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TUM

6G meets Future Networking

Wolfgang Kellerer

IEEE/IFIP NOMS 2022 - keynote

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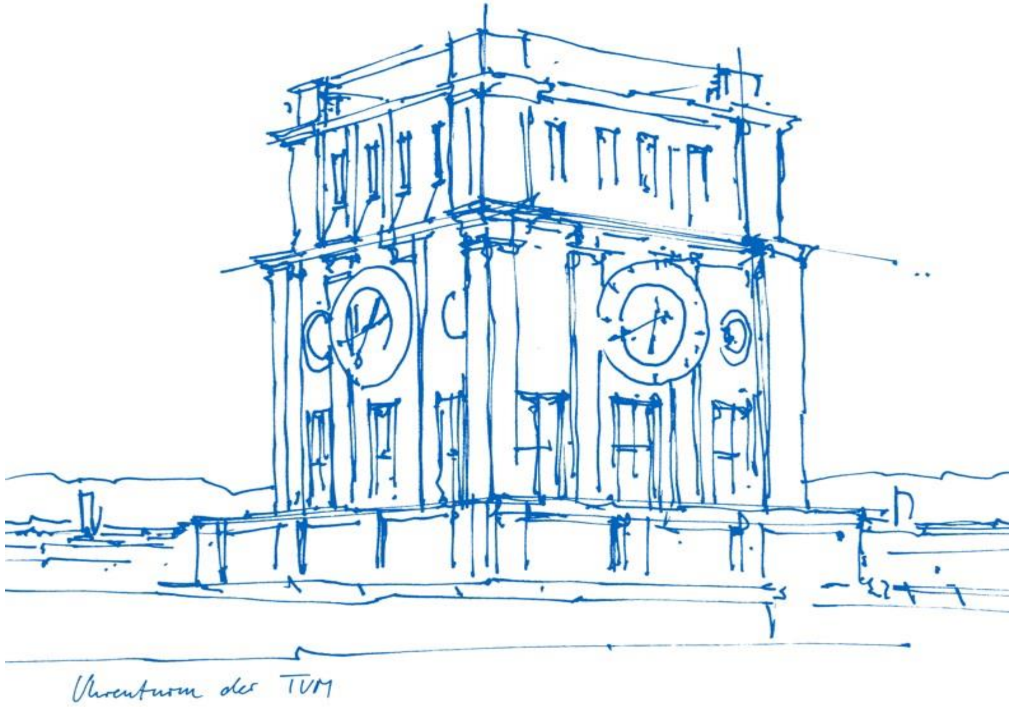
NOMS · IEEE ComSoc IEEE Communications Society · ifip · IEEE



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.

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„6G will be human focused“

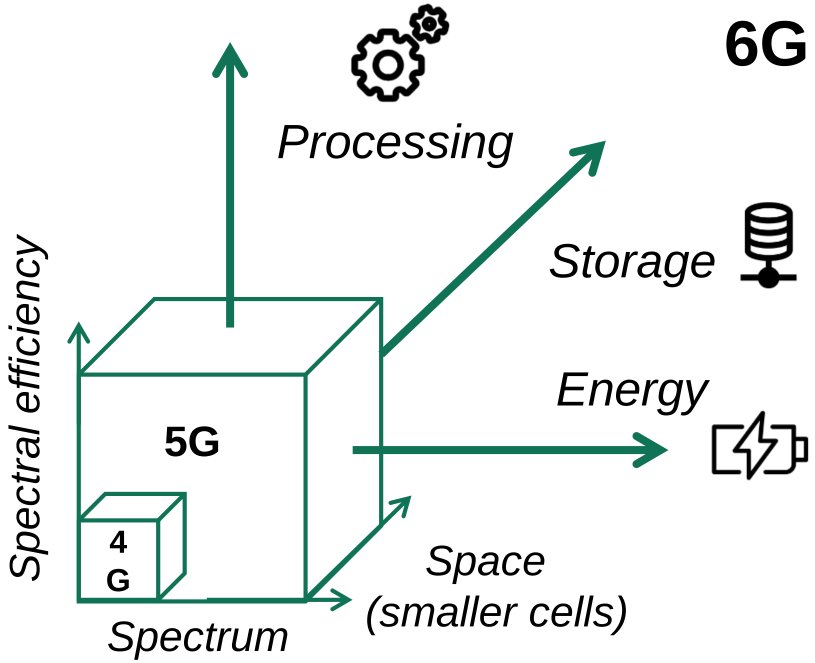
- 4G: mobile apps and video
- 5G: machine-to-machine communication
- 6G: the human in the center – extension of the human intelligence and the human abilities

- *for robots collaborating with humans 1ms RTT and 5 nines availability is no longer enough*

[Kel21] TUM press release, https://www.tum.de/en/about-tum/news/press-releases/details/36507/
[6G-life] BMBF 6G Research Hub 6G-life, https://6g-life.de

What does this mean for 6G?

- Terahertz-frequency spectrum up to LIFI
- Multi-network (network-of networks)
- In-network computing
- Network adaptation (communication + processing + storage)
- Network-as-a-Sensor: joint communication and sensing
- AI/ML-native communication
- Sustainability: end-to-end energy efficiency
- Resilience, security, privacy and trust by design
- Beyond paradigms: post-shannon communication, quantum networks, molecular networks



Processing, storage and energy are included in the 6G system optimization

[6qu22] Trommler, Hafner, Kellerer, et al. Six Questions about 6G, Bayern Innovativ, Münchner Kreis, White Paper, Feb 2022.

What is in for networking (and network management)?

6G clearly builds on strong future networking concepts

- Terahertz-frequency spectrum up to LIFI
- Multi-network (network-of-networks)
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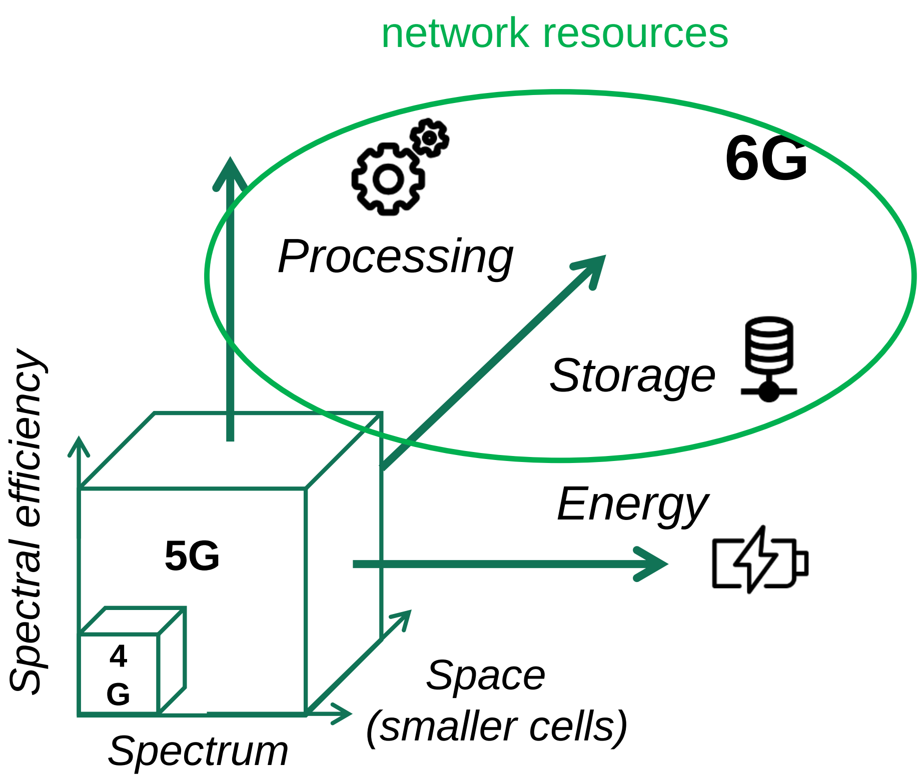

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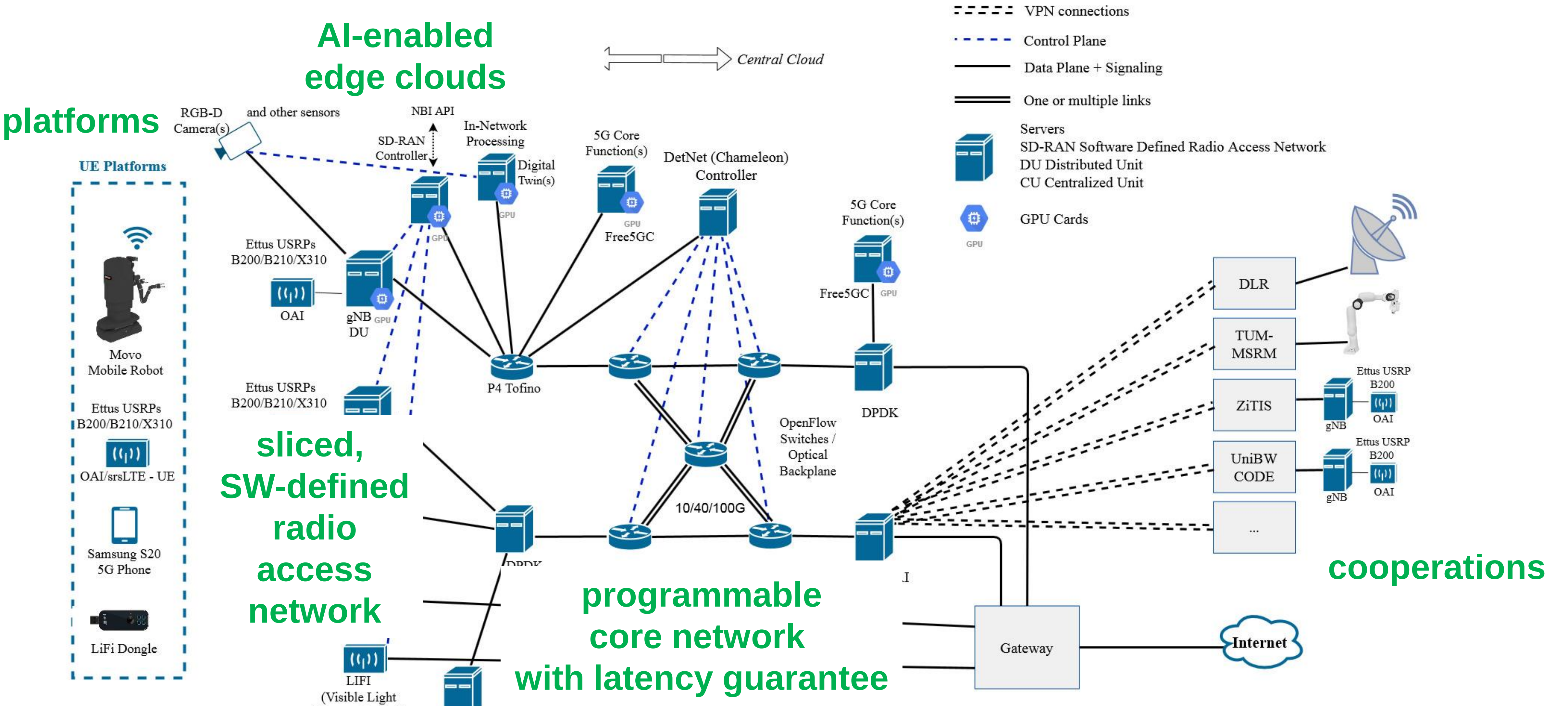
6G Experimental Platform

https://www.5g-munich.de/html/demo.html

Foto: TUM/Heddergott

5G / 6G Testbed at the Chair of Communication Networks at TUM



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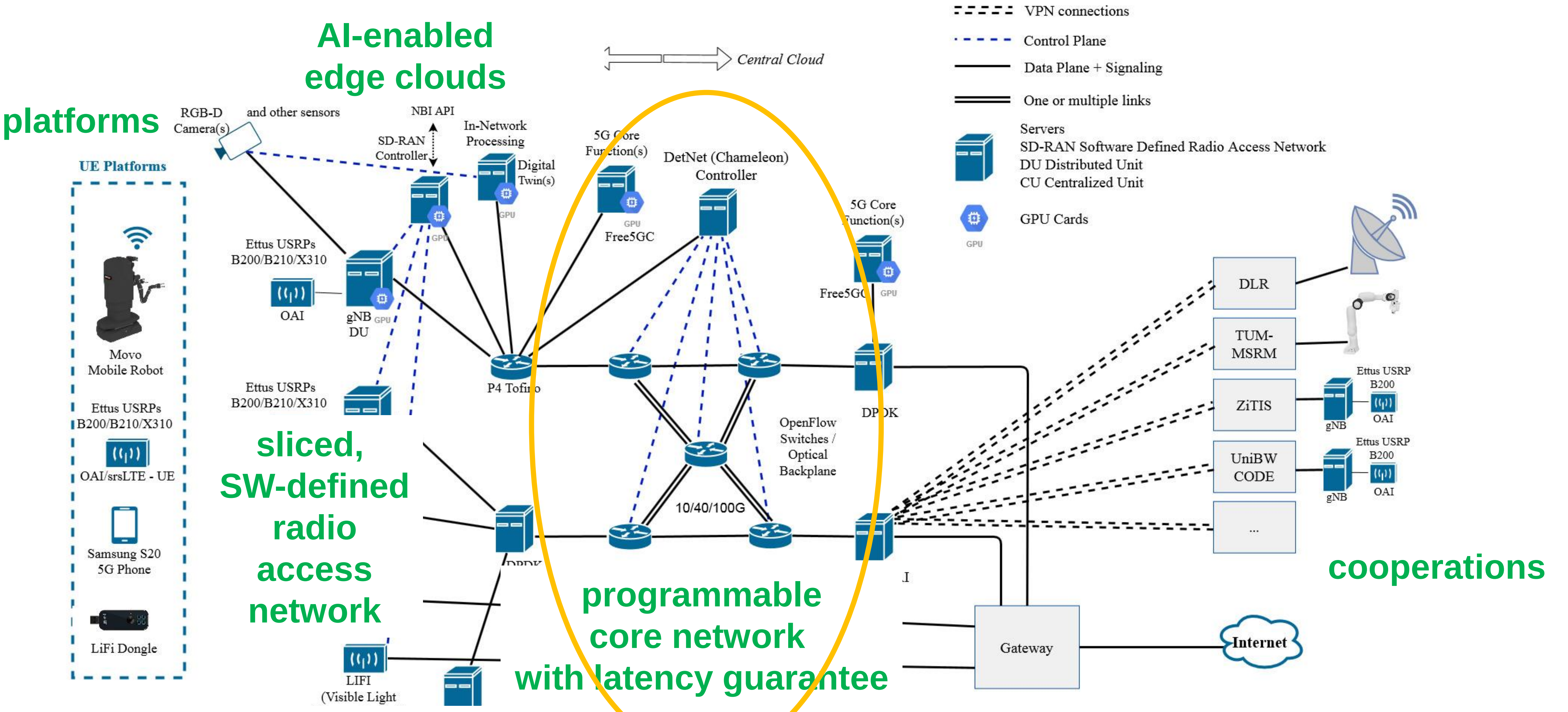

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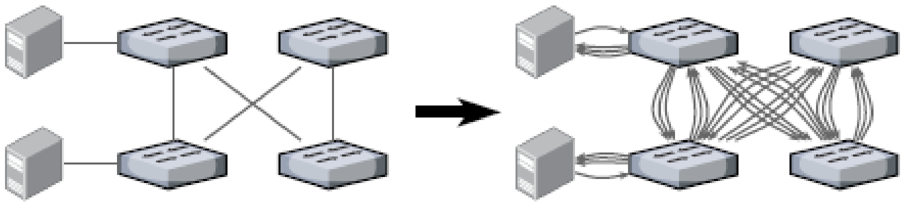
Chameleon: Guaranteed end-to-end low latency in the network

- Principle:



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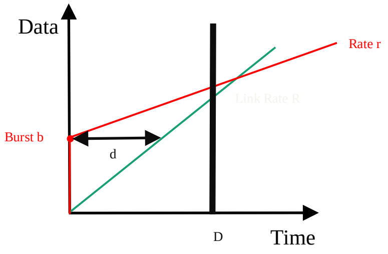
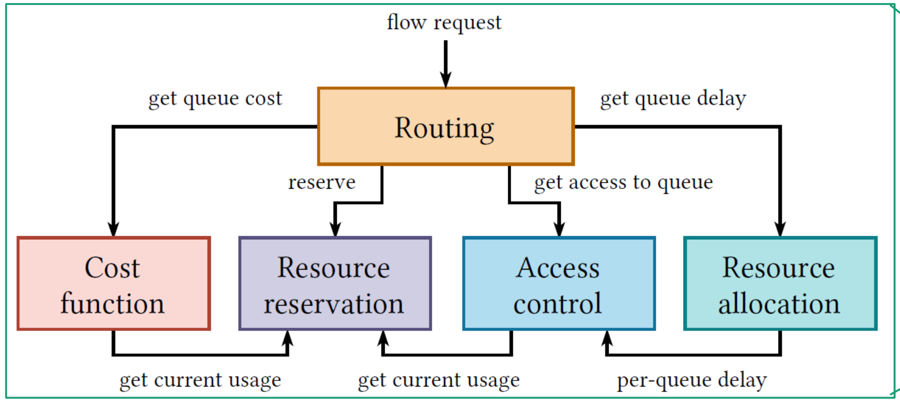
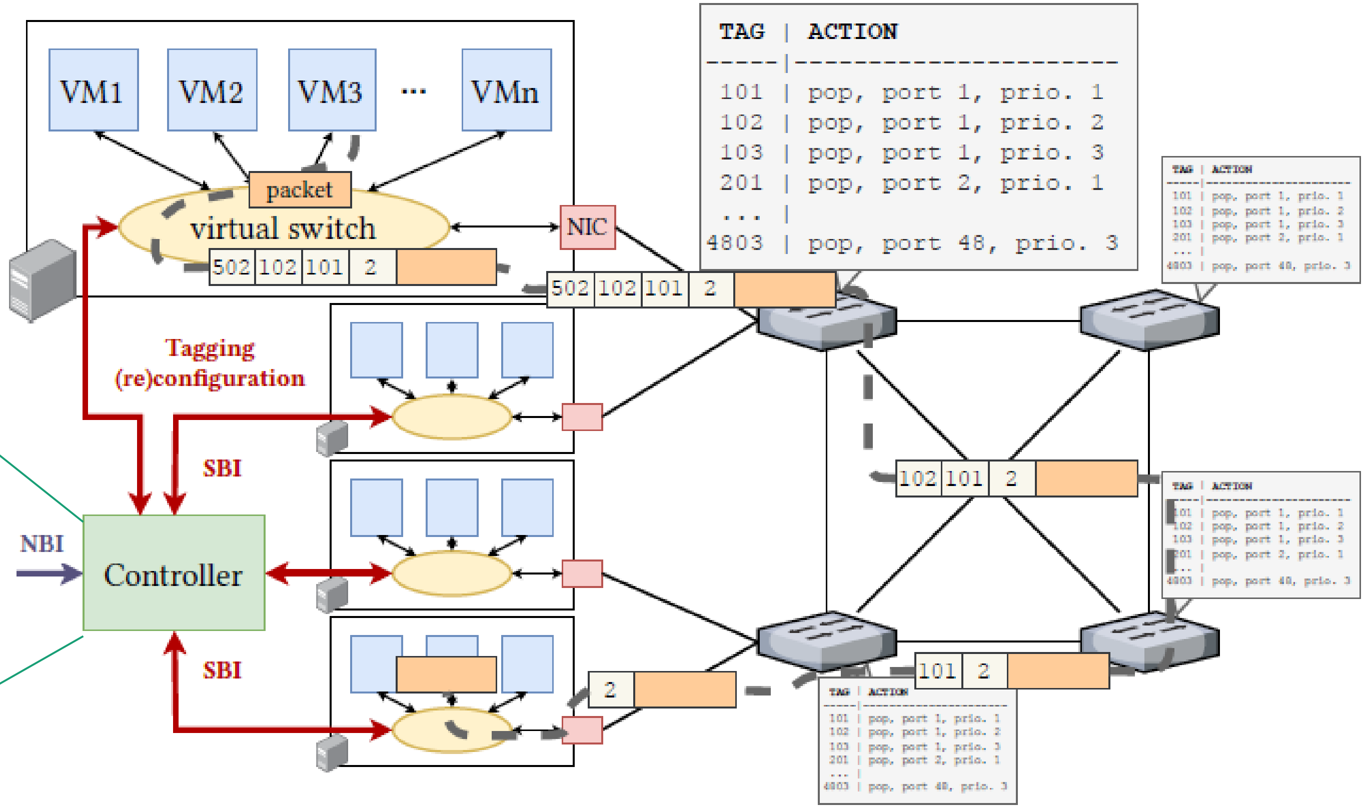


- Realization in a programmable network with central controller: „Chameleon“

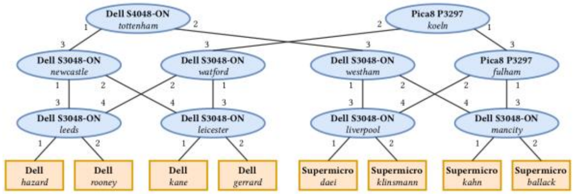


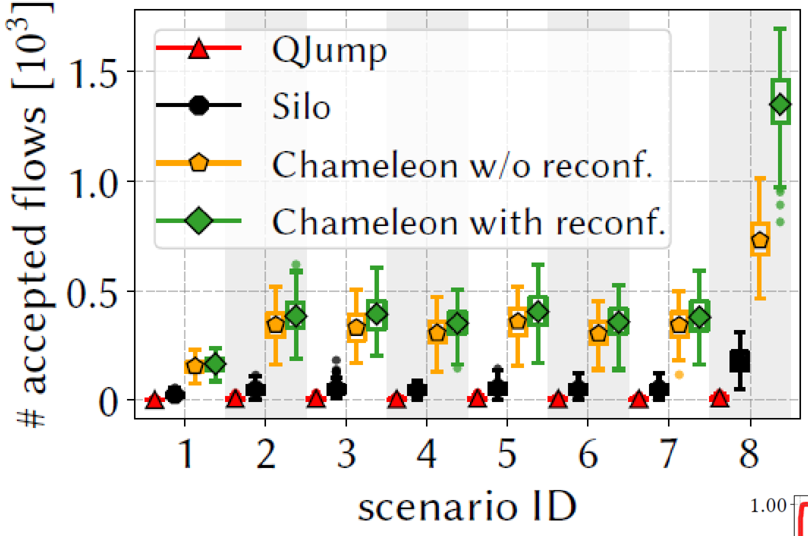


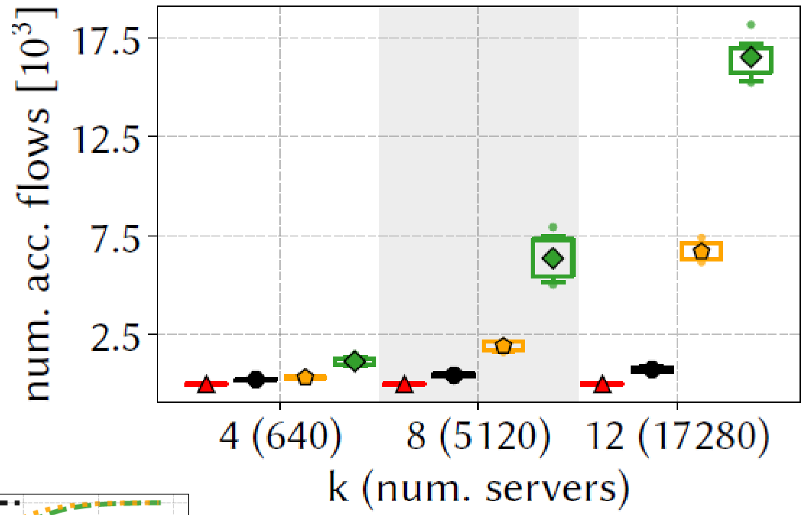
Van Bemten, Amaury; Deric,Nemanja; Varasteh,Amir; Schmid,Stefan; Mas Machuca,Carmen; Blenk,Andreas; Kellerer,Wolfgang: Chameleon: Predictable Latency and High Utilization with Queue-Aware and Adaptive Source Routing. CoNEXT 2020.

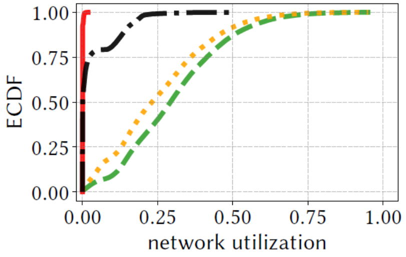
Chameleon: Guaranteed end-to-end low latency in the network

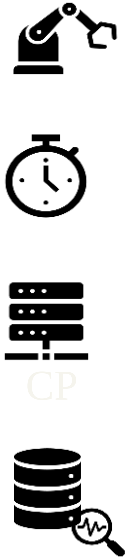
- Chameleon successfully provides latency guarantees, reaches higher network utilization than existing approaches, and scales to networks with tens of thousands of servers











30%
Industrial

30%
Clock
sync

30%
Control plane
sync

10%
High Bandwidth

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… supported by in-network computing and network programmability

- there is no free lunch
- from our research on „quantifying flexibilty in communication networks“ (ERC Consolidator Grant FlexNets: 2015 - 2021) → *Consider the Cost of Flexibility!*

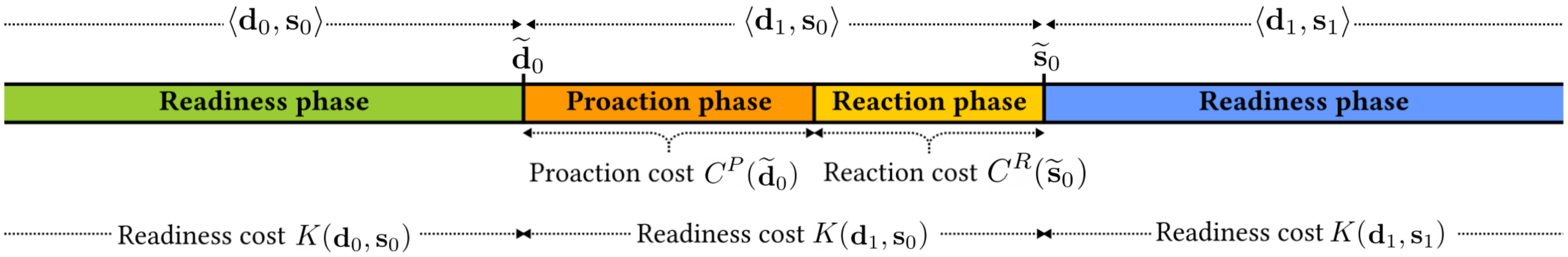
FlexNets

- The **total operating cost** $Q = K + C^P + C^R$ of a flexible network is the sum of:
  - **Readiness cost** K: cost of operating the network at the current state given an active demand
  - **Proaction cost** C^P: cost of finding a new state during the proaction phase
  - **Reaction cost** C^R: cost of implementing a new state during the reaction phase

e.g. run control plane and some embedded flows

e.g. run optimizer for new flow embedding

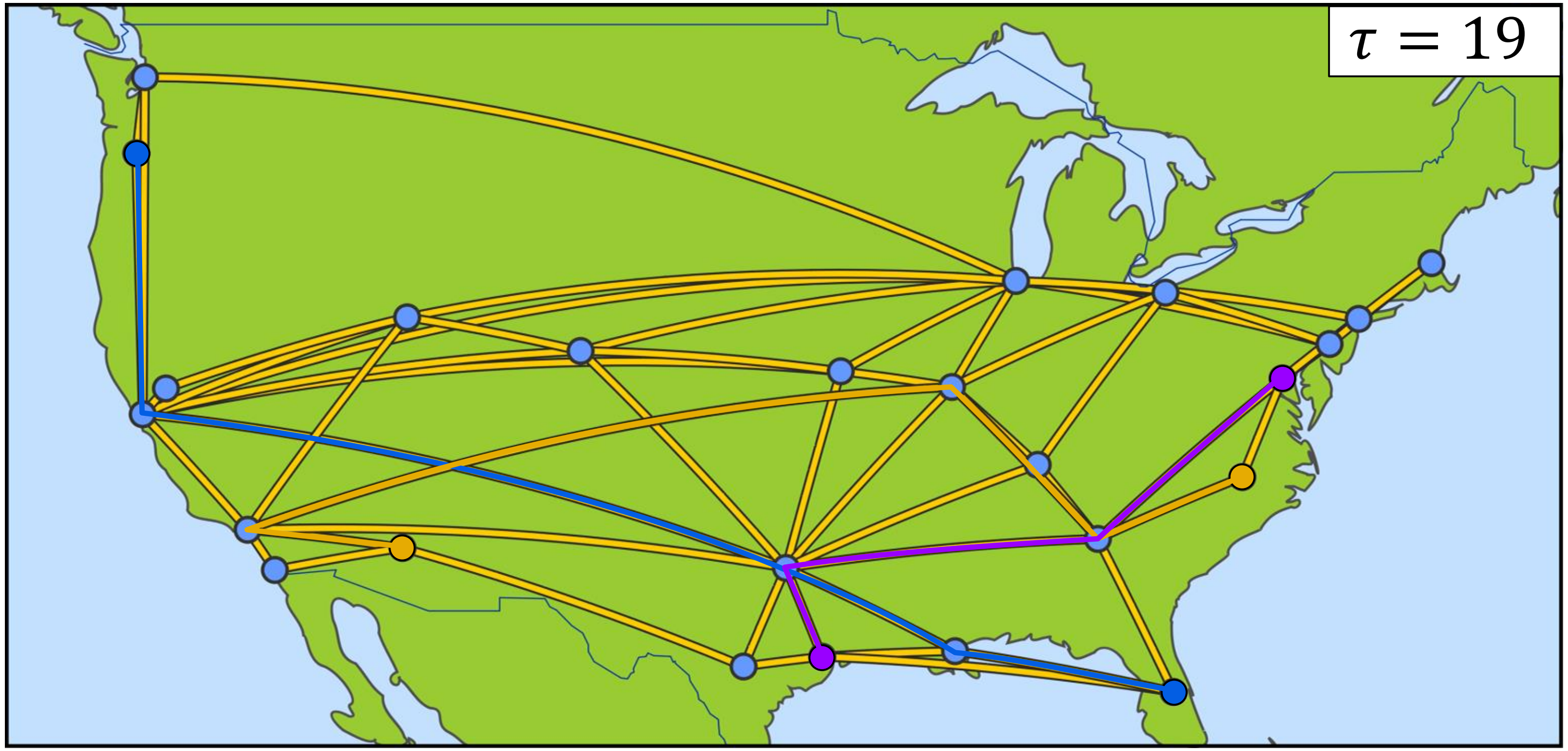
e.g. send control msg. to embedd new flow



Martínez Alba, Alberto; Babarczi, Péter; Blenk, Andreas; He, Mu; Krämer, Patrick; Zerwas, Johannes; Kellerer, Wolfgang:
Modeling the Cost of Flexibility in Communication Networks. IEEE INFOCOM 2021 - IEEE Conference on Computer Communications, 2020.

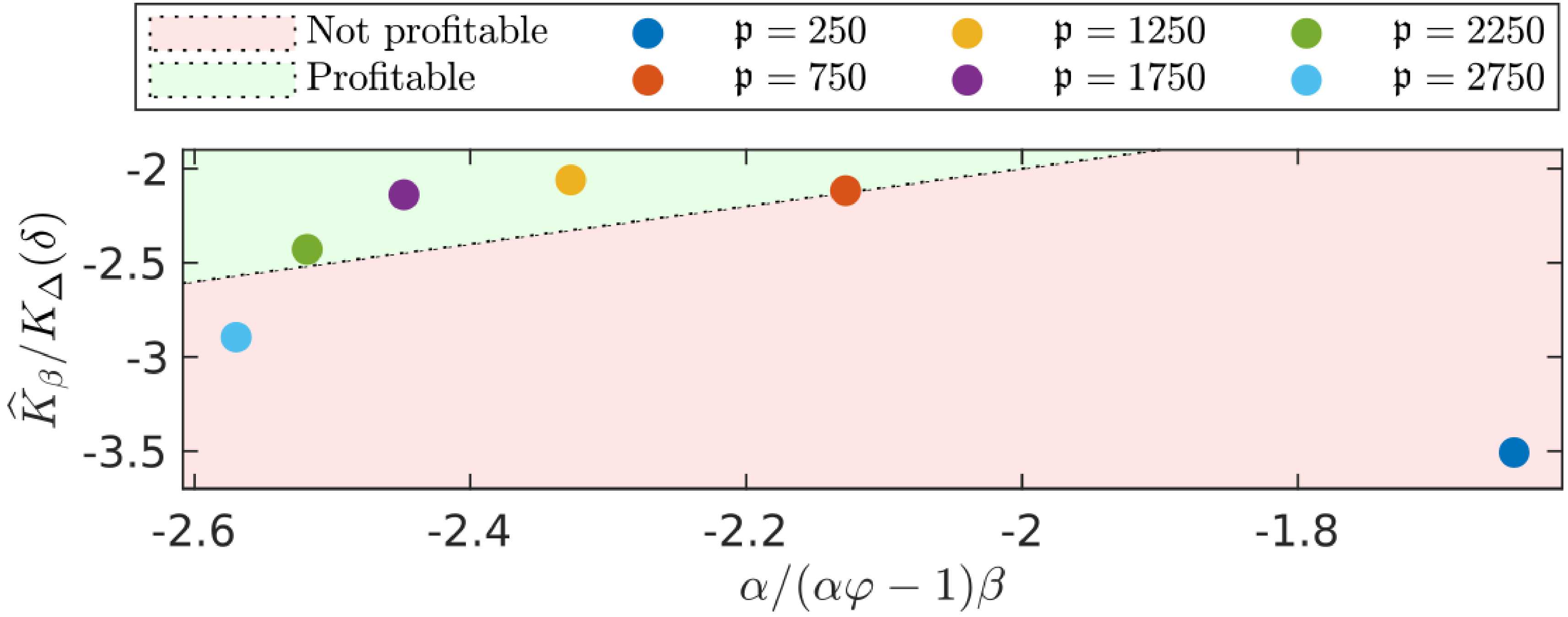
Example: dynamic flow allocation in SDN network

- **Service:** provide a connection between two nodes when demanded
- **Objective:** minimize number of used links



Example: evaluating adaptation algorithms

- Operator uses a **genetic algorithm** to find a near-optimal integer path
- Possible **initial populations**: $\mathfrak{p} = \{250, 750, 1250, 1750, 2250, 2750\}$
- Which initial population values lead to **profitable** networks?

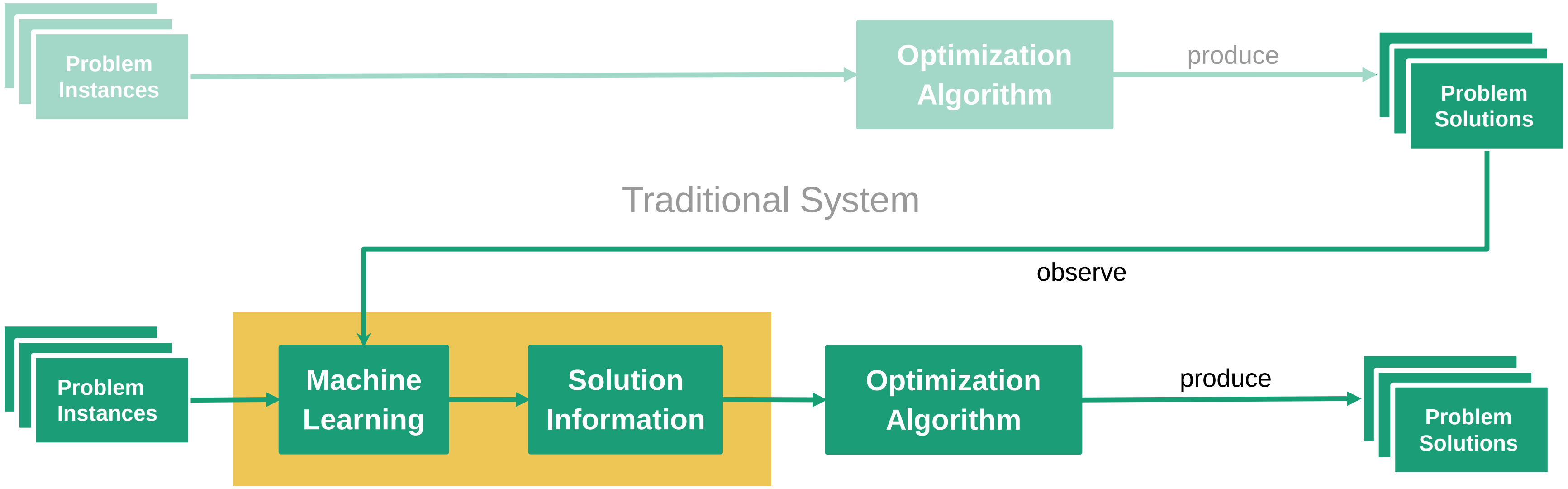


A. Martínez Alba, P. Babarczi, A. Blenk, M. He, P. Krämer, J. Zerwas, and W. Kellerer. “Modeling the Cost of Flexibility in Communication Networks”. *IEEE Conference on Computer Communications, INFOCOM* 2021.

And what about complexity?

- Softwarization vastly increases the degree of freedom
  → complexity increases, amount of data increases

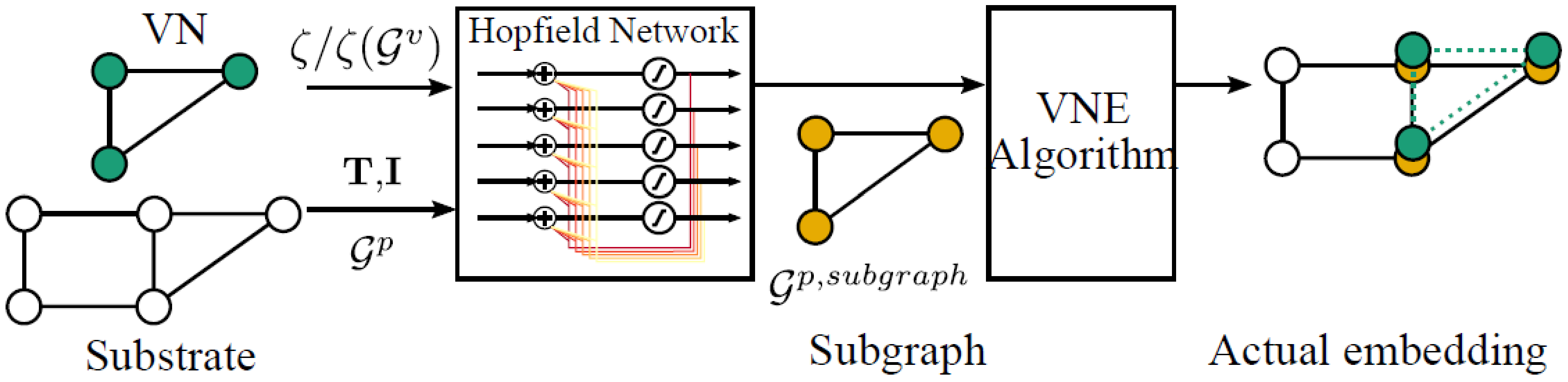
- **Artificial Intelligence** (AI) in future networks can help to solve optimization problems better



Kellerer, Wolfgang; Kalmbach, Patrick; Blenk, Andreas; Basta, Arsany; Reisslein, Martin; Schmid, Stefan:
Adaptable and Data-Driven Softwarized Networks: Review, Opportunities, and Challenges. Proceedings of the IEEE **107** (4), 2019, 711 – 731

How can we boost the solving of the related optimization problems (leaving your algorithms untouched)?

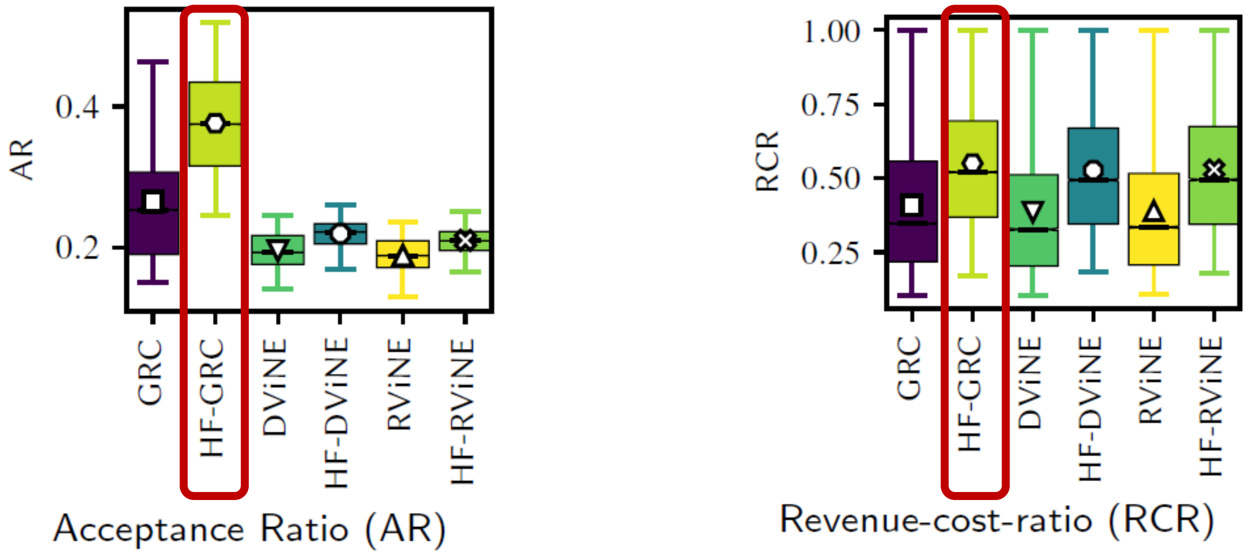
- NeuroViNE:
  Hopfield neural network to preprocess (subgraph extraction) VNE algorithms - tailored filtering



- Idea: Extract subgraph with physical nodes close to each other and high available capacities

A. Blenk, P. Kalmbach, J. Zerwas, M. Jarschel, S. Schmid, W. Kellerer: ***NeuroViNE: A Neural Preprocessor for Your Virtual Network Embedding Algorithm*** IEEE INFOCOM 2018 (main conference), Honolulu, HI, USA, April 15-19, 2018.

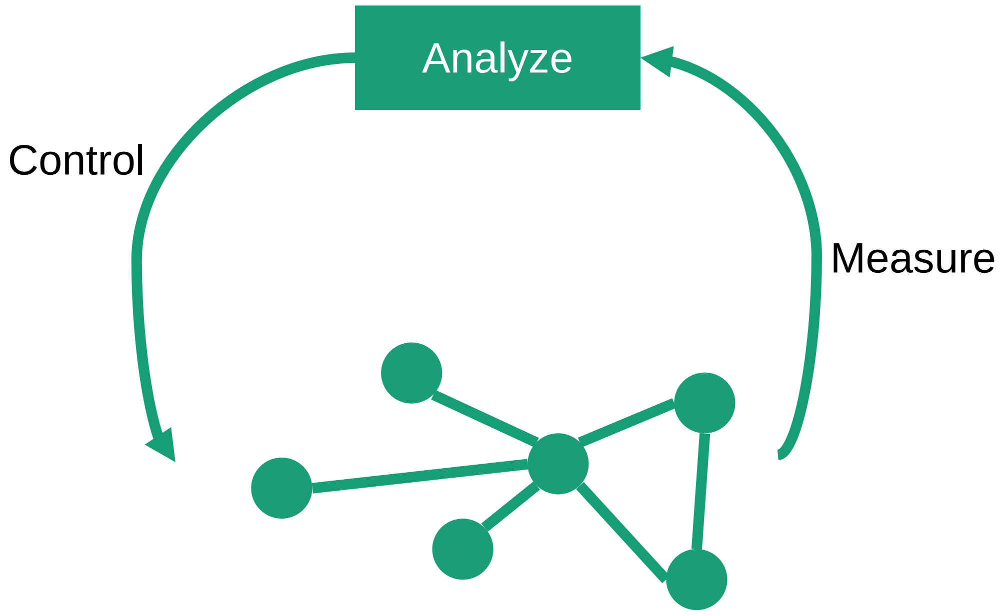
NeuroViNE: Efficiency on Real Network Topologies



- VNE algorithms (GRC, DViNE, RViNE) vs. Hopfield variants (HF-GRC, HF-DViNE, HF-RViNE)
- NeuroViNE accepts more networks with less costs

Towards Autonomous Networks

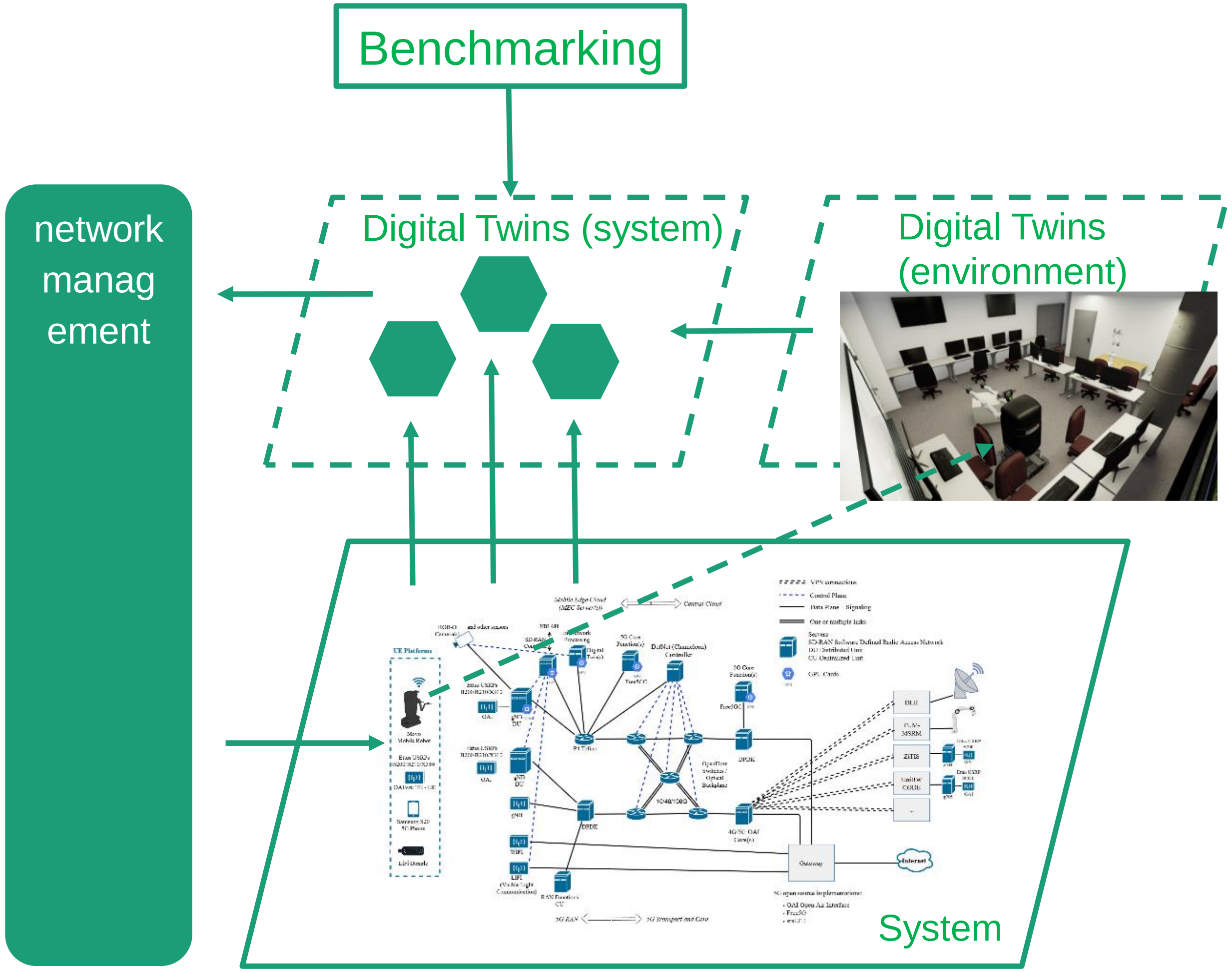
- Network Managers' all-time Dream:
  lean back and watch!



Digital Twins

- Network Digital Twin = synchronized copy of a system (component)
- DTs may interact in simulation space
- 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



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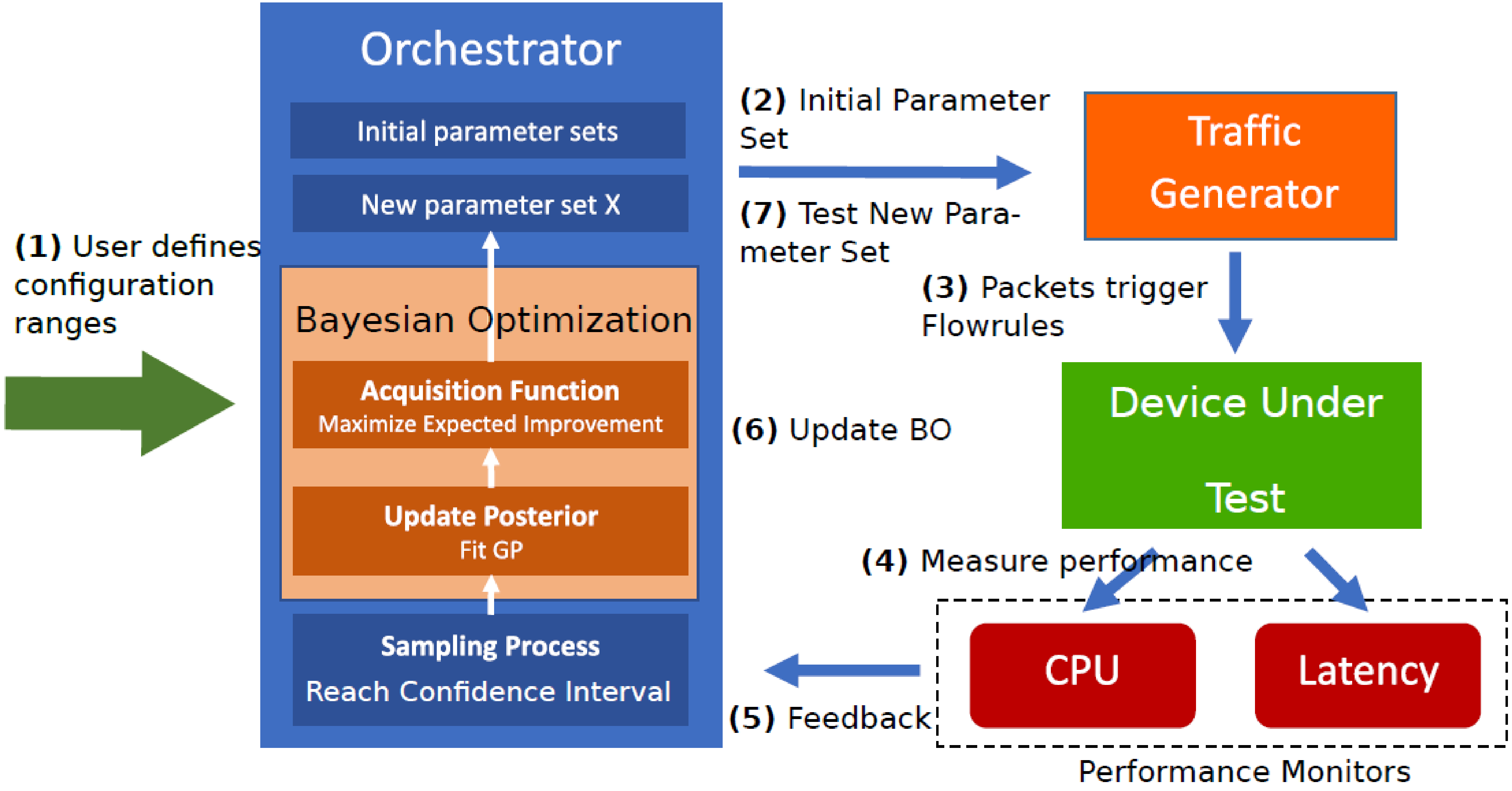
NetBOA: Self-Driving Network Benchmarking



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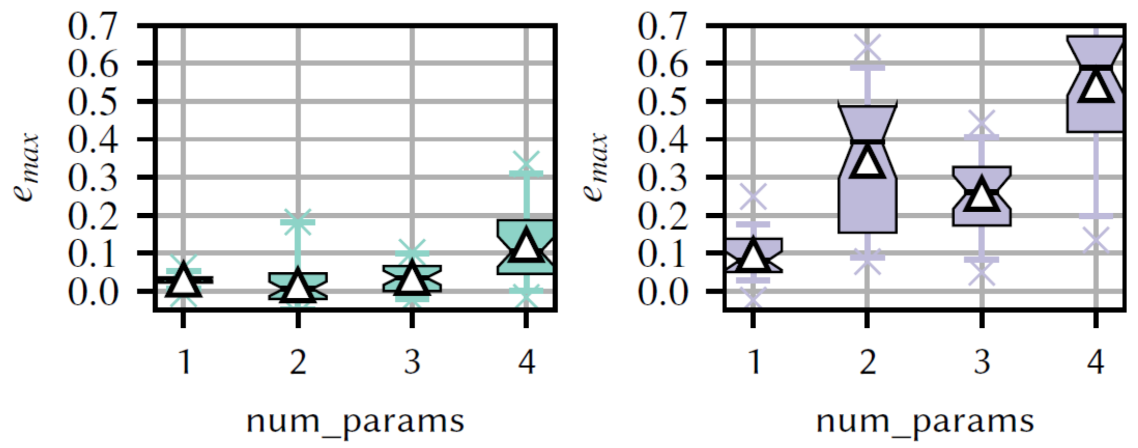
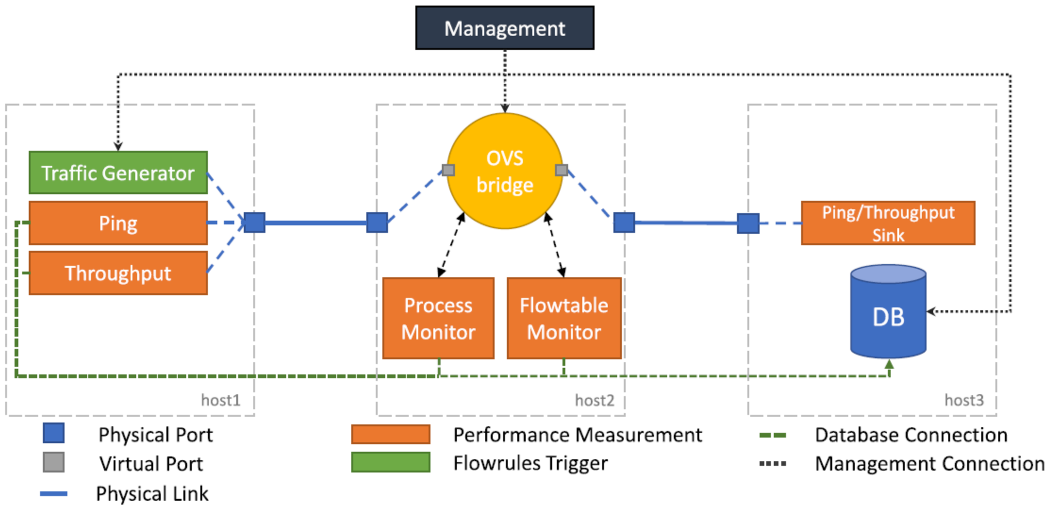
NetBOA: Self-Driving Network Benchmarking

- Example



(a) Bayesian Optimization. (b) Random Search.

Figure 6: RS vs. BO. Relative deviation of CPU load from the known optimal value after 100 iterations.



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Summary

- 6G clearly builds on a strong multi-network paradigm and addresses future networking
- New requirements demand for new networking and network management concepts on top of in-network computing and network programmability
  - Flexibility & adaptation: consider cost
  - AI-driven networking
  - Digital Twins
  - Autonomous benchmarking
  - Autonomous networking

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6G-life

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Thank you

https:/6g-life.de

https://www.6g-future-lab.de/

https://www.5g-munich.de

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