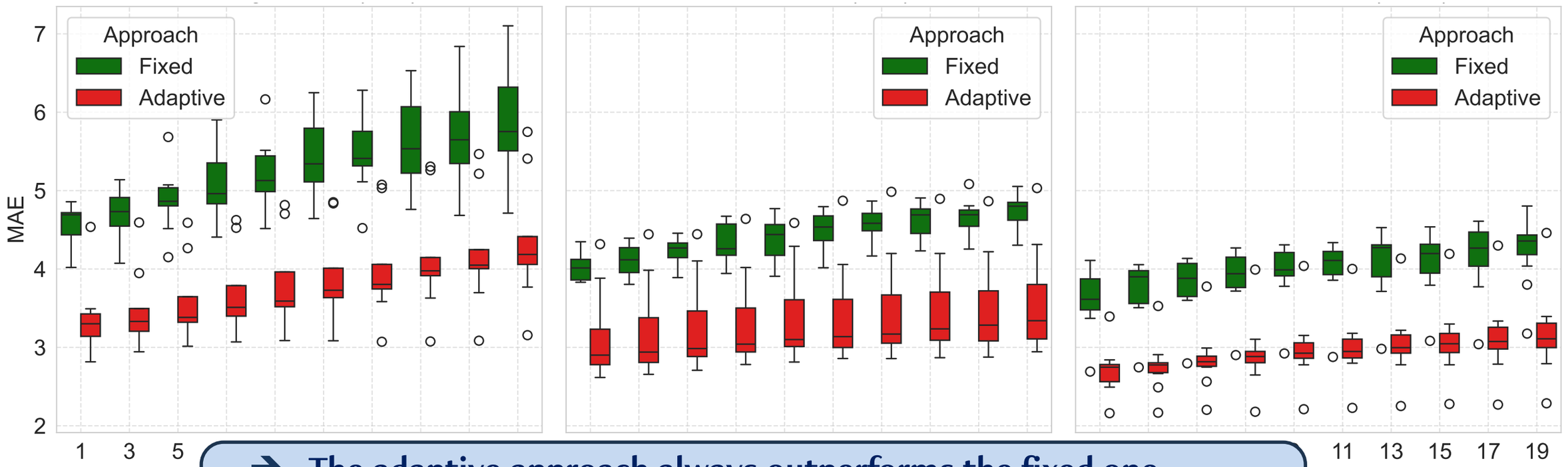

- ➔ The adaptive approach always outperforms the fixed one
- ➔ Low prediction errors for short/mid term, with a linear increasing
- ➔ Better predictions for stable links

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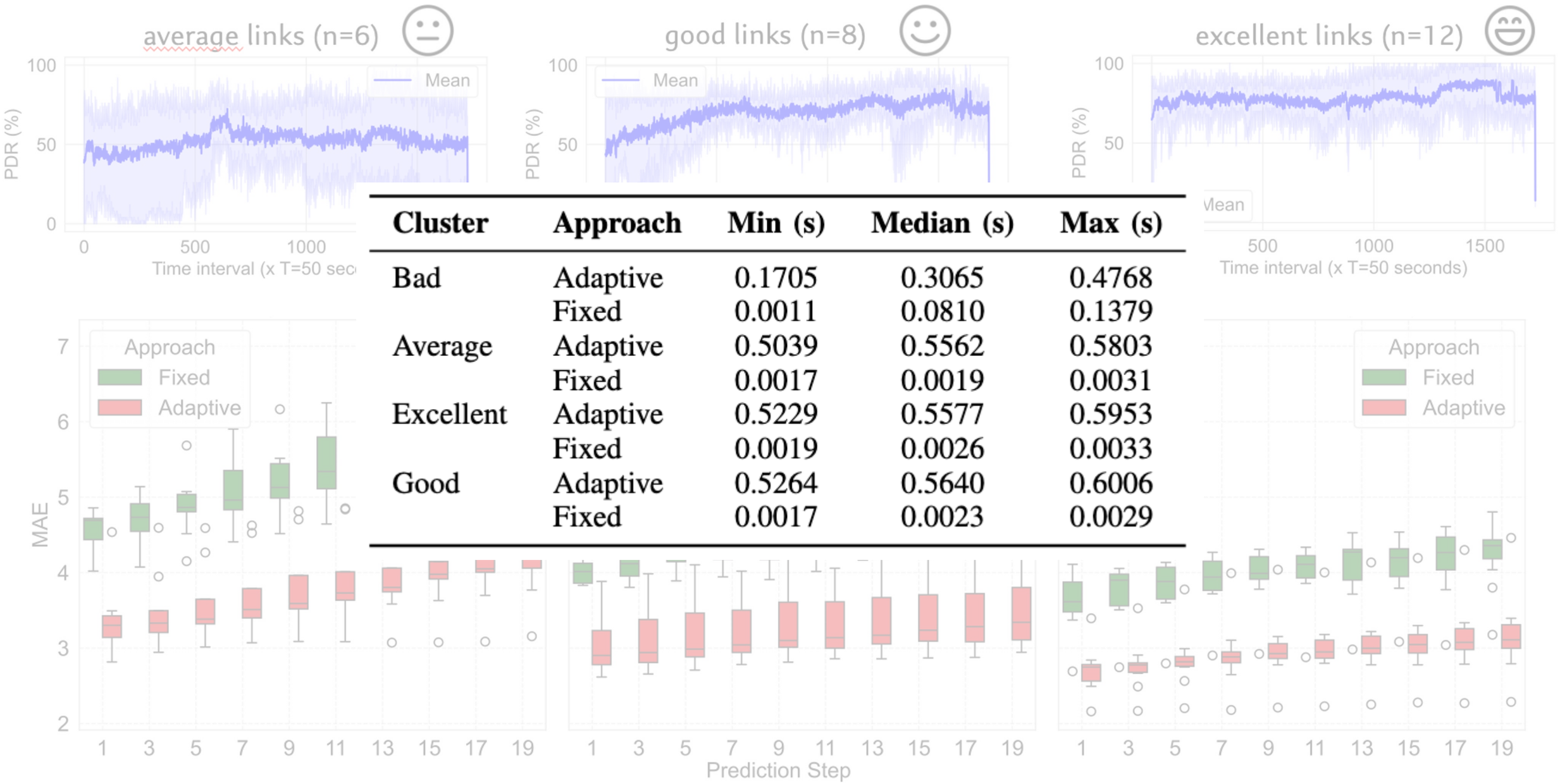

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	Fixed	0.0011	0.0810	0.1379
Average	Adaptive	0.5039	0.5562	0.5803
	Fixed	0.0017	0.0019	0.0031
Excellent	Adaptive	0.5229	0.5577	0.5953
	Fixed	0.0019	0.0026	0.0033
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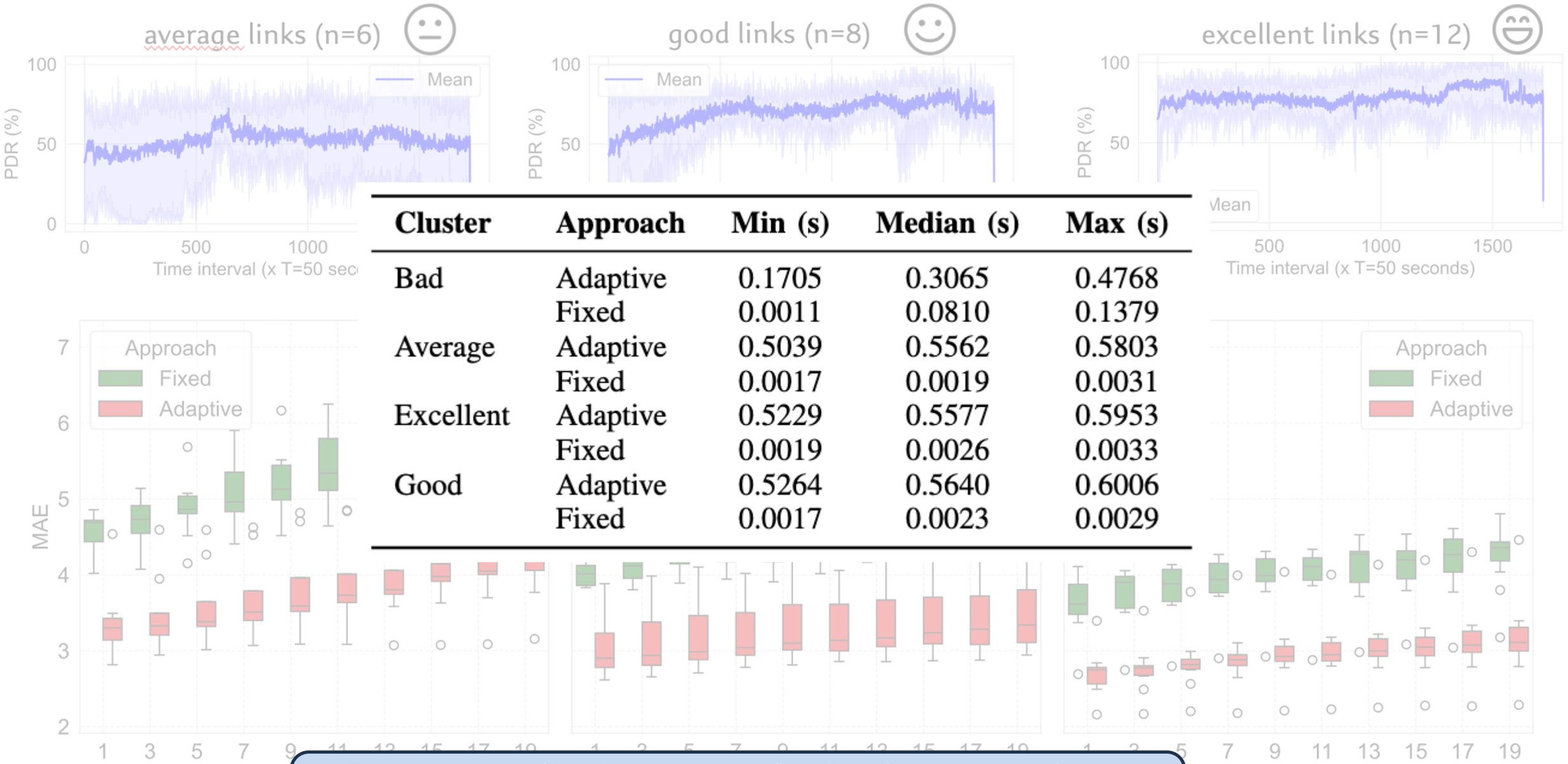

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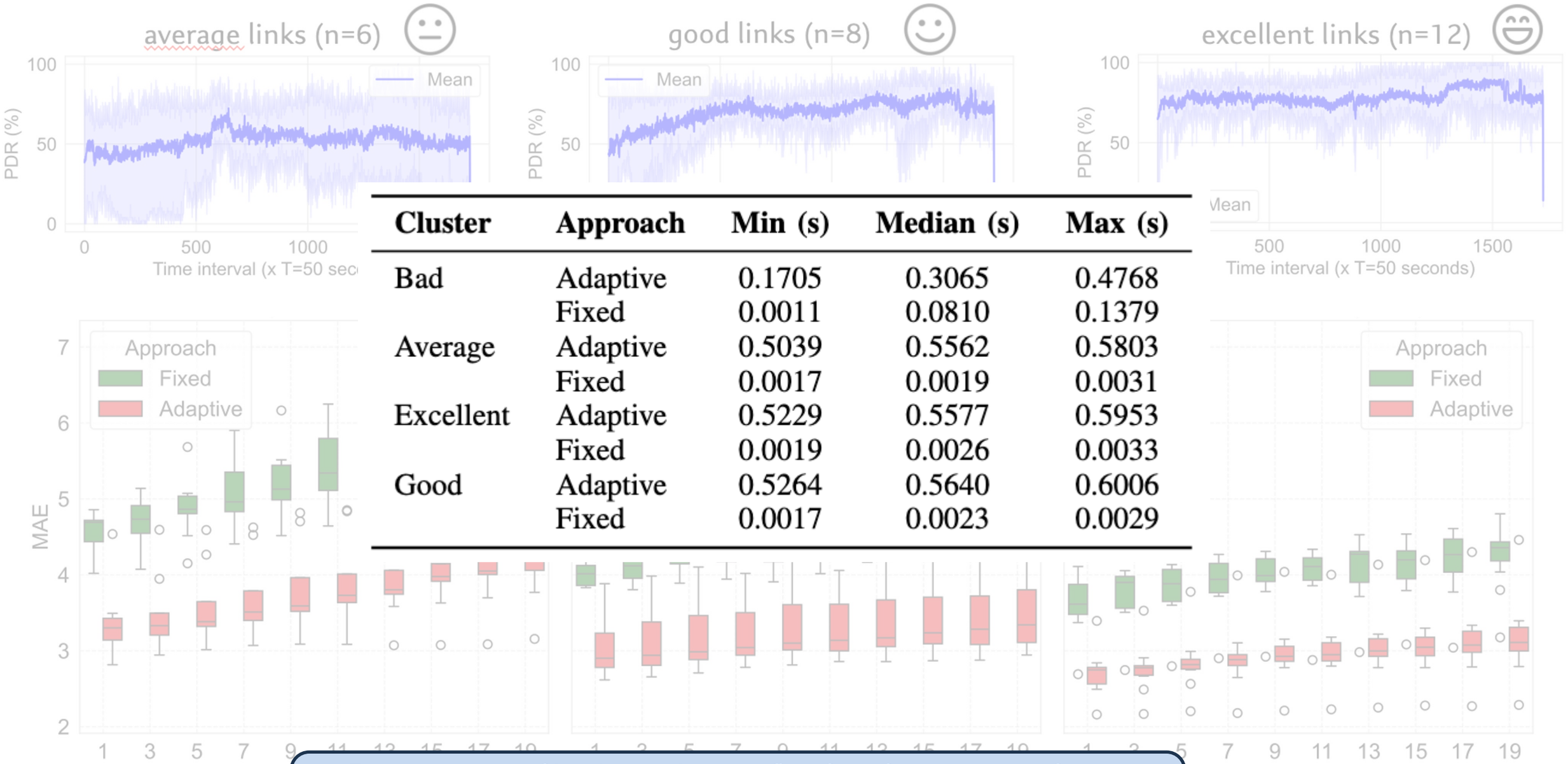

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➔ **Low prediction times for both approaches**
➔ **Accuracy comes at a cost…**

Contributions

- **Individual link modeling**
  - **Captures radio links heterogeneity**
  - **Uses lightweight models**

- **Adaptive algorithm for model selection**
  - **Captures radio links dynamics**
  - **Showcases tradeoff between accuracy and complexity**

- **Completely reproducible experiments and results:**
  https://github.com/SamirSim/Wireless-Link-Quality-Prediction

Takeaways & Perspectives

Takeaways:

- Importance of deployment conditions
  - **Need for reproducible experimental data**

- Network heterogeneity and dynamics
  - **Need for per-link modeling in network performance evaluation**
  - **Need for adaptive approaches**

Perspectives:

- Metrology with a dynamic traffic?
- Scalability?
- Generalization capabilities?

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