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Are There Any Innovations on The Road to 6G?

(incl. Energy- and Resource-Efficient Cell-Free Massive MIMO Networks)

Slawomir Stanczak

BOWW
BERLIN OPEN RAN WORKING WEEK

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Do we expect any innovations on the road to 6G?

Domains of innovation

- **Intelligence**
- **Sustainability**
- **Performance & New Features**
- Network Architecture
  - In-network computing (& sensing)
- Resilience
  - Quantum-safe security

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Intelligence

AI for Networks

AI everywhere

- broad integration of AI across network layers for general automation, orchestration and optimization

Advanced AI/ML

- targeted, high-performance AI for specialized tasks, often involving real-time decision-making, estimation, and prediction

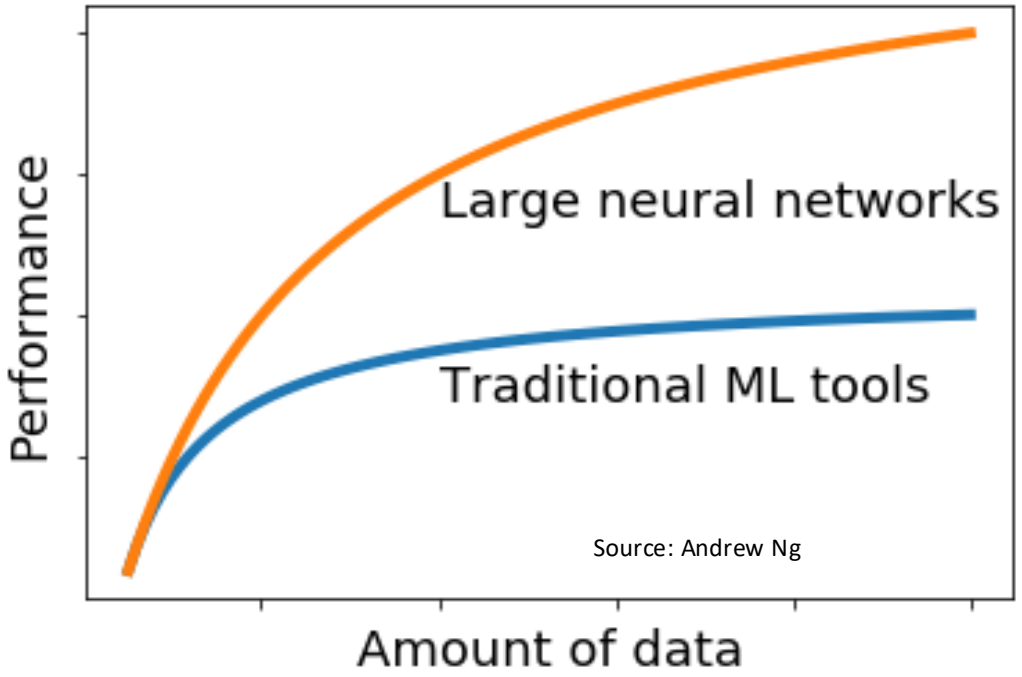
Digital twin networks

- Real-time digital representation for optimization

Intent-Based Networking

Intelligence

ML/AI for RAN



Limited applicability of DNN at PHY/MAC

- Difficult to include domain knowledge
- Energy efficiency matters
- Function properties not preserved
- No robustness guarantees
- Non-stationary environment (10-40ms)
  -> Only small training data sets

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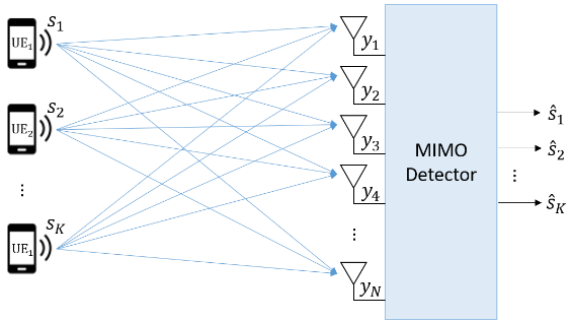
AI-RAN: HYBRID ML/AI OPTIMIZATION

- lightweight ML/AI with performance guarantees
- exploit domain knowledge
- fast, small training sets

MIMO Detection

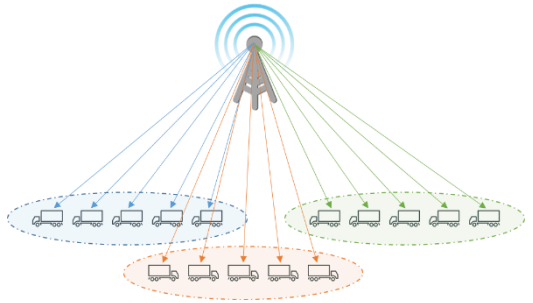


PoC: Online Machine Learning for MIMO-NOMA Detection

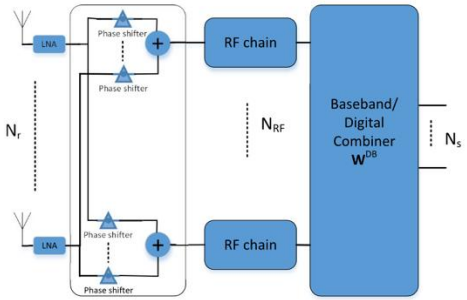
Co-Design of Hardware and Software is essential

https://youtu.be/dk-QWtYgZgY

Multicast Beamforming

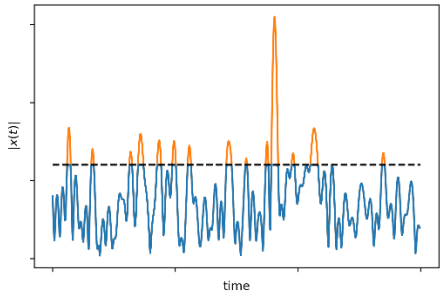


Hybrid Beamforming Channel Estimation



(Image source: Ahmed, Irfan, et al. "A survey on hybrid beamforming techniques in 5G: Architecture and system model perspectives.")

PAPR Reduction



Matthias Mehlhose, et al.: Real-Time GPU-Accelerated Machine Learning Based Multiuser Detection for 5G and Beyond, IEEE Access, 2022

Fink, J., Cavalcante, R. L. G., & Stańczak, S. (2023). Superiorized adaptive projected subgradient method with application to MIMO detection. IEEE Transactions on Signal Processing, 71, 1350-1362

Sustainability

Low-carbon energy consumption

Energy harvesting (solar, wind, RF-powered components…)

Resource recycling

Two Fundamental Levers for Reducing Energy Consumption

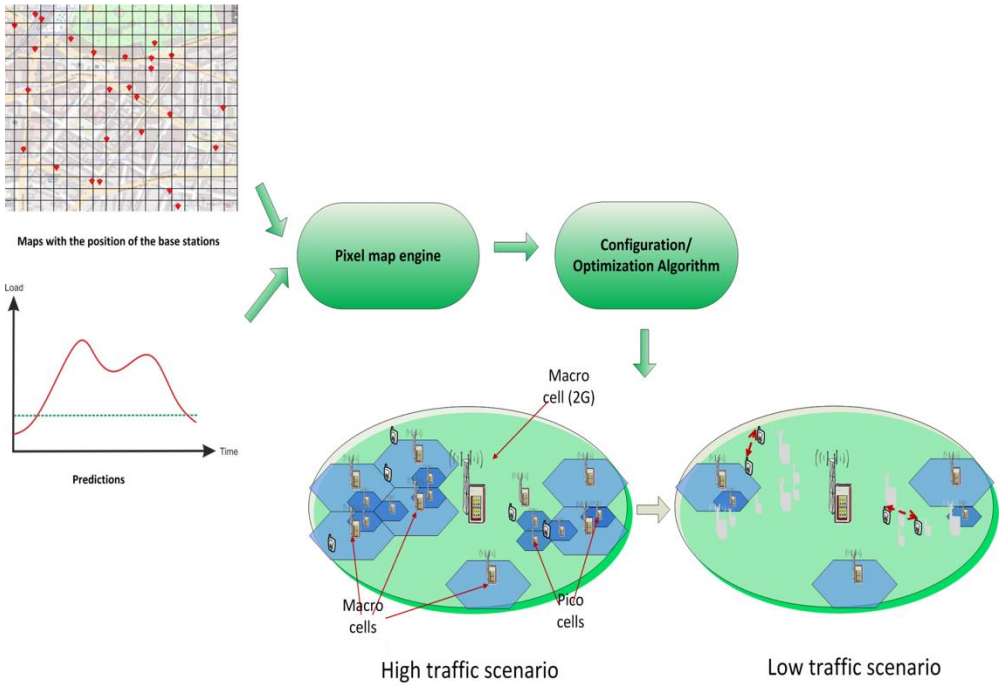
Energy consumption includes radiated and operational (static) energy

Minimize energy consumption ***while hardware is operational***

- Efficient amplifiers, low-power chipsets (incl. hardware-level optimization)
- Resource allocation adaptation, energy-aware protocols

Minimize the ***operational time*** of hardware

- Turn off or put components into sleep mode when not needed.



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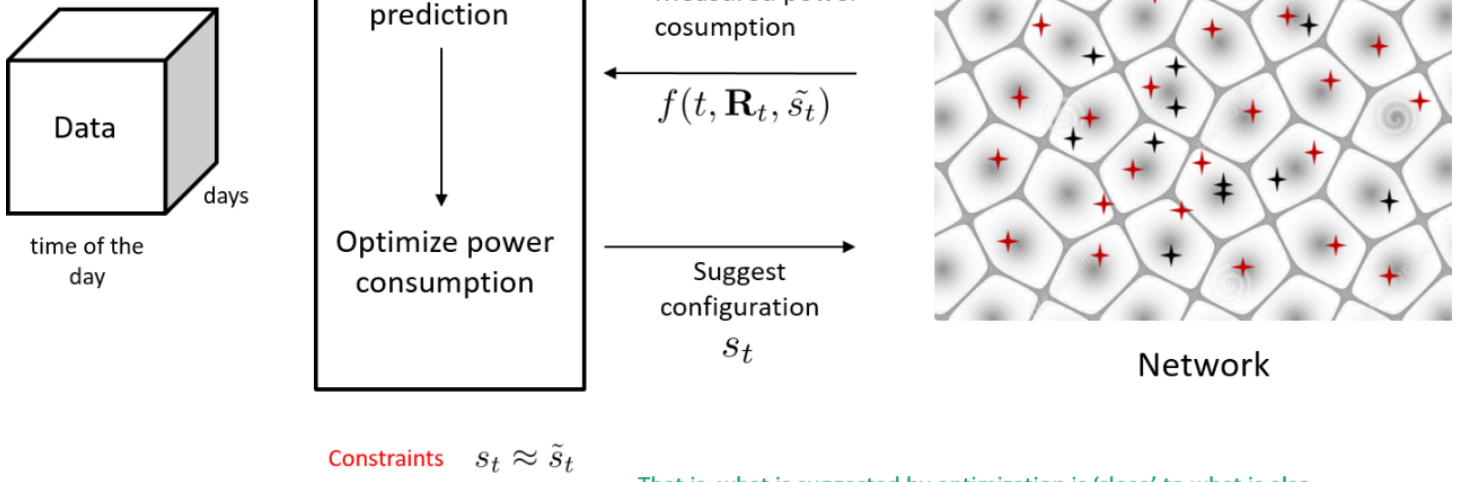
Energy Control Framework with Feedback



Constraints $s_t \approx \tilde{s}_t$

That is, what is suggested by optimization is 'close' to what is also feasible, i.e., a strategy that is not rejected by the network

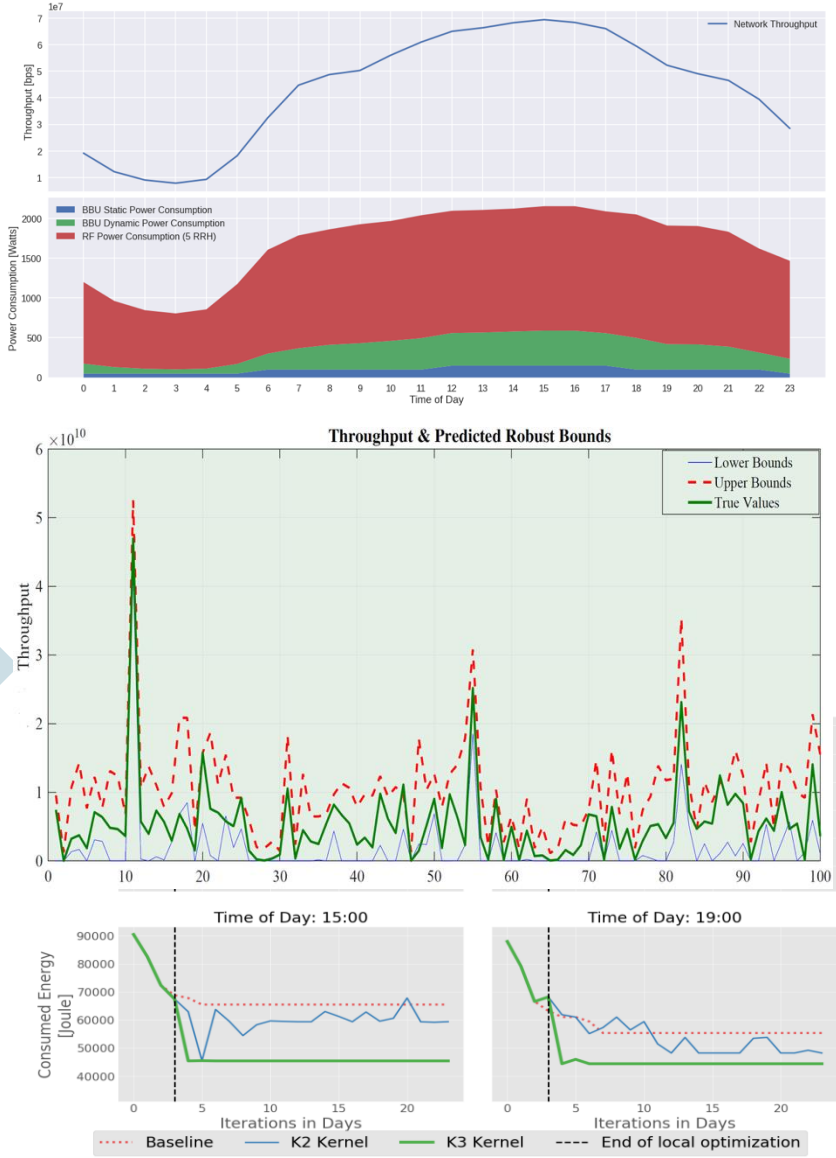
Bayesian Optimization

$$\underset{\mathbf{s}\in\mathcal{S}_t}{\text{maximize}} \quad \mathbf{EI}(t, \mathbf{R}_t, \mathbf{s}) \times \Pr\{c(\mathbf{s}) \leq 0\}$$

Set of ‚good' topology/configurations)

Expected improvement in power consumption given QoS and topology

Probability that the suggested configuration is ‚feasible' in the network



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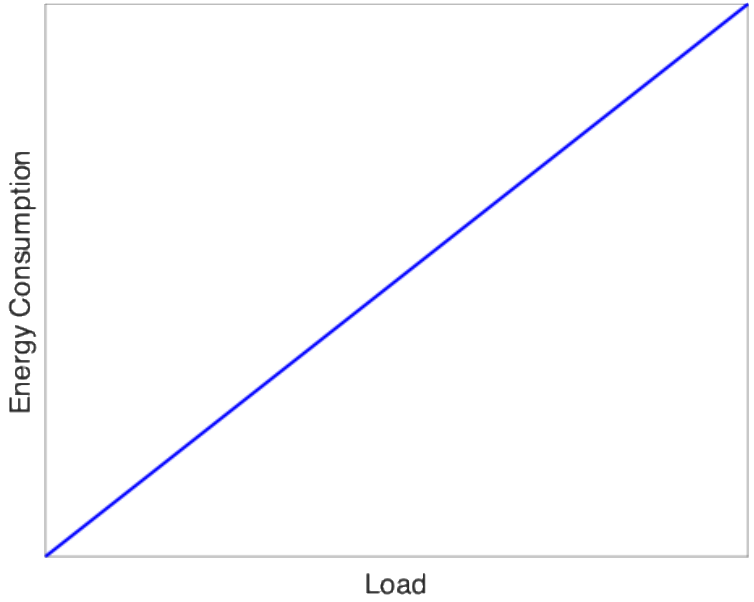
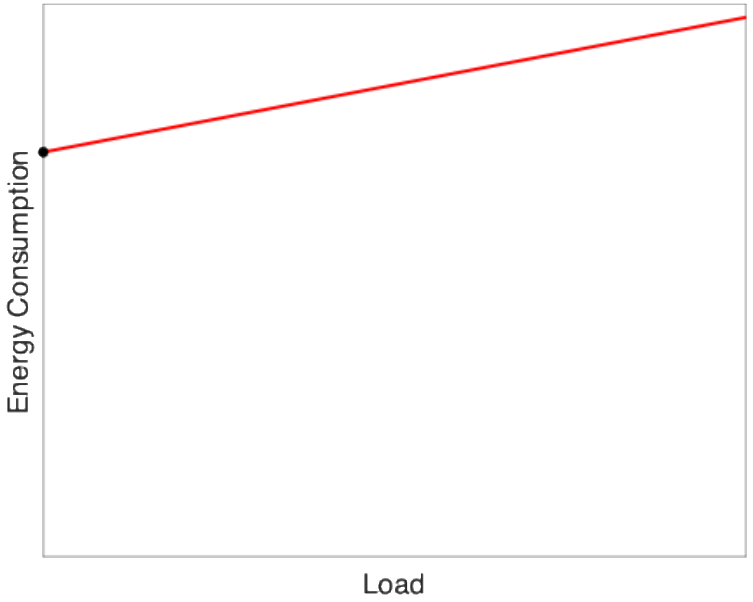
Balancing Power Use and Operation Time

The trade-off depends on the relationship between the load and energy consumption

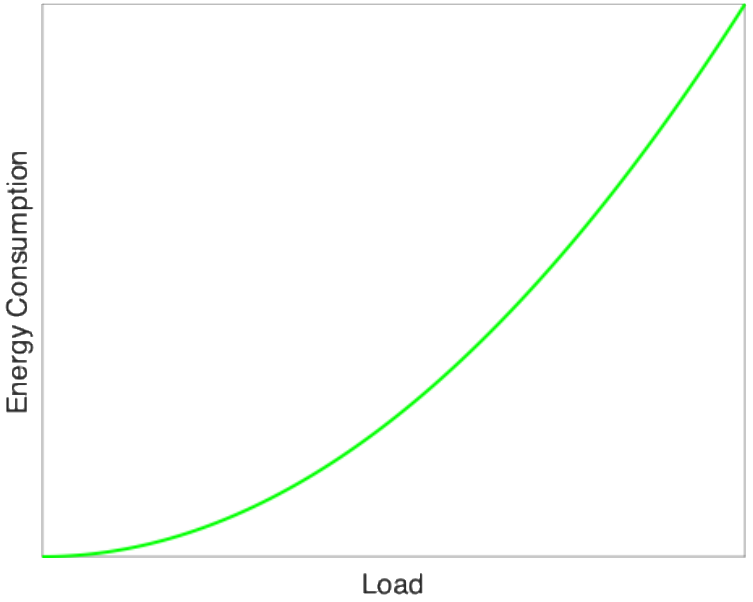
Linear → switching on/off the component doesn't matter



Affine with a large static part → keep the minimum number of components on



Convex → the more components on, the lower the energy consumption



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Load in Virtualized Open RAN (Open vRAN)

Radio load

- The fraction of radio resources used to serve traffic at a RU.
- Load of different RUs is coupled via **interference** and is a fixed point of a non-linear function.

Computational load

- The percentage of the required **computation effort** at a DU for baseband processing.
- Computation effort is linear in code rate and modulation but is **quadratic** in # antennas.

We need to better capture the underlying relationships: Entry point for AI and digital twins

H. Zafar, M. Kasparick, S. Maghsudi and S. Stańczak, "A Deep Reinforcement Learning Approach for Load Balancing in Open Radio Access Networks," GLOBECOM 2023 - Kuala Lumpur, Malaysia, 2023

Performance & New Features

Better performance

- Distributed MIMO, user-centric radio access, full-duplex, RIS

Network as a Sensor:

- Integrated sensing and communication (ISAC)

Better coverage through NTN

There is a fundamental trade-off between throughput and energy efficiency

Energy efficiency improvement ≠ energy consumption reduction: Rebound effect

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Scaling laws of throughput

Cellular networks with treating interference as noise

Cellular (n is #UE, m is #BS)

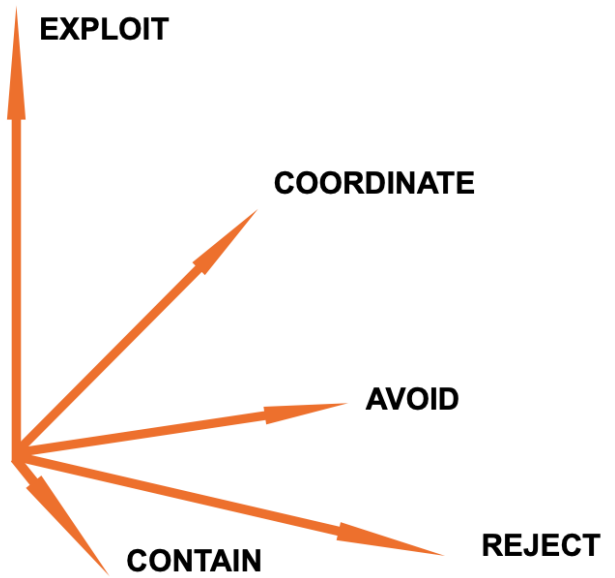
- Throughput per user: $\Theta\left(\frac{m}{n}\right)$

  if $m = \omega\left(\sqrt{\frac{n}{\log n}}\right)$

Increasing #BS improves throughput

Hardware energy becomes dominant

Key is interference control



A. Zemlianov and G. de Veciana, “Capacity of ad hoc wireless networks with infrastructure support,” IEEE Journal on Selected Areas in Communications, vol. 23, no. 3, pp. 657–667, Mar. 2005.

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If the PHY and MAC layers are poorly designed or fail to manage interference, it's like building a skyscraper on unstable ground
 — no matter how advanced the upper floors (layers) are, the whole structure is compromised.

Improving Scaling Laws of Information

Transmit only task-relevant information while ensuring reliable communication:

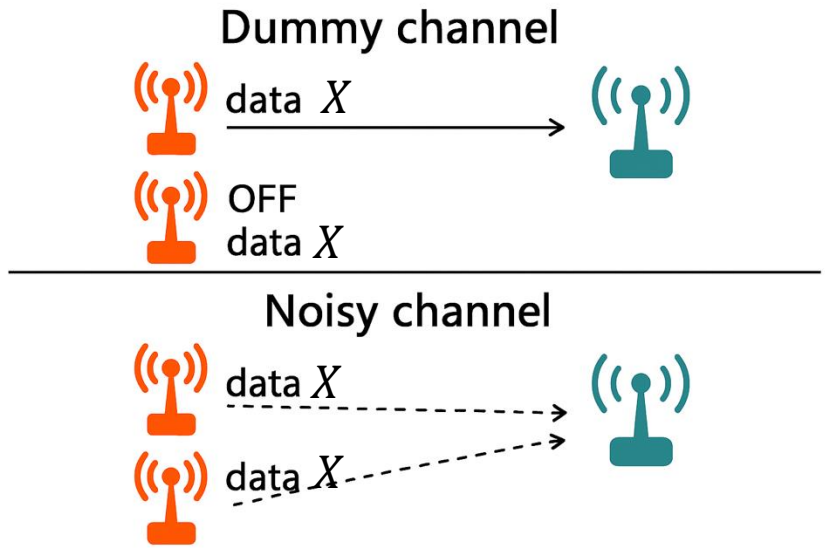
- Semantic/task-oriented communication
- Spatial and temporal content reuse (caching)

Exploit interference:

- **Distributed/cell-free massive MIMO**

Contain/avoid/coordinate interference

- Infrastructure densification
- Interference management



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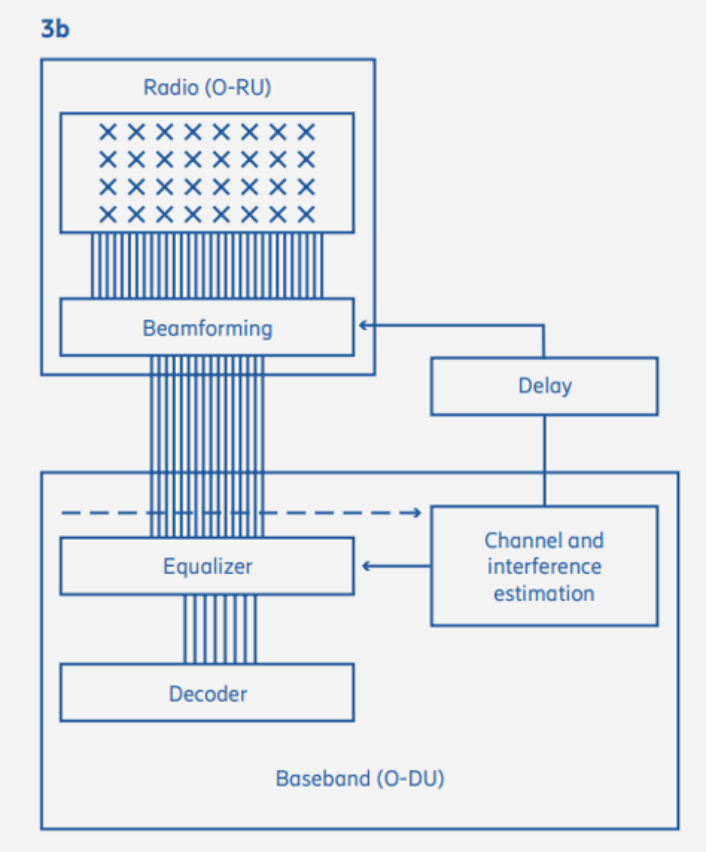
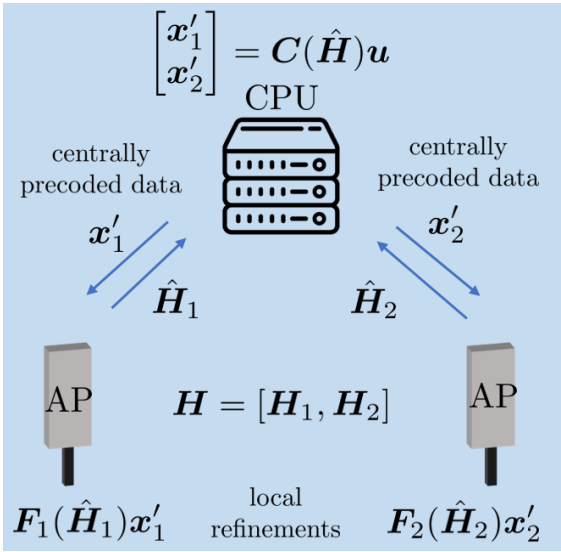
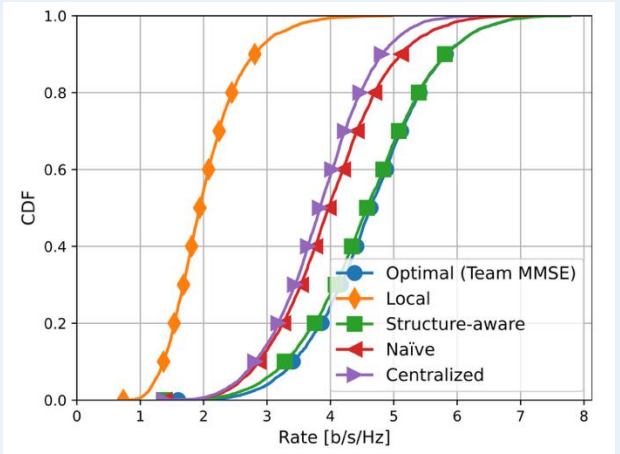
Centralized vs. decentralized

Delayed Channel State Information



Timely Local CSI + Delayed Global CSI





Centralized MMSE outperformed under fronthaul delays

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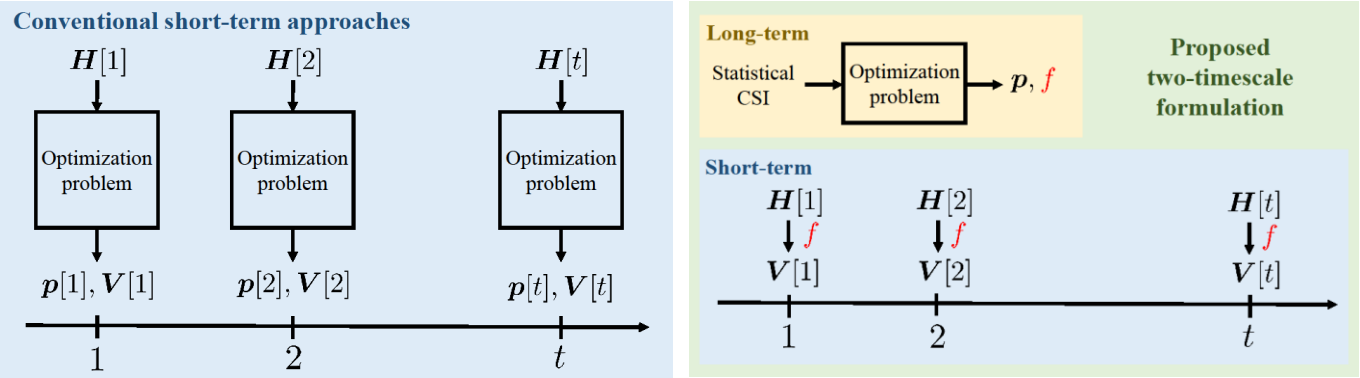
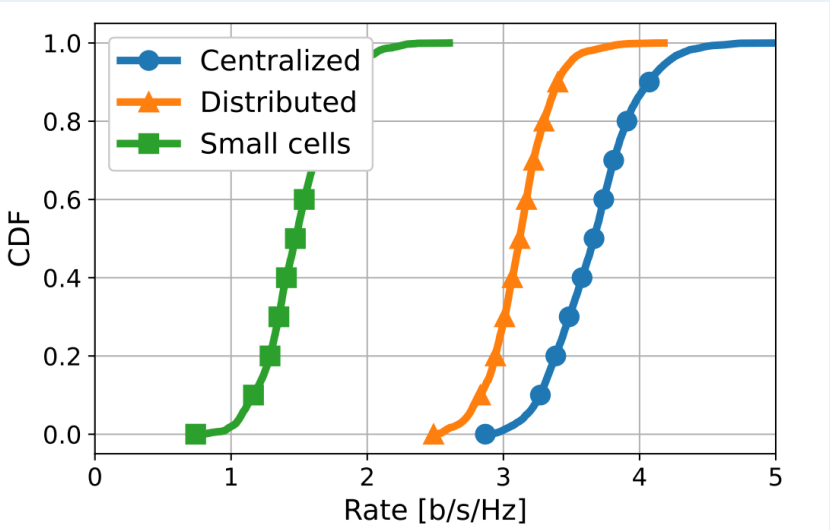
Two-timescale resource allocation



L. Miretti, R. L. G. Cavalcante, S. Stanczak, "Joint optimal beamforming and power control in cell-free massive MIMO," IEEE GLOBECOM 2022
L. Miretti, R. L. G. Cavalcante, E. Björnson, S. Stanczak, "UL-DL duality for cell-free massive MIMO with per-AP power and information constraints," IEEE TSP 2024
L. Miretti, E. Björnson, S. Stanczak, "Two-timescale weighted sum-rate maximization for large cellular and cell-free massive MIMO," IEEE SPAWC 2024
L. Miretti, R. L. G. Cavalcante, E. Björnson, S. Stanczak, "Two-timescale joint power control and beamforming design with applications to cell-free massive MIMO," IEEE TWC, 2025

R. Ooi, R. Diab, L. Miretti, R. L. G. Cavalcante and S. Stańczak, "**Joint power control, beamforming, and sleep-mode selection for energy-efficient cell-free networks using surrogate machine learning models**," GLOBECOM 2024



Max-min optimal design
Local CSI is enough to provide uniformly good service

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Our Strategic Pillars of Innovation: 6G-RIC and i14y Lab

6G-RIC:

- Purpose: National flagship initiative driving foundational 6G research.
- Focus Areas: Cell-free massive MIMO, Sub-THz, RIS, ISAC, semantic communication, edge intelligence, post-quantum security, autonomous networks and energy efficiency.
- Impact: Providing the strategic framework and funding for long-term innovation.

I14y Lab:

- Purpose: Open, interoperable testing environment for disaggregated network components.
- Focus Areas: Open RAN, interoperability, conformance testing, digital twins.
- Impact: Enabled rapid prototyping, validation, and collaboration with industry partners.

6G-RIC
Research and
Innovation Cluster

RESEARCH AND INNOVATION FOR SUSTAINABLE AND SECURE 6G TECHNOLOGIES.

COORDINATED BY
FRAUNHOFER HEINRICH
HERTZ INSTITUTE

6G-RIC
Research and Innovation Cluster

Research and Innovation for Sustainable and Secure 6G Technologies

Coordination :
Fraunhofer Heinrich Hertz Institute
Prof. Slawomir Stanczak

Funding: BMFTR

€ 70 Million

Investments approx. € 12 Million

Subcontracts approx. € 11 Million

- Development of Key 6G Technologies
- Demonstration of the Technologies‘ Application to selected Use Cases
- Open Test-/Development Infrastructure
- Contribution to the Development of an Open 6G Ecosystem
- Support and Promotion of Young Researchers

https://6g-ric.de

Follow us on LinkedIn

Excellent Research

Papers, Talks, Demos, Events, Standardization

Publications

550+ papers (more than 50 joint papers)

Many IEEE Transactions

Most IEEE papers incl. the flagship IEEE conferences such as ICC, GLOBECOM, ICASSP, ISIT, VTC

3 IEEE Magazines

1 White paper and Position Paper

Impact, Recognition and Contributions

100+ invited talks/tutorials/lectures

30+ demos (19 shown at the Berlin 6G Conference)

10+ paper/demo awards ★

10+ 6G industry projects

10+ SME/Startup involvement (ca. 2,5M€)

70+ events (Workshops, Summits, Booths, ABM, school events)

10+ Press releases and press articles in which 6G-RIC is mentioned

Active contributions to the open source development (Open Air Interface)

100+ standardization contributions (3GPP, ETSI)

10+ patent applications

Collaboration with ITU-T (new focus group)

xG-RIC
Research and
Innovation Cluster

From 2026: Technologie Transfer Cluster

6G for the Health (and Mobility) of the Future

6G-RIC
Research and Innovation Cluster

xG-RIC

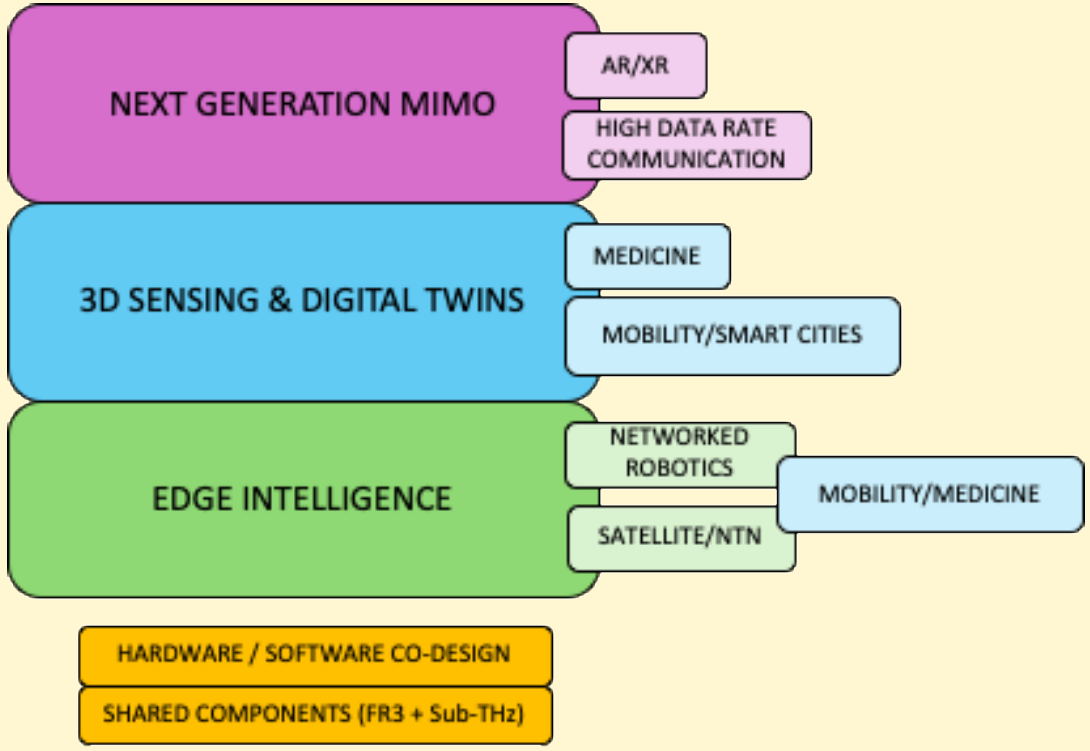
BALANCE BETWEEN EXPLOITATION AND EXPLORATION

Project Philosophy: *TECHNOLOGY PUSH*
Technology Development
Tight alignment with Industry and Industry-led Projects
Use Cases Development & PoC Demonstration (E2E)
System Aspects
Recommendations for Standardization

SIX TECHNOLOGY INOVATION AREAS (TIAs)

TIA 1	SUB-THZ MOBILE ACCESS
TIA 2	INTELLIGENT RADIO ENVIRONMENTS
TIA 3	NETWORK AS A SENSOR
TIA 4	6G CONNECTIVITY
TIA 5	POST-QUANTUM SECURITY BY DESIGN
TIA 6	AUTONOMOUS CONVERGENT NETWORKS

Selection based on project results and interaction with Industry (*Advisory Board Meetings and joint Workshops*)



xG-RIC Locations in Berlin

Technologie Transfer Cluster

xG-RIC
Research and Innovation Cluster

Charité / DHZC

DHZC New Clinic

Showrooms

Testbeds

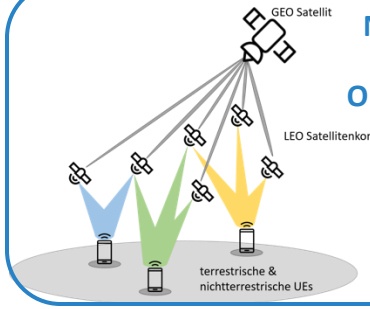
HHI

Integrationslabor

HPC

Testbeds

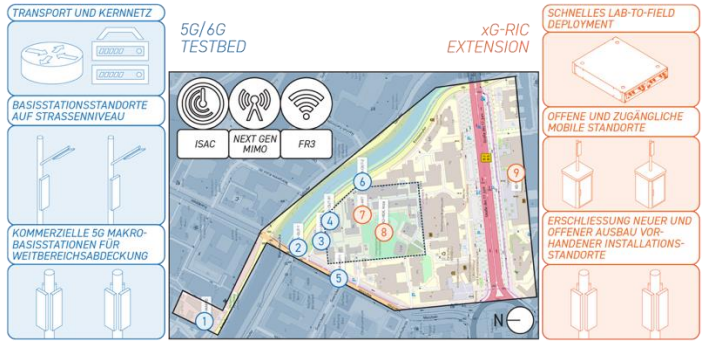
Science Forum



NTN Hotspot at the DLR in Oberpfaffenhofen

TU Berlin

Microwave Lab



i14y Lab Mission

The i14y Lab is an Open Lab
accelerating time to market

for multi-vendor disaggregated telco
systems like Open RAN

through testing, validation, certification
of hardware | software components,

And connecting the ecosystem

It provides validation & certification.

Open RAN because it offers
- more supply-chain resilience
- more innovation and flexibility
- drives down RAN costs.

Testing, validation, and certification reduces integration efforts and expenditures.

Connecting the ecosystem to
- agree on how and what to test.
- create market volume.

i14y LAB

i14y Lab – High-End Test Lab for Europe

Vision

- Strengthen innovation and transfer in the industry and society

Key Activities

- Testing & Certification: Reliable, reproducible tests for Open RAN, AI, and security
- Research & Development: Realistic data, digital twins, scalable infrastructure
- Knowledge Transfer: Training for engineers and industry professionals
- Standardization: Active role in global standards
- Cooperation: partnership and cooperation with 5G Berlin and xG-ALOE on private 5G networks

Strategic Impact

- Supports secure, energy-efficient, and innovative telecom ecosystems

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Thank you!

Questions?

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