Chair of Communication Networks, Prof. W. Kellerer
Department of Computer Engineering (CE)
School of Computation, Information and Technology (CIT)
Technical University of Munich (TUM)

Twin your network to (auto-)manage flexibility

AI-based management for flexible networks based on digital twins

Wolfgang Kellerer

Professor, IEEE Fellow

May 16, 2025

This work receives financial support by the Federal Ministry of Education and Research of Germany (BMBF) in the programme of "Souverän. Digital. Vernetzt." joint project 6G-life, project identification number 16KISK002, and the Bavarian Ministry of Economic Affairs, Regional Development and Energy as part of the project "6G Future Lab Bavaria" and "5G Testbed" and "6G und Quantentechnologie", and the German Research Foundation (DFG), grant number: 316878574.

Bundesministerium für Bildung und Forschung

DFG Deutsche Forschungsgemeinschaft

Gefördert durch Bayerisches Staatsministerium für Wirtschaft, Landesentwicklung und Energie

6G-life

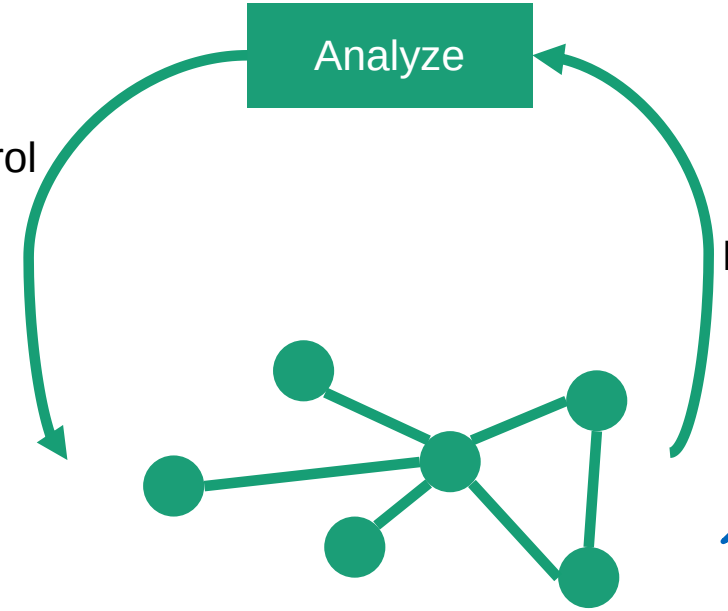
Autonomous Network Management

Network Managers' all-time Dream:

lean back and watch!

Why now?

too risky?



Network softwarization and data analytics vastly increase the degrees of freedom for network operations and management

This talk …

- will discuss a path towards autonomous network management
- we raise the challenge of network flexibility, and
- introduce the role of Network Digital Twins for autonomous network management, and
- how AI/ML may lead to a solution

based on Software-defined RAN and Kubernetes examples

Challenge 1: Network Flexibility

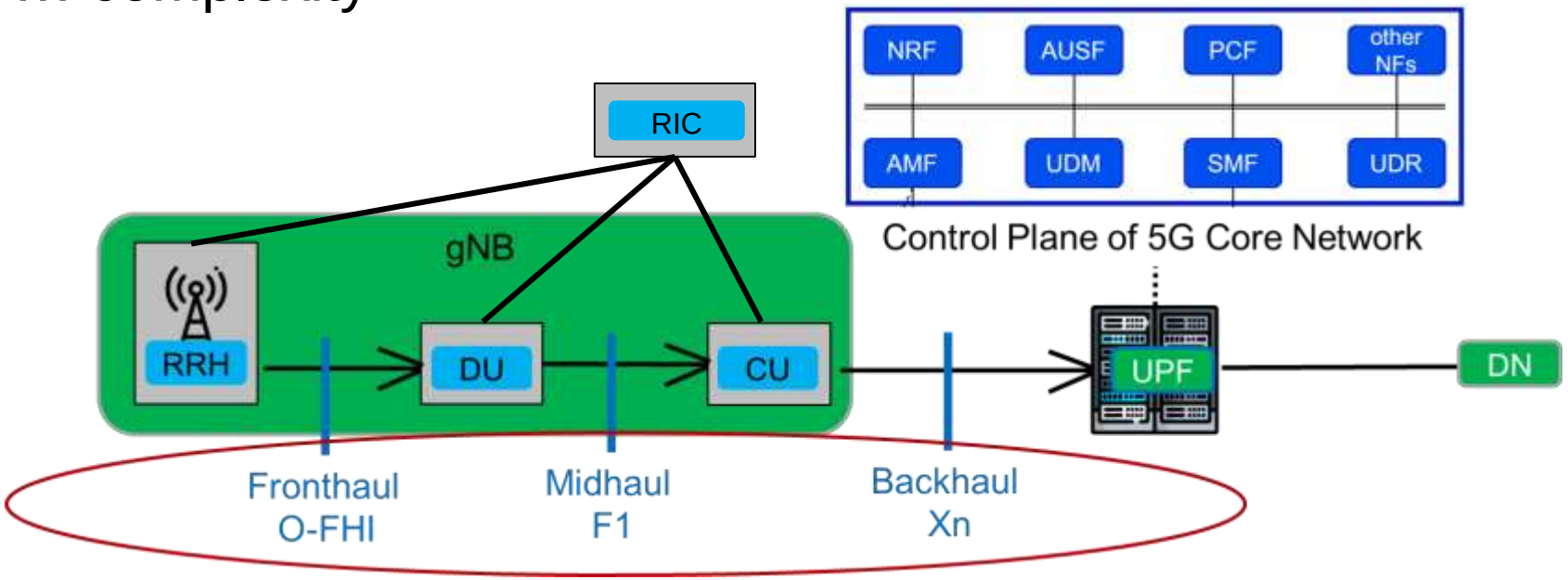
Challenge 1: Network Flexibility

Example: Software-Defined RAN

Flexibility in Software-Defined RAN

Open RAN

- extends Software-Defined Networking → Software-Defined RAN
- offers new, open interfaces, **RAN function split**, multi-vendor concepts, programmability, dynamic adaptation (RIC)→ unprecedented **flexibility**
- increases … complexity

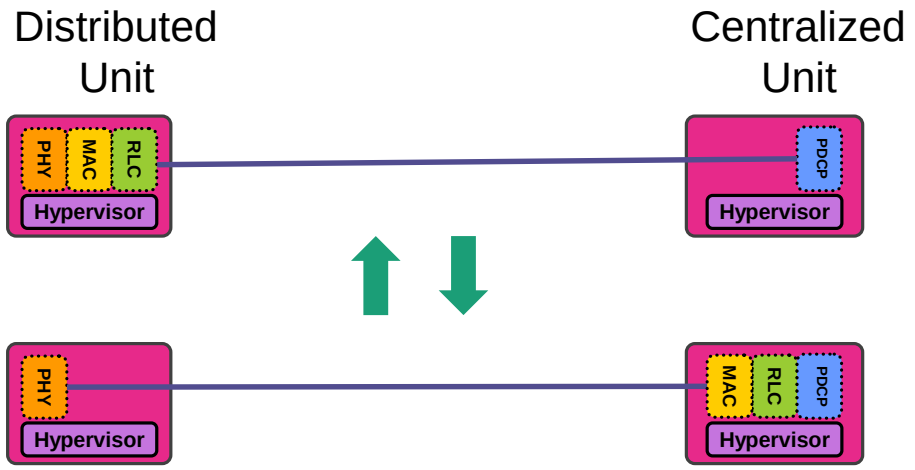


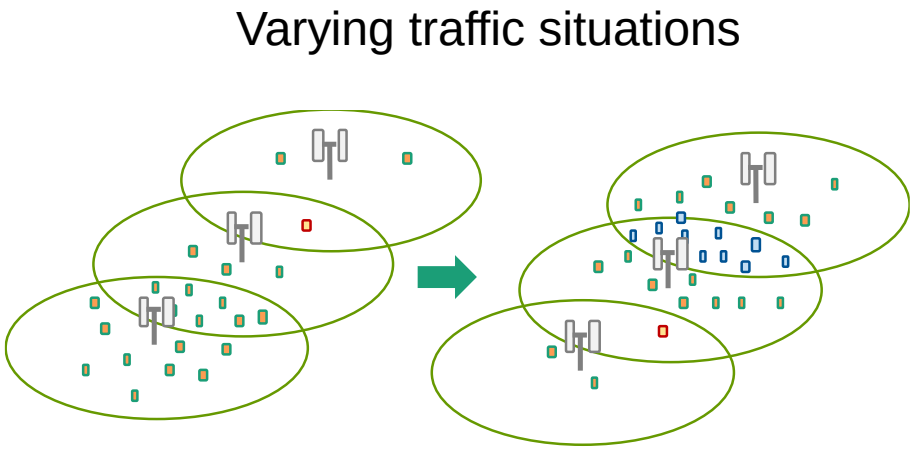
Function Splits - Case Study for Network Flexibility

- Fixed function split configuration vs.
- Dynamic migration (between the PHY-MAC split and RLC-PDCP split)

Measure for Network Flexibility: $\varphi = \frac{\text{successful (re}-\text{)configurations given } T \text{ and } C}{\text{all demands}}$

T reaction time constraint
C adaptation cost constraint

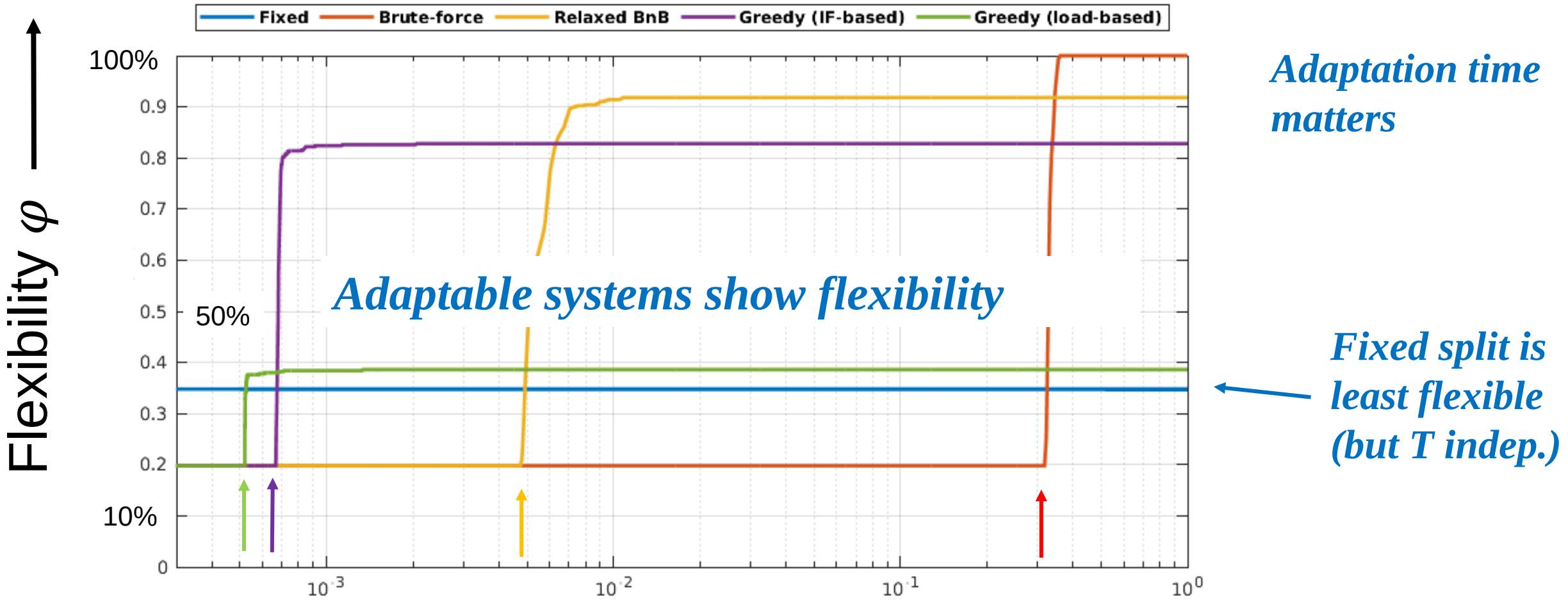




A. Martínez Alba, P. Babarczi, A. Blenk, M. He, P. Krämer, J. Zerwas, and W. Kellerer.
“Modeling the Cost of Flexibility in Communication Networks”. *IEEE Conference on Computer Communications, INFOCOM* 2021.

Function Splits - Case Study for Network Flexibility

- Comparison of different adaptation algorithms



Conclusion 1

- **we can measure network flexibility**
- **(adaptation) time matters**

www.networkflexibility.org

This work is part of a project that has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program grant agreement No 647158 – **FlexNets (2015 – 2020)**.

W. Kellerer, P. Kalmbach, A. Blenk, A. Basta, M. Reisslein, S. Schmid:
Adaptable and Data-Driven Softwarized Networks: Review, Opportunities, and Challenges. Proceedings of the IEEE **107** (4), 2019, 711 – 731.

What if the time is (too) short?

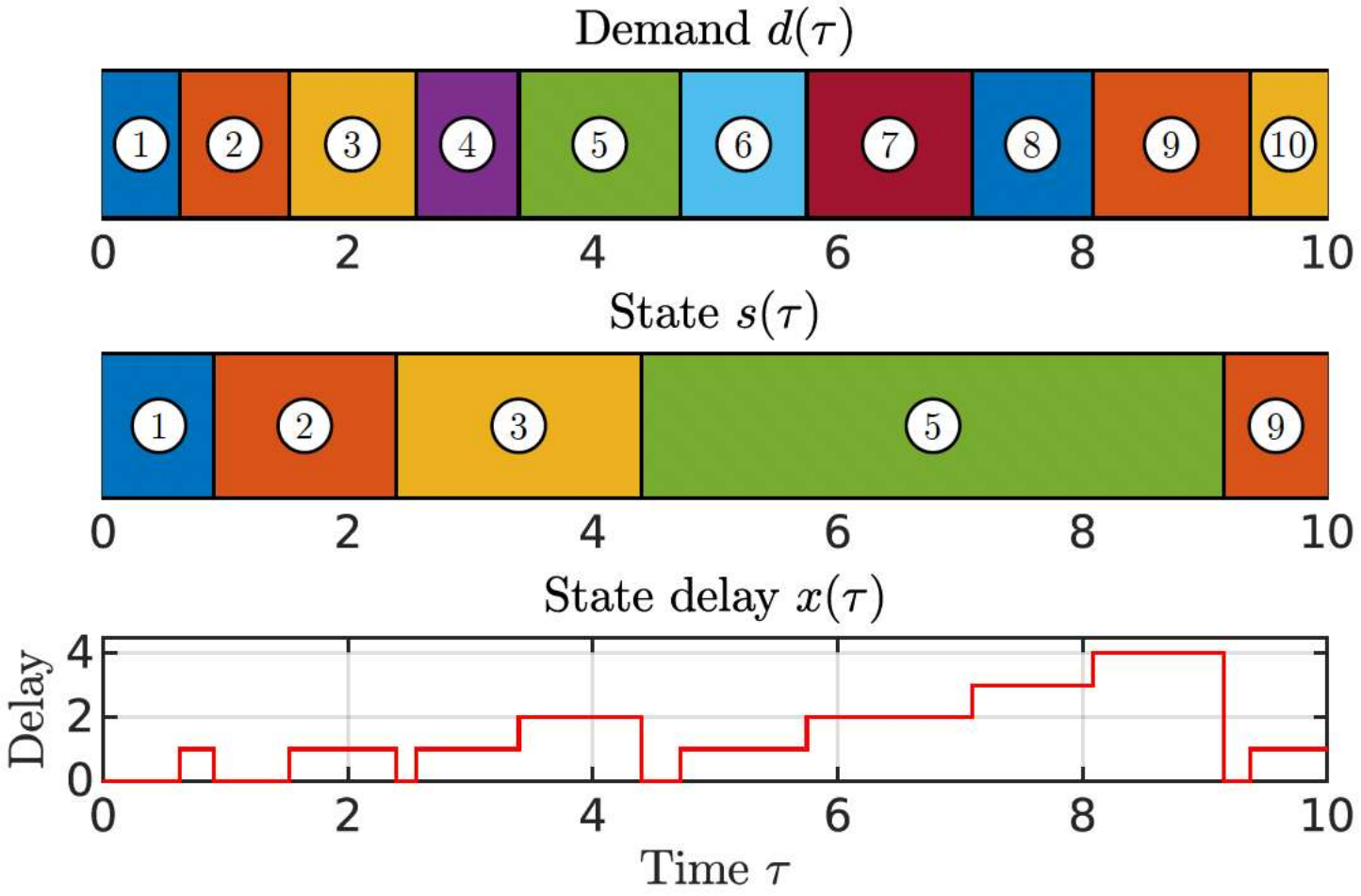
A. Martínez Alba, P. Babarczi, A. Blenk, M. He, P. Krämer, J. Zerwas, and W. Kellerer.
“Modeling the Cost of Flexibility in Communication Networks”. *IEEE Conference on Computer Communications, INFOCOM* 2021.

What if the time is (too) short?

… in highly dynamic systems such as (Open-)RAN?

A. Martínez Alba, P. Babarczi, A. Blenk, M. He, P. Krämer, J. Zerwas, and W. Kellerer.
“Modeling the Cost of Flexibility in Communication Networks”. *IEEE Conference on Computer Communications, INFOCOM* 2021.

Reacting to a demand takes time



Demands (for possible re-configuration)

Actual realized reconfigurations (state changes)

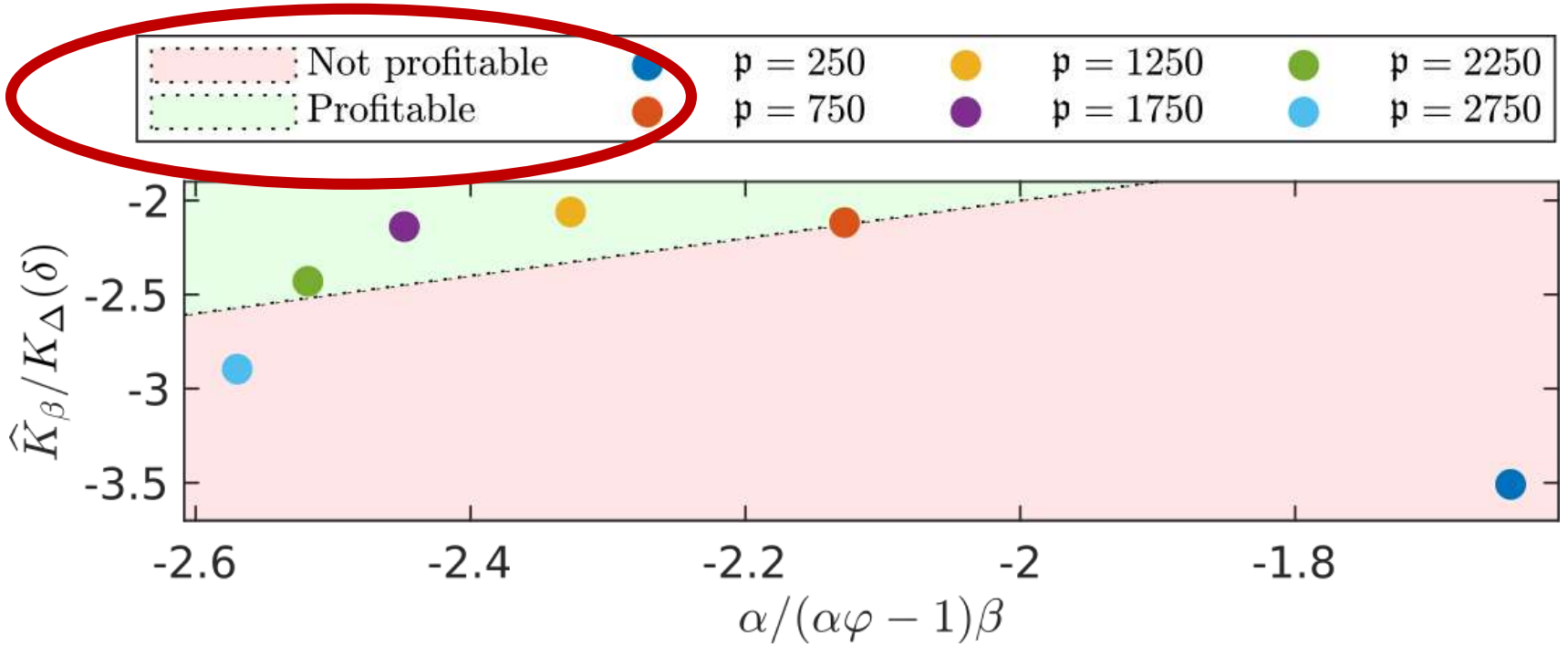
Delay between demand occurence and reconfiguration completed

A. Martínez Alba, P. Babarczi, A. Blenk, M. He, P. Krämer, J. Zerwas, and W. Kellerer.
“Modeling the Cost of Flexibility in Communication Networks”. *IEEE Conference on Computer Communications, INFOCOM* 2021.

Some reconfigurations might not be feasible (not profitable)

- Use case: dynamic flow allocation in SDN network
  - Possible initial populations for a GA: $\mathfrak{p}$={250, 750, 1250, 1750, 2250, 2750}
  - Which initial population values of this Genetic Alg. lead to profitable networks?

normalized cost



normalized representation of demand parameters and flexibility measure

A. Martínez Alba, P. Babarczi, A. Blenk, M. He, P. Krämer, J. Zerwas, and W. Kellerer.
"Modeling the Cost of Flexibility in Communication Networks". *IEEE Conference on Computer Communications, INFOCOM* 2021.

Conclusion 2

- **Reacting to a demand takes time and cost**
- **Carefully consider which re-configuration to apply**

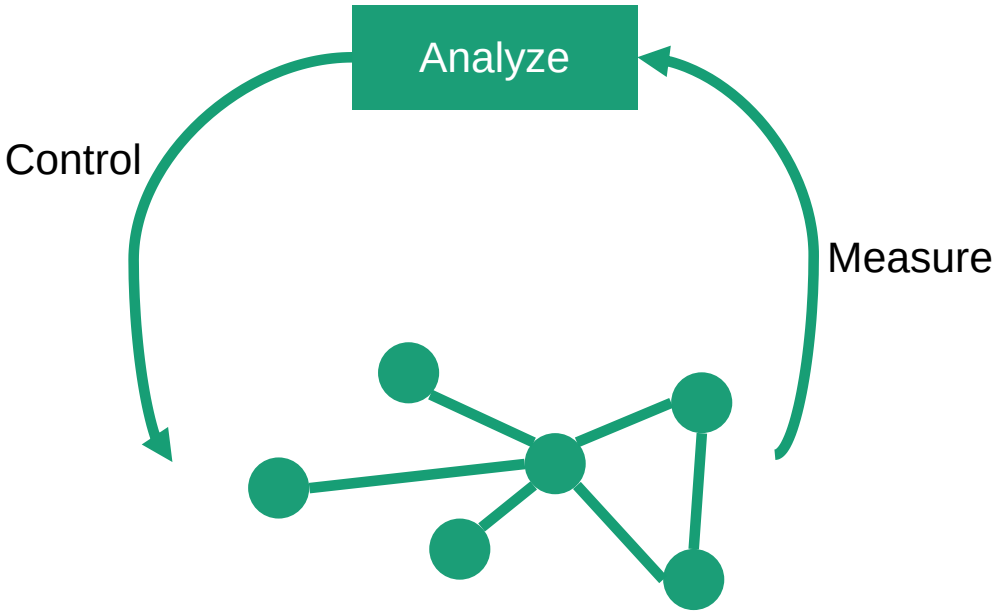
Conclusion 2

- Reacting to a demand takes time and cost
- Carefully consider which re-configuration to apply

Can we automate this?

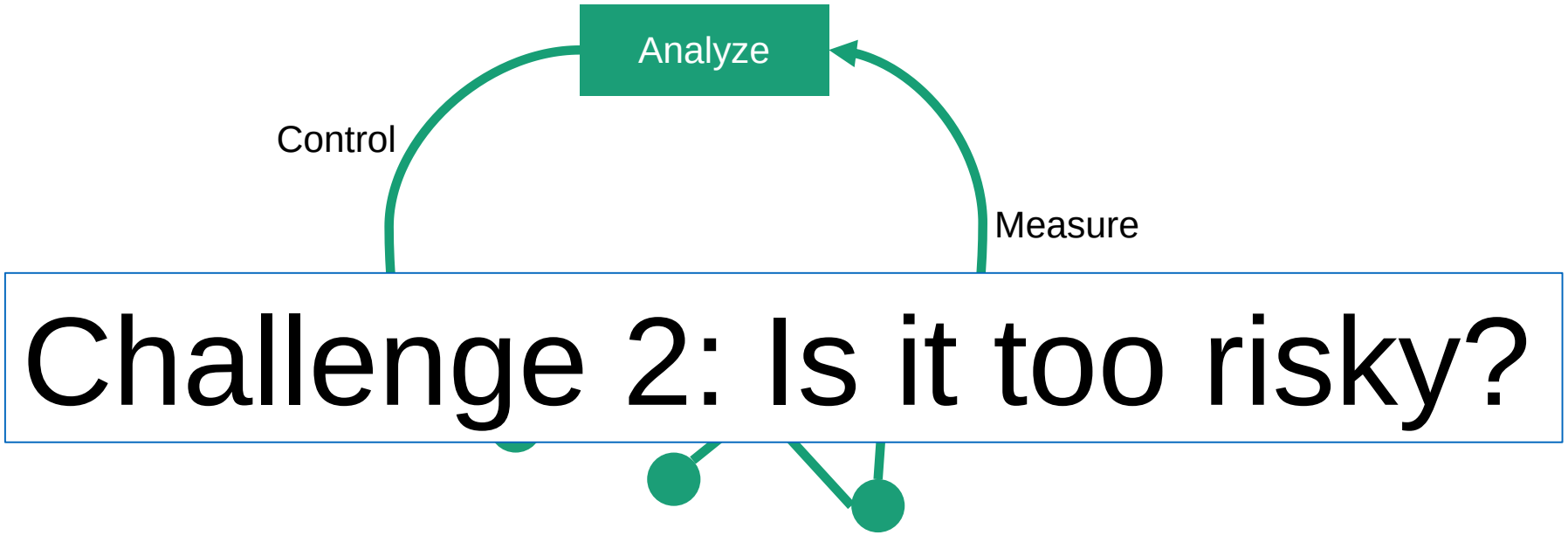
Autonomous Network Management

- Network Managers' all-time Dream:
  lean back and watch!



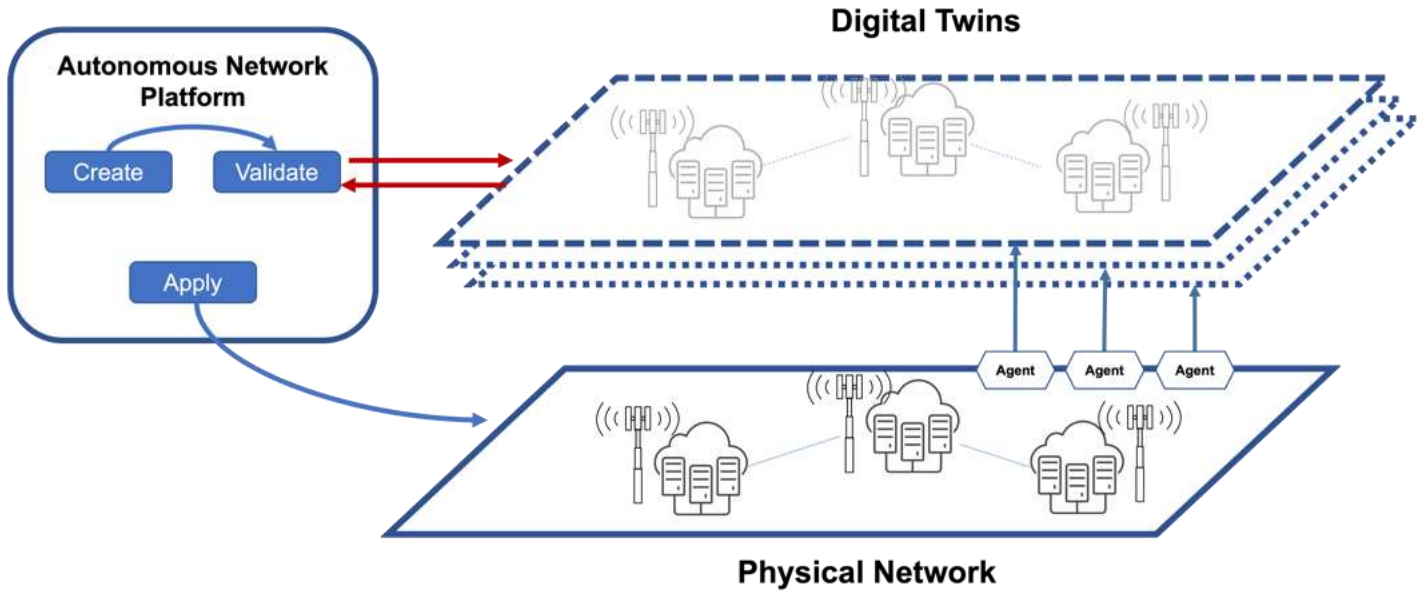
Autonomous Network Management

- Network Managers' all-time Dream:
  lean back and watch!



Limit the immediate impact on operational network

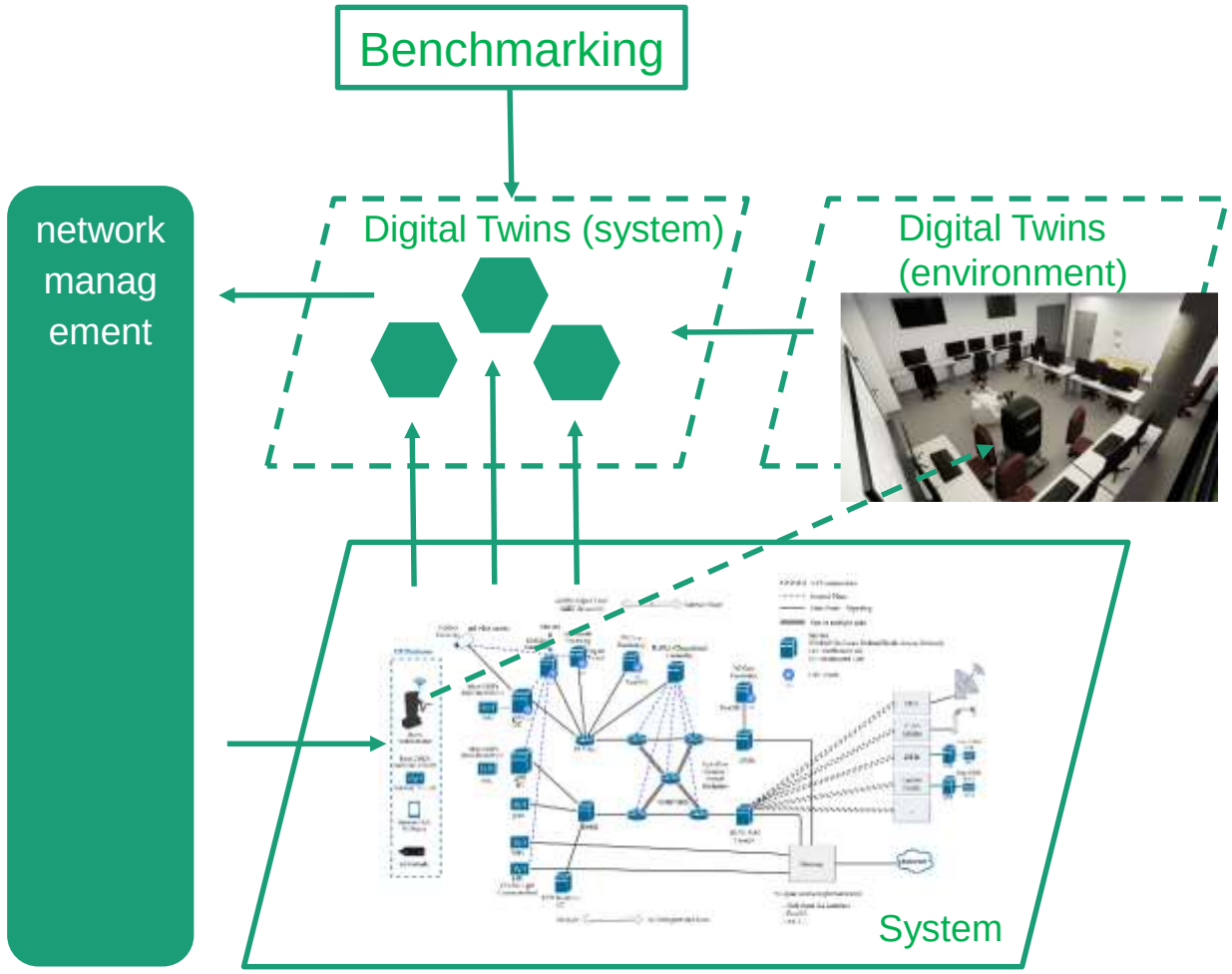
Twin your network!



https://corp.mobile.rakuten.co.jp/english/news/press/2022/0420_01/

Network Digital Twins

- Network Digital Twin = synchronized copy of a system (component)
- DTs may get information from DTs representing the environment / channel (sensors, trajectories)
- DTs simulate system behavior to improve the system
- Input to simulation: (autonomous) benchmarking



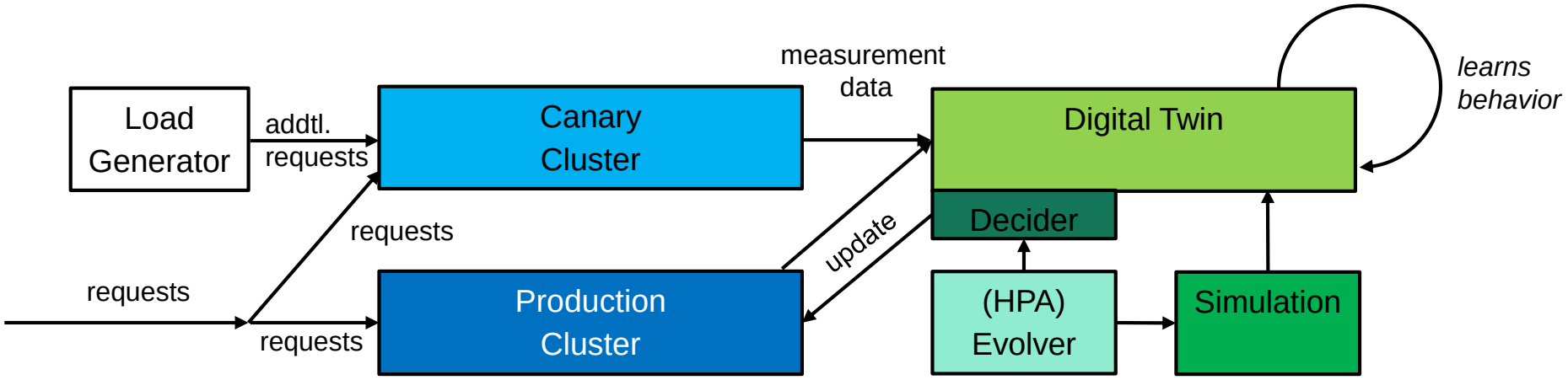
Zerwas, Johannes; Kalmbach, Patrick; Henkel, Laurenz; Retvari, Gabor; Kellerer, Wolfgang; Blenk, Andreas; Schmid, Stefan: NetBOA: Self-Driving Network Benchmarking. ACM SIGCOMM 2019 Workshop on Network Meets AI & ML (NetAI '19), 2019

Our contribution:

KAPETÅNIOS: Automated Kubernetes Adaptation through a Digital Twin

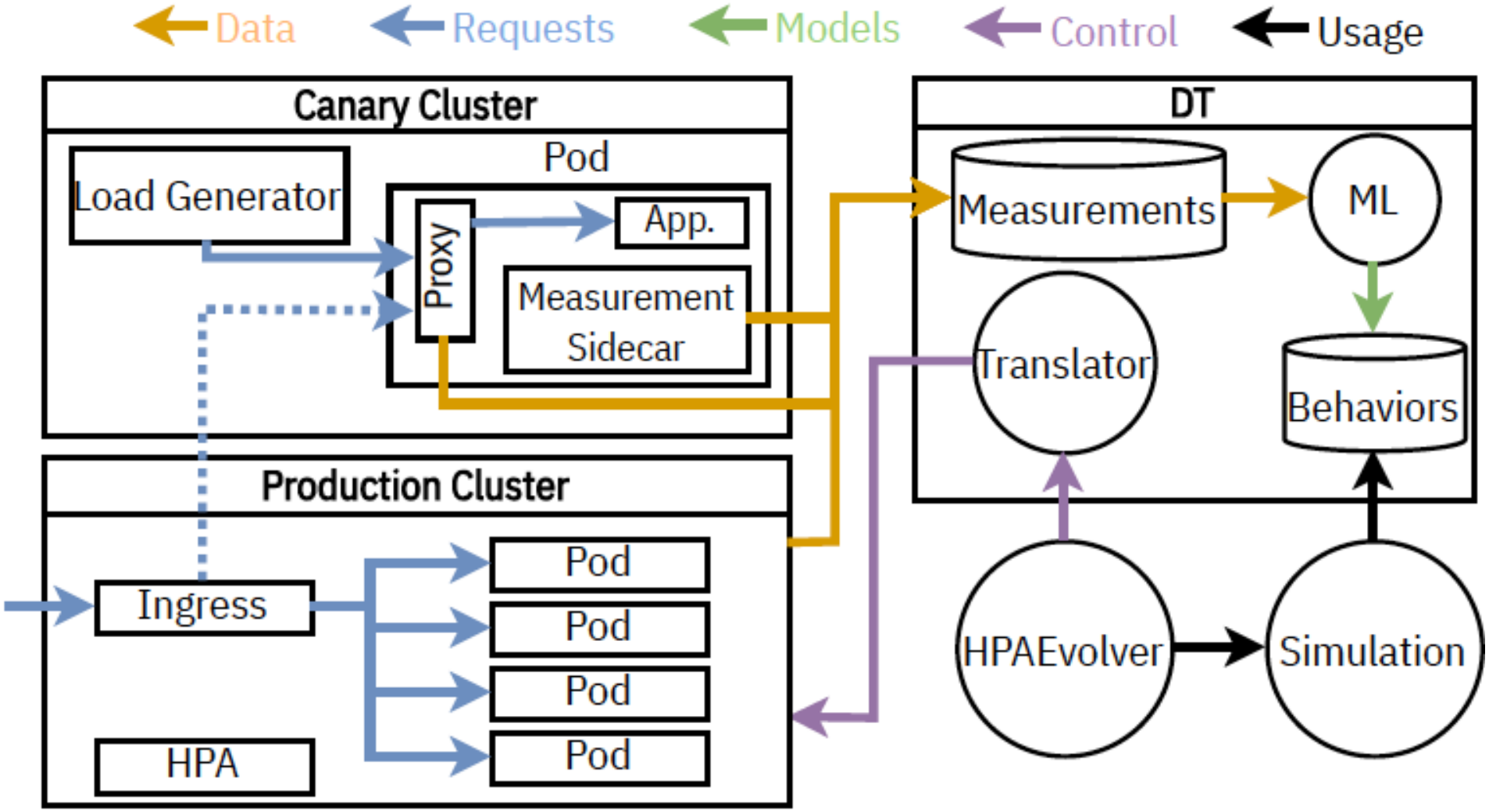
Concept

- self-operating Kubernetes (K8s) cluster
- uses digital twinning and machine learning to
- autonomously adapt its Horizontal Pod Autoscaler (HPA) to workload changes



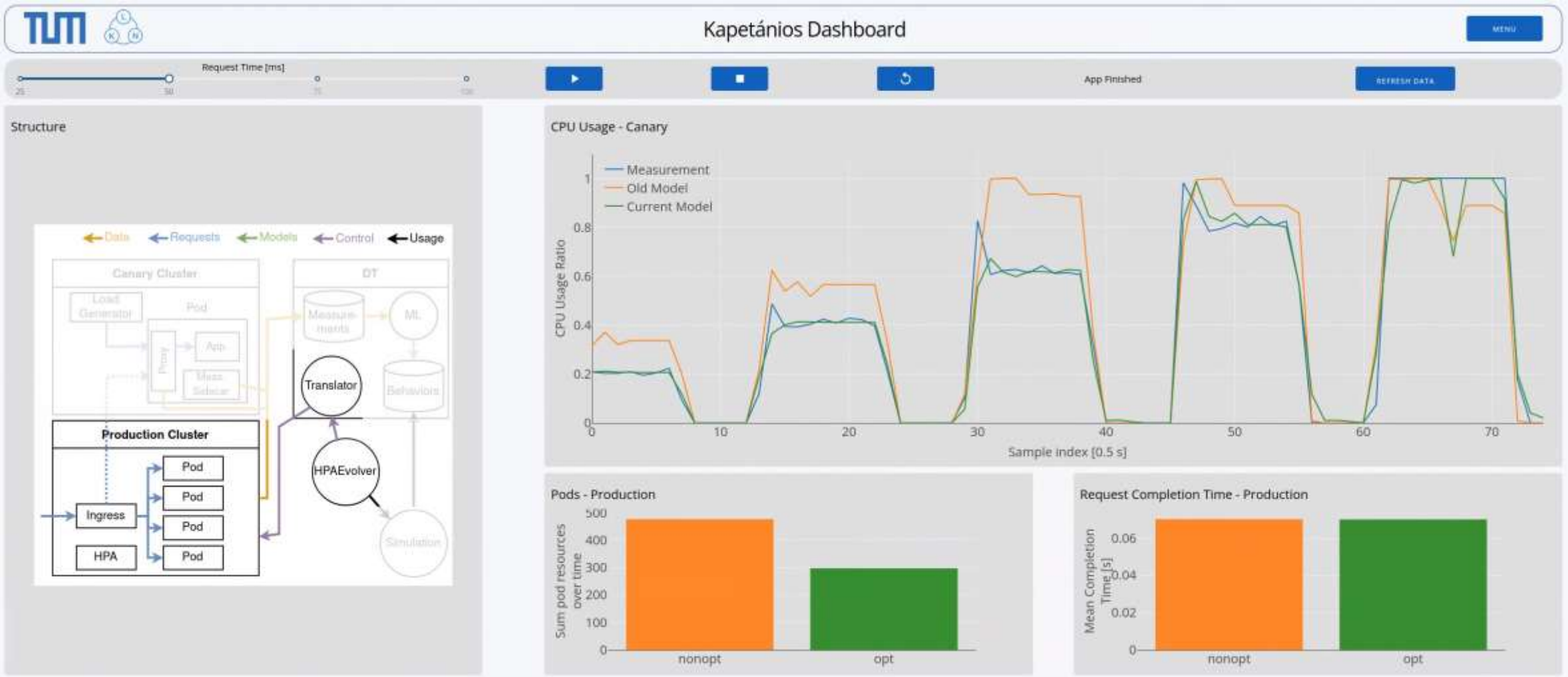
Johannes Zerwas, Patrick Krämer, Razvan-Mihai Ursu, Navidreza Asadi, Phil Rodgers, Leon Wong, Wolfgang Kellerer
KAPETÅNIOS: Automated Kubernetes Adaptation through a Digital Twin. IEEE Networks of the Future, Ghent, Belgium, 2022.

KAPETÅNIOS: Automated Kubernetes Adaptation through a Digital Twin



Johannes Zerwas, Patrick Krämer, Razvan-Mihai Ursu, Navidreza Asadi, Phil Rodgers, Leon Wong, Wolfgang Kellerer
KAPETÅNIOS: Automated Kubernetes Adaptation through a Digital Twin. IEEE Networks of the Future, Ghent, Belgium, 2022.

KAPETÅNIOS: Automated Kubernetes Adaptation through a Digital Twin



Johannes Zerwas, Patrick Krämer, Razvan-Mihai Ursu, Navidreza Asadi, Phil Rodgers, Leon Wong, Wolfgang Kellerer
KAPETÅNIOS: Automated Kubernetes Adaptation through a Digital Twin. IEEE Networks of the Future, Ghent, Belgium, 2022.

How to obtain a Network Digital Twin?

… AI/ML may help

R.-M. Ursu, J. Zerwas, P. KrÅNamer, N. Asadi, P. Rodgers, L. Wong, and W. Kellerer, “Towards Digital Network Twins: Can we Machine Learn Network Function Behaviors?” in 2023 IEEE 9th International Conference on Network Softwarization (NetSoft), 2023,

How to obtain a Network Digital Twin?

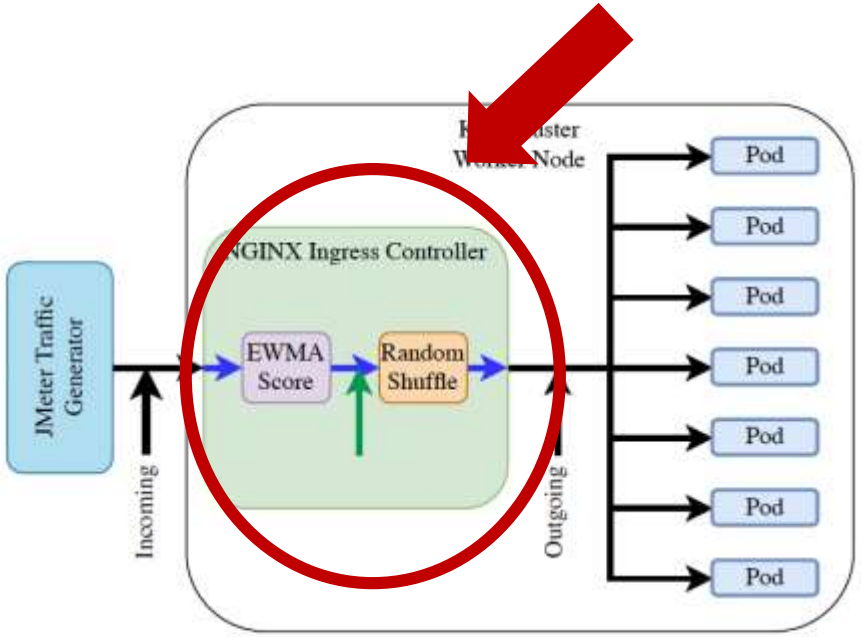
… AI/ML may help

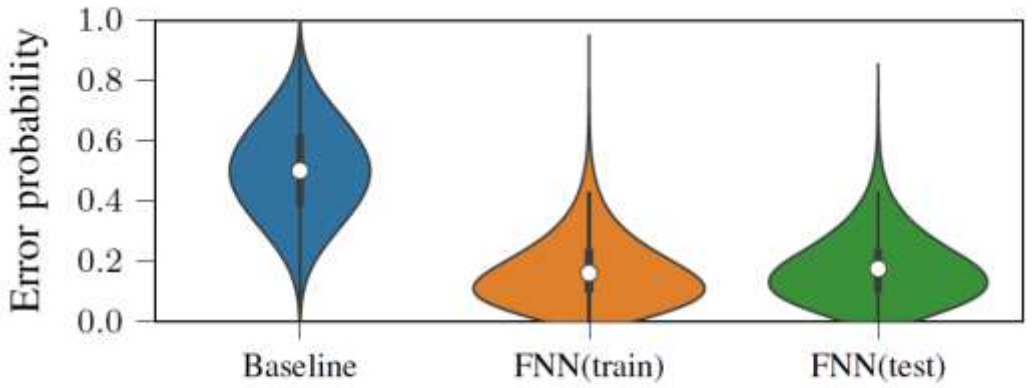
- *Can we Machine Learn Network Function Behavior?*

R.-M. Ursu, J. Zerwas, P. KrÅNamer, N. Asadi, P. Rodgers, L. Wong, and W. Kellerer, “Towards Digital Network Twins: Can we Machine Learn Network Function Behaviors?” in 2023 IEEE 9th International Conference on Network Softwarization (NetSoft), 2023,

Can we machine learn network Functions Behavior?

Use case: Kubernetes Load Balancer





random decision

learned behavior

R.-M. Ursu, J. Zerwas, P. Kräamer, N. Asadi, P. Rodgers, L. Wong, and W. Kellerer, “Towards Digital Network Twins: Can we Machine Learn Network Function Behaviors?” in 2023 IEEE 9th International Conference on Network Softwarization (NetSoft), 2023,

How to obtain a Network Digital Twin?

… AI/ML may help

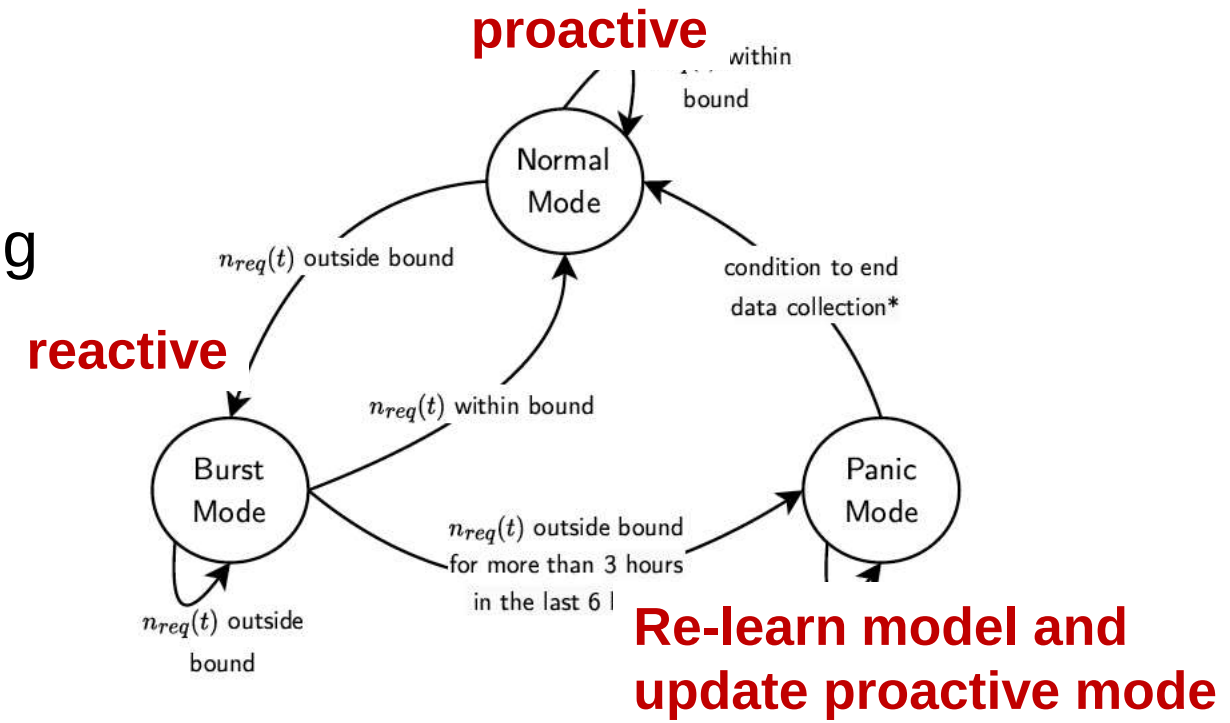
- *Can we Machine Learn Network Function Behavior?*
- *Can AI/ML automate learning?*

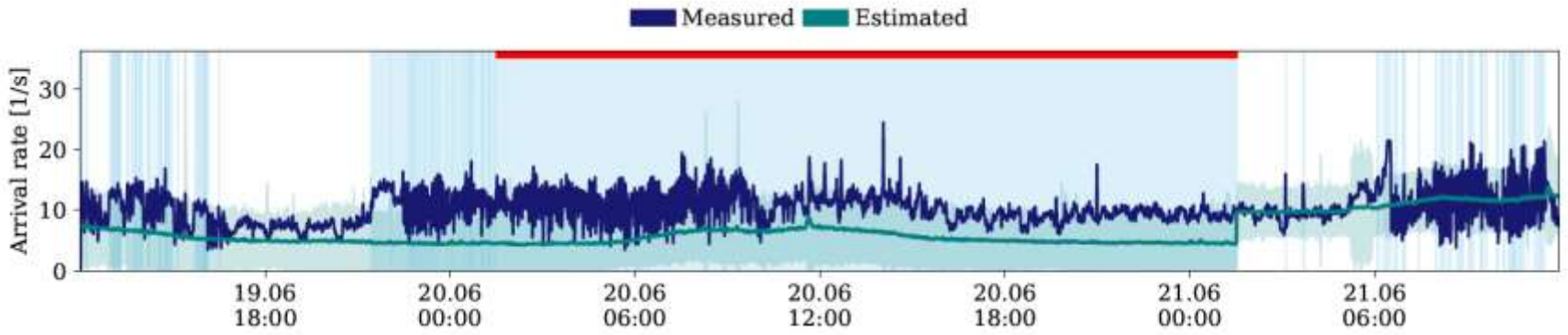
R.-M. Ursu, J. Zerwas, P. KrÅNamer, N. Asadi, P. Rodgers, L. Wong, and W. Kellerer, “Towards Digital Network Twins: Can we Machine Learn Network Function Behaviors?” in 2023 IEEE 9th International Conference on Network Softwarization (NetSoft), 2023,

Can AI/ML automate learning?

- Use Case

  HYPA: Hybrid Horizontal Pod Autoscaling with Automated Model Updates





K. Aykurt, R.-M. Ursu, J. Zerwas, P. Krämer, N. Asadi, L. Wong, and W. Kellerer, "HyPA: Hybrid Horizontal Pod Autoscaling with Automated Model Updates," in 2023 IEEE Conference on Network Function Virtualization and Software Defined Networks (NFV-SDN), 2023

Final Conclusion and Lessons Learned

- After SDN in the core, O-RAN provides SD-x based flexibility to the RAN
- We can actually measure such **network flexibility**
- Adaptation time and adaptation cost matter

www.networkflexibility.org

FlexNets

This work is part of a project that has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program grant agreement No 647158 – **FlexNets (2015 – 2020)**.

- Towards **automated network management**
  we need a playground to decide in runtime, which reconfigurations to apply (feasible, profitable)

- **Network Digital Twins** provide a solution
- We provide Kapetanios
- We show that NDTs can be learned (instead of complex modeling)

Bundesministerium für Bildung und Forschung

DFG Deutsche Forschungsgemeinschaft

Gefördert durch Bayerisches Staatsministerium für Wirtschaft, Landesentwicklung und Energie

Rakuten Mobile

6G-life

This work receives financial support by the Federal Ministry of Education and Research of Germany (BMBF) in the programme of "Souverän. Digital. Vernetzt." joint project 6G-life, project identification number 16KISK002, and the Bavarian Ministry of Economic Affairs, Regional Development and Energy as part of the project "6G Future Lab Bavaria" and "5G Testbed" and "6G und Quantentechnologie", and the German Research Foundation (DFG), grant numbers: 316878574, 438892507, 315177489.

Selected References

- A. Martínez Alba, P. Babarczi, A. Blenk, M. He, P. Krämer, J. Zerwas, W. Kellerer: *Modeling the Cost of Flexibility in Communication Networks.* IEEE INFOCOM 2021.
- W. Kellerer, P. Kalmbach, A. Blenk, A. Basta, M. Reisslein, S. Schmid: *Adaptable and Data-Driven Softwarized Networks: Review, Opportunities, and Challenges*. Proceedings of the IEEE **107** (4), 2019, 711 – 731.
- J. Zerwas, P. Kalmbach, L. Henkel, G. Retvari, W. Kellerer, A. Blenk, S. Schmid: *NetBOA: Self-Driving Network Benchmarking*. ACM SIGCOMM 2019 Workshop NetAI 2019.
- J. Zerwas, P. Krämer, R.-M. Ursu, N. Asadi, P. Rodgers, L. Wong, and W. Kellerer: *KAPETANIOS: Automated Kubernetes Adaptation through a Digital Twin*. IEEE NoF 2022.
- R.-M. Ursu, J. Zerwas, P. Krämer, N. Asadi, P. Rodgers, L. Wong, and W. Kellerer: *Towards Digital Network Twins: Can we Machine Learn Network Function Behaviors?* IEEE NetSoft 2023.
- K. Aykurt, R.-M. Ursu, J. Zerwas, P. KrÅNamer, N. Asadi, L. Wong, and W. Kellerer: *HyPA: Hybrid Horizontal Pod Autoscaling with Automated Model Updates*. IEEE NFV-SDN 2023.