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Towards 6G: Opportunities and Challenges of future Multi-Dimensional Networking Solutions

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10 May 2023

VDE ITG Mobilkommunikation 2023

CNI

Faculty of Electrical Engineering and Information Technology
Communication Networks Institute
Prof. Dr.-Ing. Christian Wietfeld

CNI in a nutshell:
Reliable Connectivity for Cyber-Physical Systems in Harsh Environments

Core team of 15+ scientists
plus numerous students

Research Focus

5G/6G for Mission-Critical Services

Integrated Communication & Sensing

Resource-Efficient Communications Leveraging Machine Learning

Website YouTube

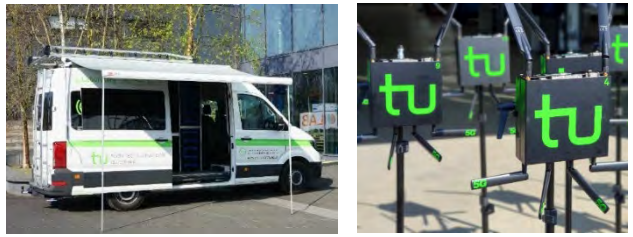
Extensive Lab Equipment

Multi-Radio Technology Lab

5G NR (incl. mmWave), cIoT, Wi-Fi6, LPWAN, Software-Defined Radio based Open Source O-RAN & 6G solutions, Network/Channel Emulation

Networked Robotics Lab

Successful in field operation and testing using Mobile Radio Lab



Lead Projects

5G.NRW Competence Center

6GEM open - efficient - secure - safe

SFB 876 DFG

6G-ANNA

DRZ Deutsches Rettungsrobotik Zentrum

LARUS PRO

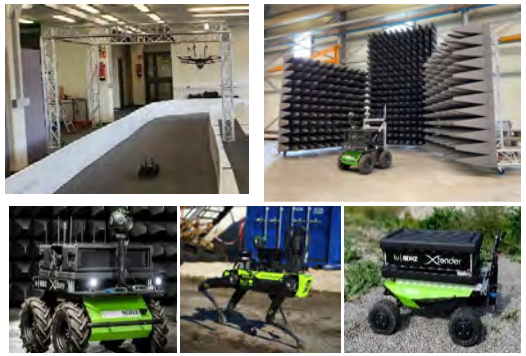
Research process: interplay between lab, transfer and real-life environments

Experimental Environment

Lab Environment
(fully reproducable)

Recommended configurations

Transfer Environment
(partially reproducable)

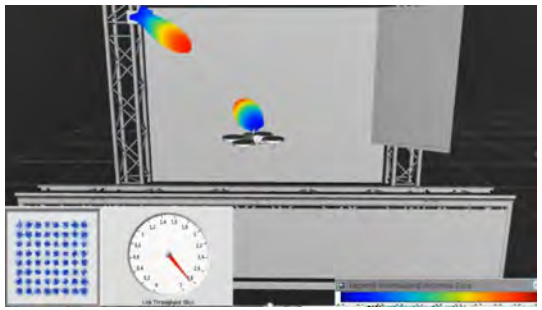


Recommended configurations

Real-life Environment
(Field tests)

Data-driven modeling using online learning (channel characteristics, mobility behavior,...).

Digital Network Twin



Research environment for selective mapping of reproducible system states (e.g. mobility)

Realistic Single Models

Modelled environment for the transfer between laboratory and real environment

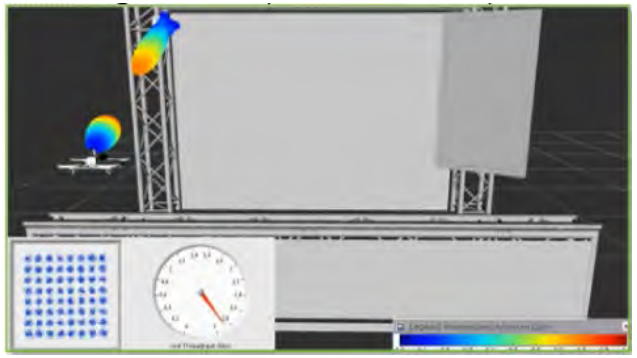
Scaled Realistic Models

Complete representation of a real environment with realistic models of radio channel, mobility, and transmission characteristics

Research process: interplay between lab, transfer and real-life environments

Example: anticipate mobility to allow for mmWave beam and RIS selection and steering

mmWave Digital Twin (focussed on lab)



mmWave lab environment

K. Heimann, J. Tiemann, D. Yolchyan, C. Wietfeld, "Experimental 5G mmWave Beam Tracking Testbed for Evaluation of Vehicular Communications," *In IEEE 2nd 5G World Forum (5GWF) (WF-5G'19)*, September 2019. [bibtex] [pdf] [video].

Simulation environment (larger scale realistically modelled scenario)

Based on:

- Light-weight ICT-centric Mobility Simulation **LimoSIM**
- **Lean 3D channel model** derived from experiments

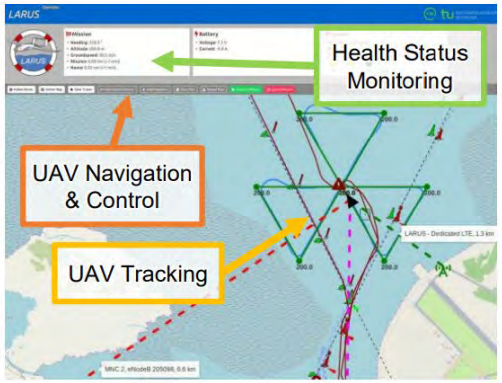
B. Sliwa, M. Patchou, K. Heimann, C. Wietfeld, "Simulating hybrid aerial- and ground-based vehicular networks with ns-3 and LIMoSim," *In Proceedings of the 2020 Workshop on Ns-3,* Gaithersburg, Maryland, USA, June 2020. [bibtex] [arxiv] [pdf] [video].

K. Heimann, A. Marsch, B. Sliwa, C. Wietfeld, "Reflecting Surfaces for Beyond Line-Of-Sight Coverage in Millimeter Wave Vehicular Networks," In IEEE Vehicular Networking Conference (VNC), December 2020. [bibtex] [pdf] [video].

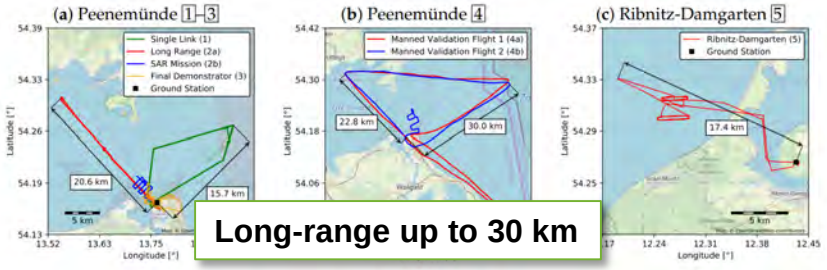
Field trial highlight: Multi-Link Networking for SAR drone at Baltic Sea

October 2019 search and rescue exercise @ Baltic sea

Mobile wireless lab with dedicated, private network (SDR-based)

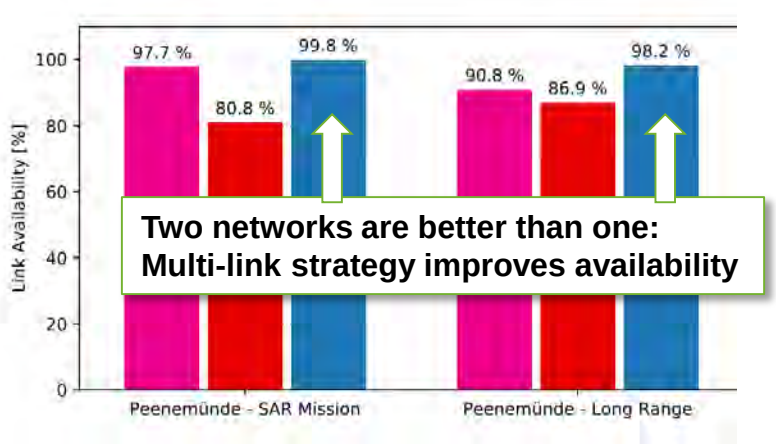


Gathering data in large scale experiments

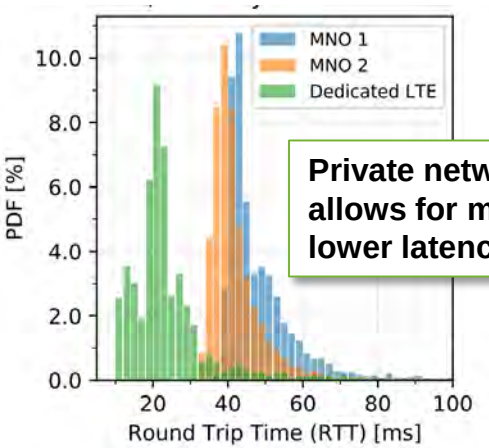


Long-range up to 30 km

Example results



Two networks are better than one: Multi-link strategy improves availability

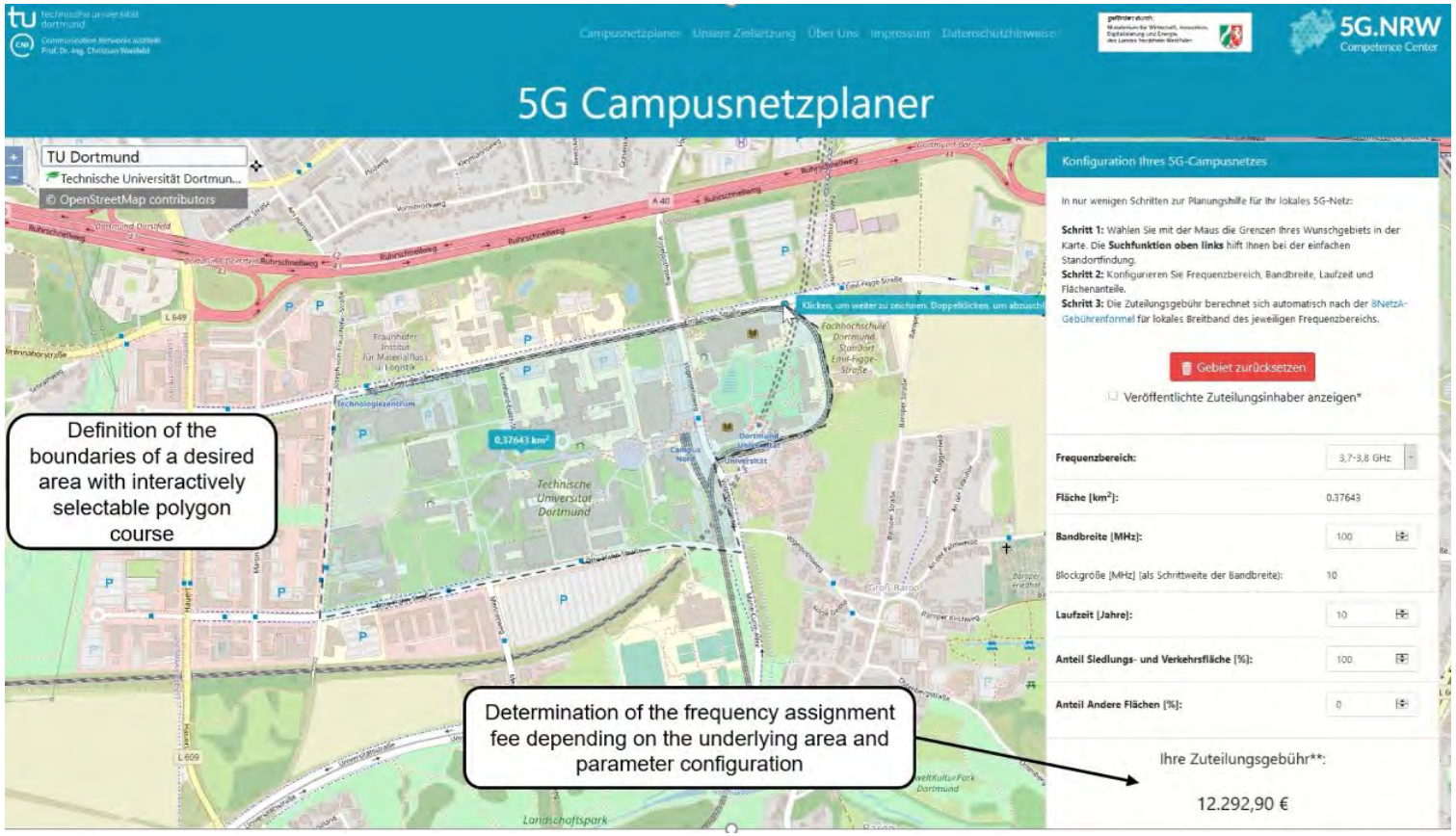


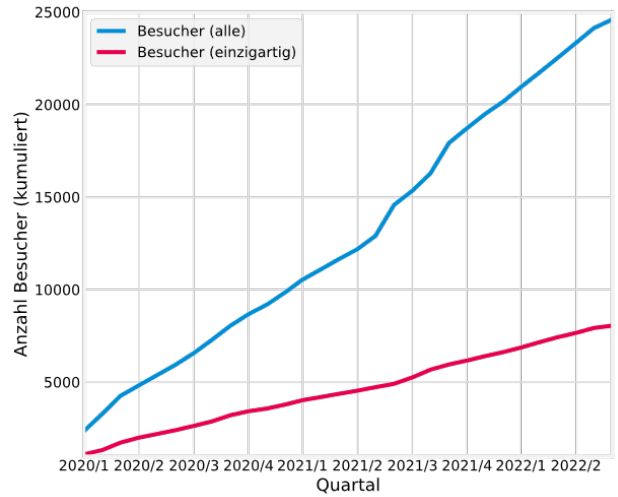
Private network allows for much lower latency

J. Güldenring, P. Gorczak, F. Eckermann, M. Patchou, J. Tiemann, F. Kurtz, C. Wietfeld, "Reliable Long-Range Multi-Link Communication for Unmanned Search and Rescue Aircraft Systems in Beyond Visual Line of Sight Operation", *In Drones*, MDPI, vol. 4, no. 2, May 2020.

Transfer highlight: The Free Online Campus Network Planer

Lowering entry barrier by supporting the licensing process for private 5G networks





Overall visits	24606
Unique visits	8140

Currently being evolved towards AI-enabled network planning tool for temporary 5G networks

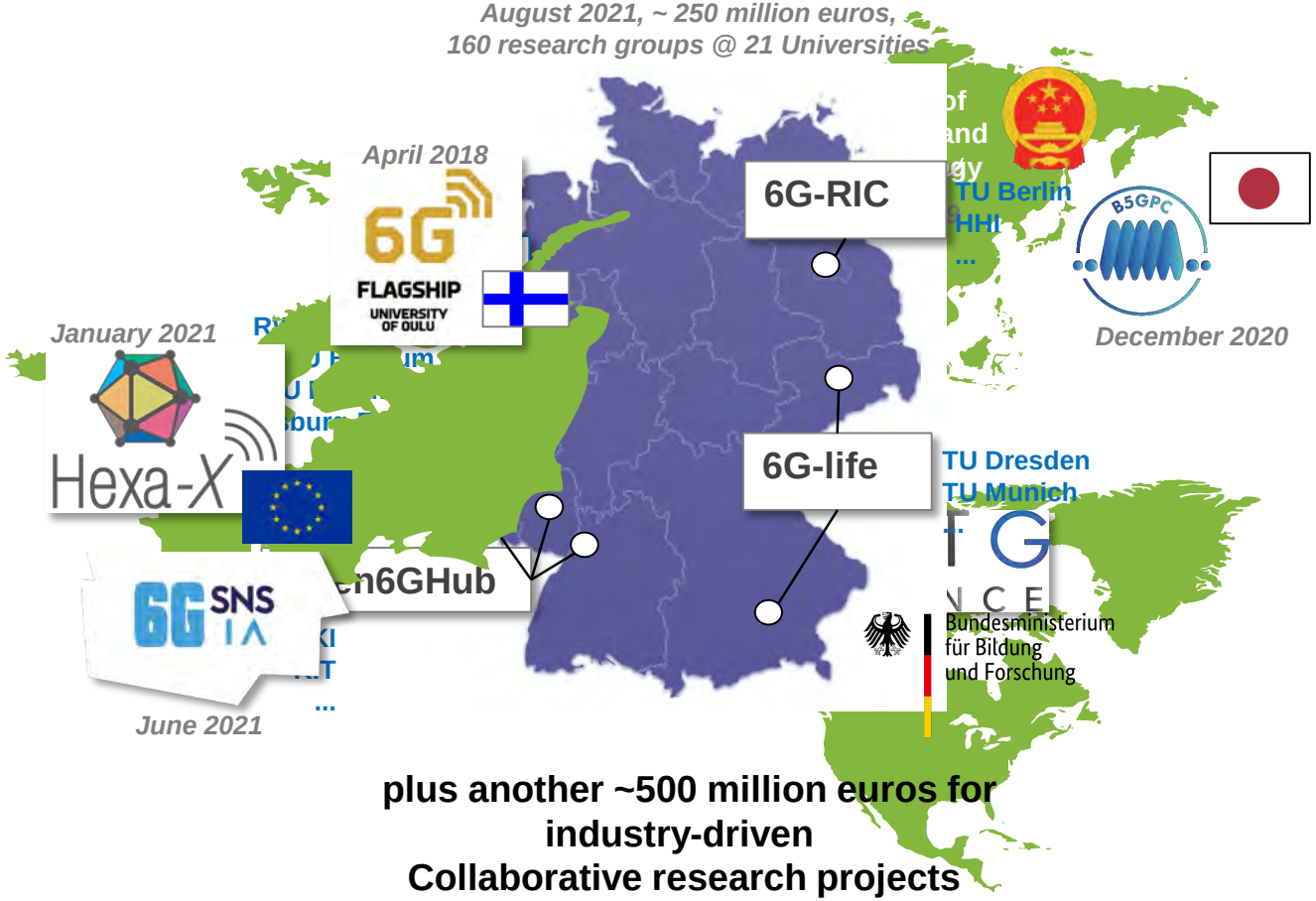
Plan & Play
Zuverlässige ad-hoc 5G-Campusnetze für den temporären Einsatz

The mobile communications community is moving towards 6G

... and since 2021 at the latest, Germany has been a hotspot for 6G development

6G research hubs

August 2021, ~ 250 million euros,
160 research groups @ 21 Universities



plus another ~500 million euros for industry-driven Collaborative research projects

BMBF 6G Research Hub 6GEM in a nutshell

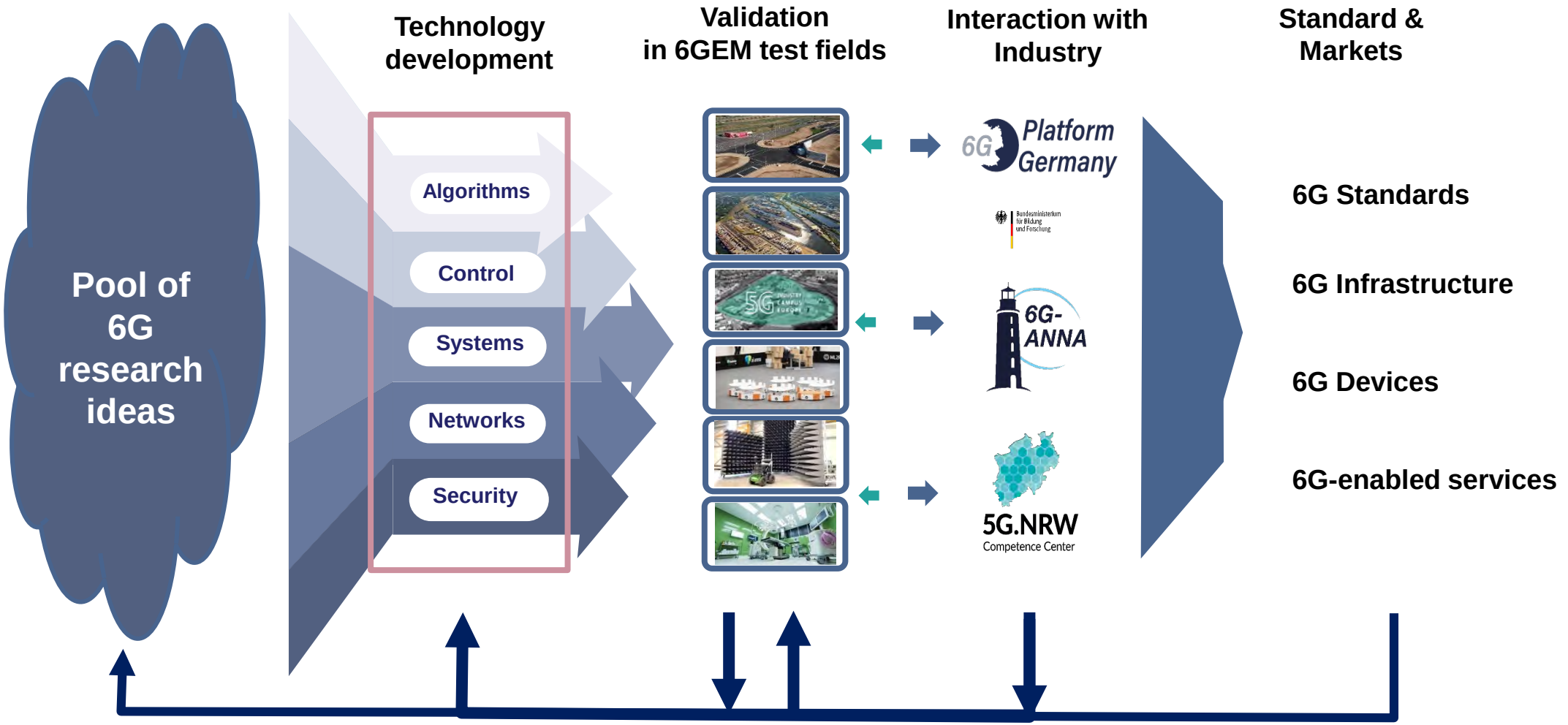
Five research areas

Six test fields

39 PIs

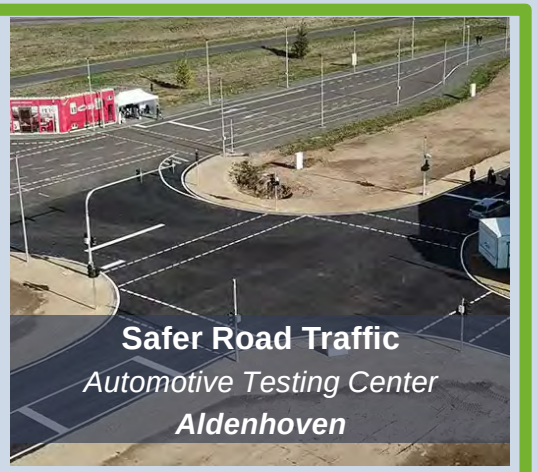
SPONSORED BY THE
Federal Ministry of Education and Research

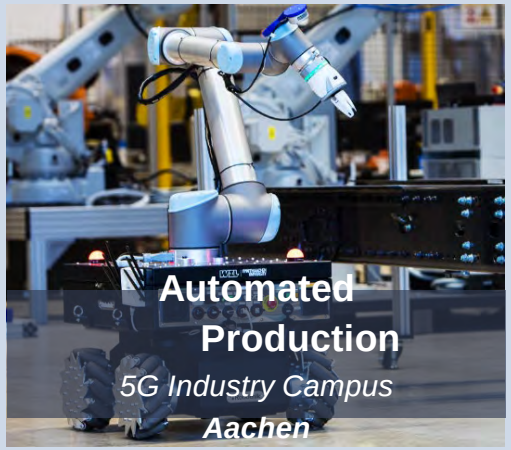
An agile 6G innovation cycle: Validation in testfields at an early stage



Realistic validation of „running code“ in specialized test fields

6GEM test fields



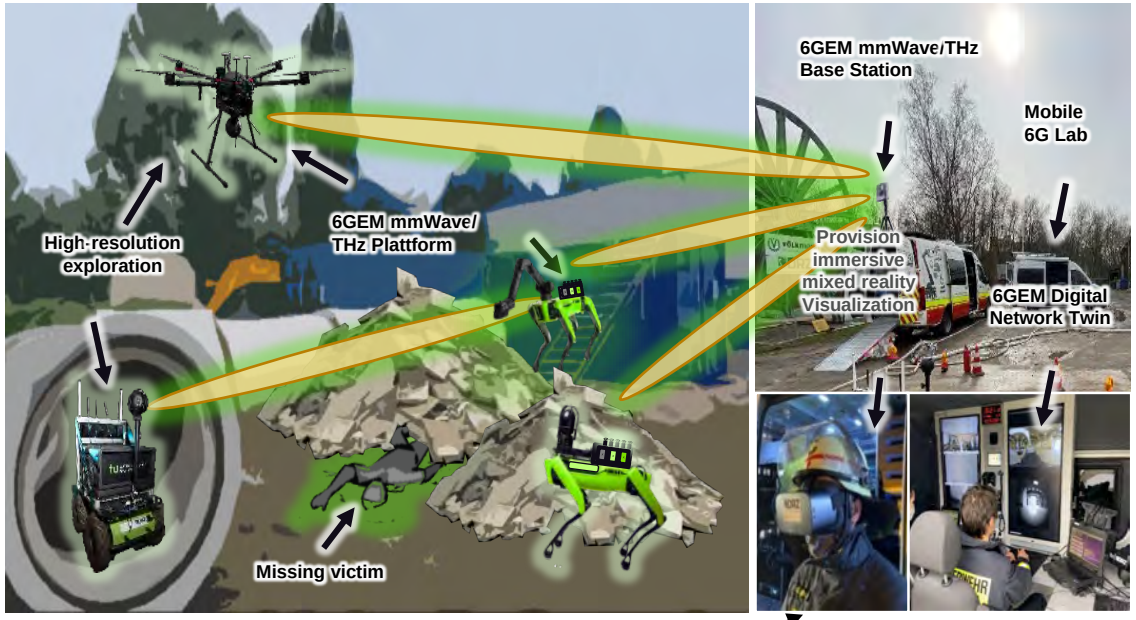


Example 6G Validation in test fields – Interacting with future users

Implementing 6G technologies for Rescue Robotics

Unique living lab for rescue robotics

Reliable 6G support and immersive situation awareness



Involvement of first responders

RoboCup Rescue
GERMAN OPEN 2023
DRZ Edition

- **April 25/26 2023 in Dortmund with 10 international teams**
- **New communications challenge introduced by TU Dortmund**
- **Transfer to international Robocup 2023, July 2023, Bordeaux, France**

M. Patchou, J. Tiemann, C. Arendt, S. Böcker, C. Wietfeld, "**Realtime Wireless Network Emulation for Evaluation of Teleoperated Mobile Robots**", In 2022 IEEE International Conference on Safety, Security, and Rescue Robotics (SSRR), Sevilla, Spain, November 2022.

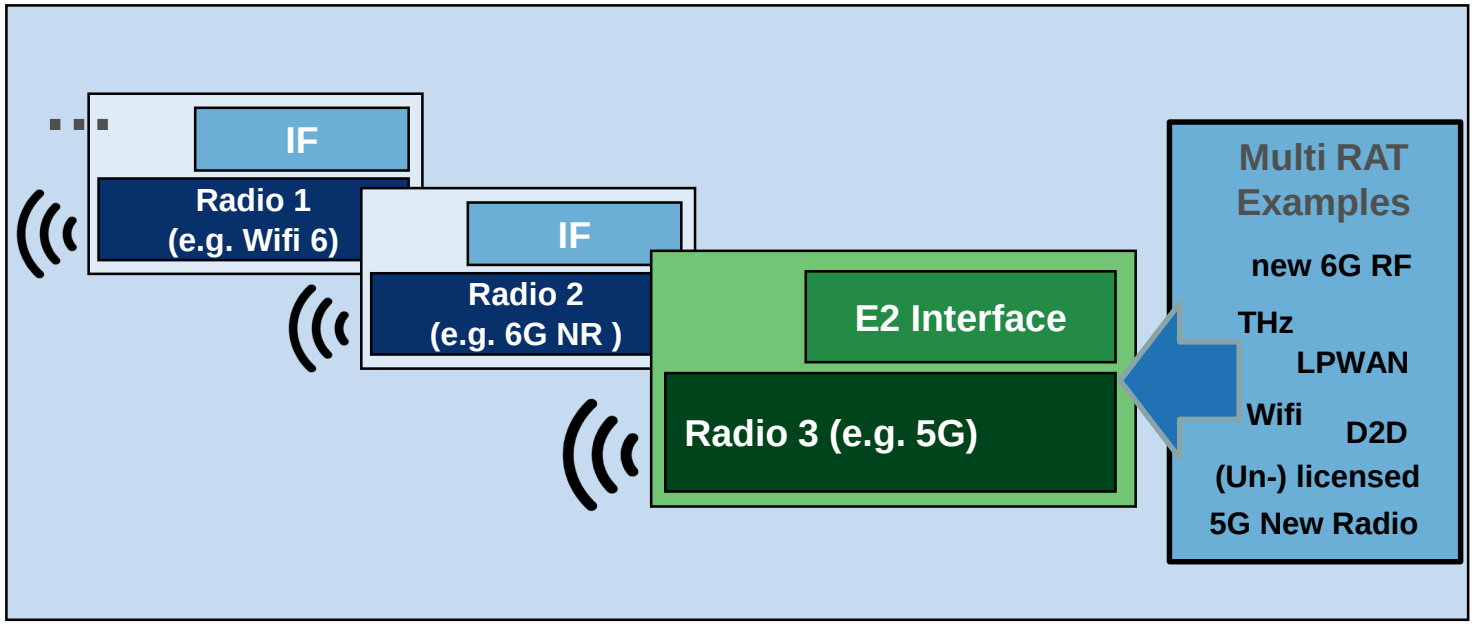
Example Test Field: Rescue Robotics

First experiments with networked agile robots producing several HD/360° video streams for immersive situational awareness
→ serves to enable detailed definition of 6GEM validation scenarios

Youtube-Video:
Insights into
Rescue Robotics
Test Field

Managing multiple dimensions of future 6G Networks

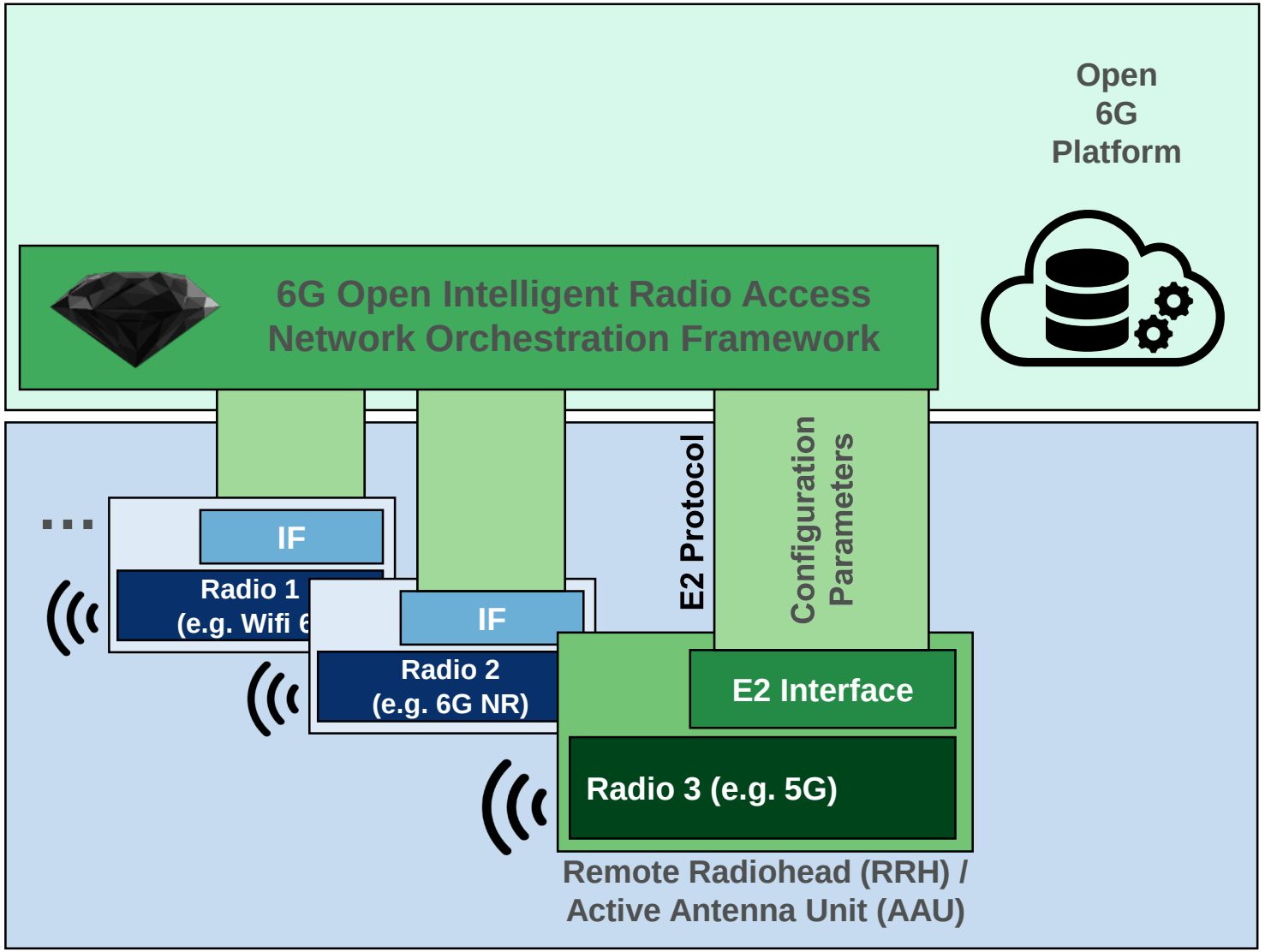
6G New Radio will be one element in a Multi-Radio-Access-Technology environment



Managing multiple dimensions of future 6G Networks

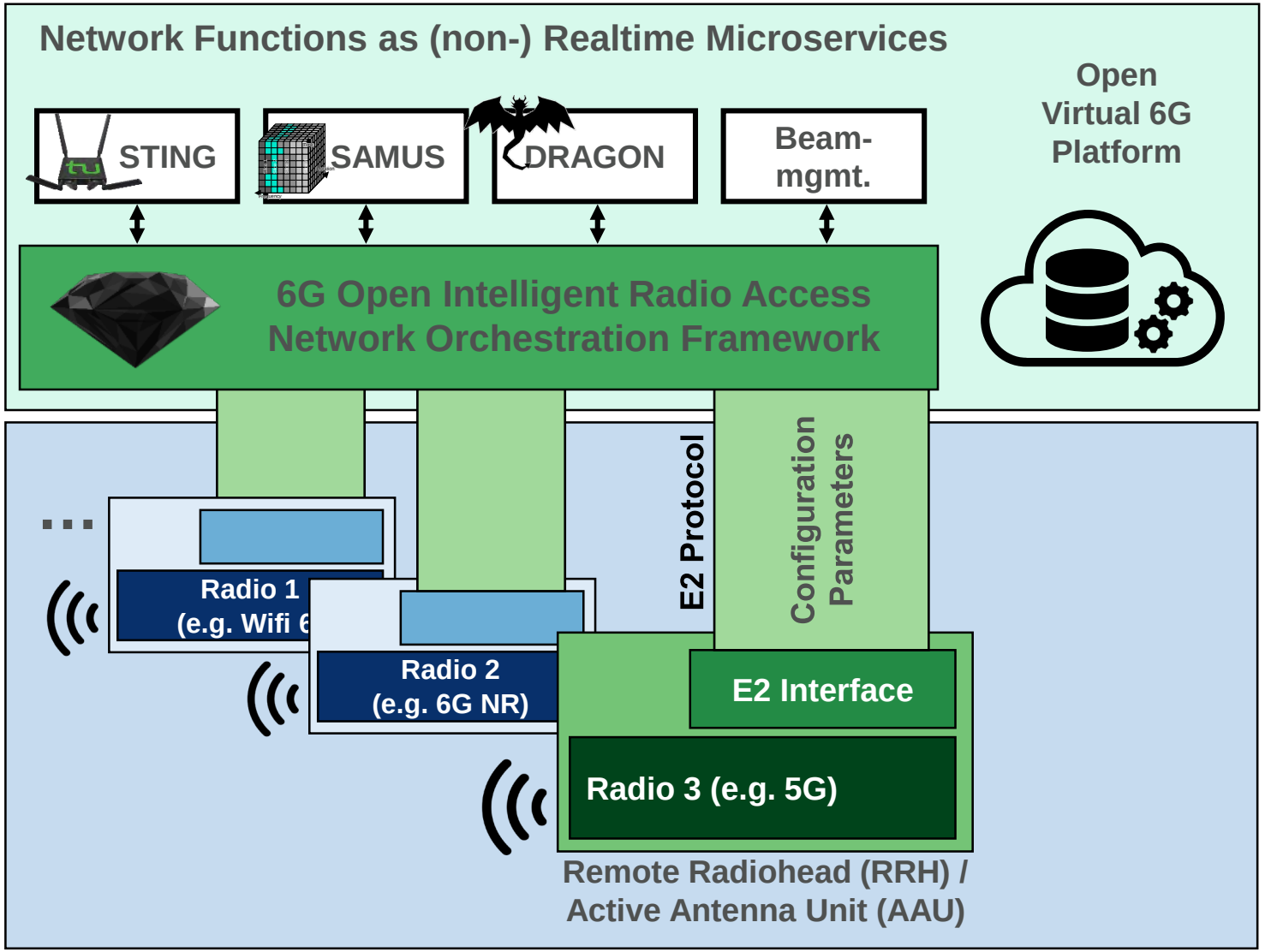
Proposed Framework for the Orchestration of Multi-RAT environments

cf. Evolved 6G-RIC (RAN Intelligent Controller)



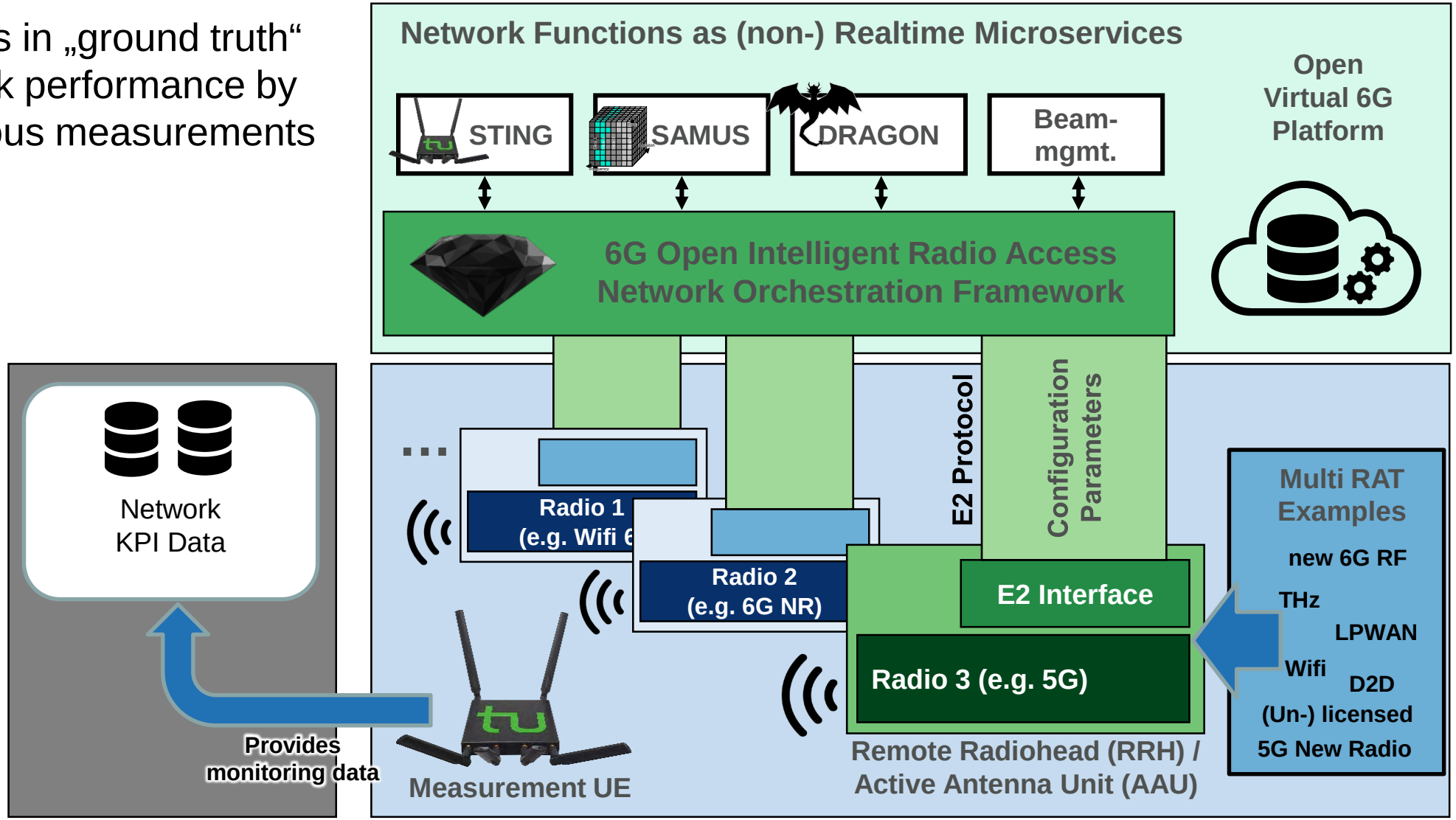
Managing multiple dimensions of future 6G Networks

Network Innovations via micro services

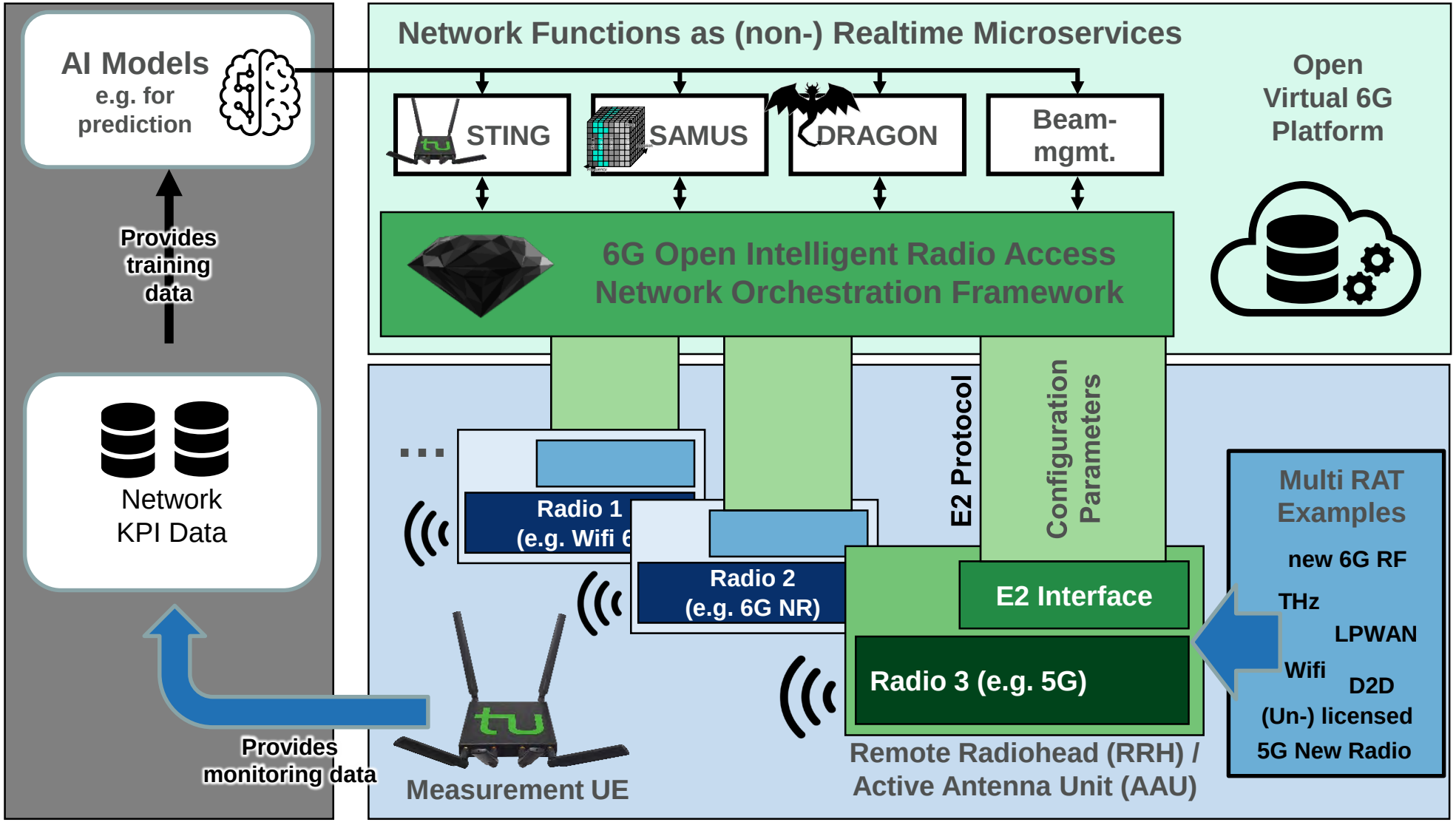


Managing multiple dimensions of future 6G Networks

Insights in „ground truth“ network performance by continous measurements



Data-driven Management of multiple dimensions of future 6G Networks



Selected research approaches for data-driven, multi-dimensional networks

Specific Methods

Ground Truth KPI Monitoring & Prediction

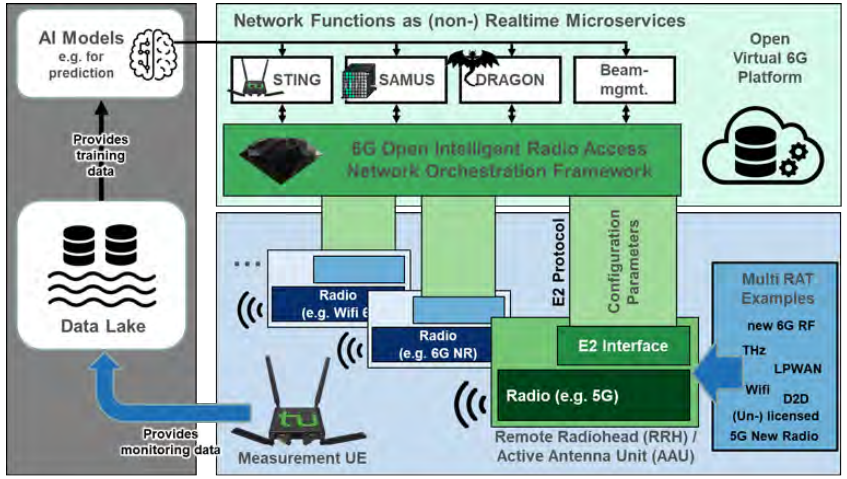
STING

6G Open Intelligent Radio Access Network Orchestration Framework

6G-evolved RIC

High reliability

Low Latencies



Resource-efficiency

Energy

Spectrum

Proposed solution approaches

Data-driven Accurate Channel Prediction

DraGon

AI-enabled resource awareness and scheduling

SAMUS

Programmable mmWave Radio Environments

HELIOS

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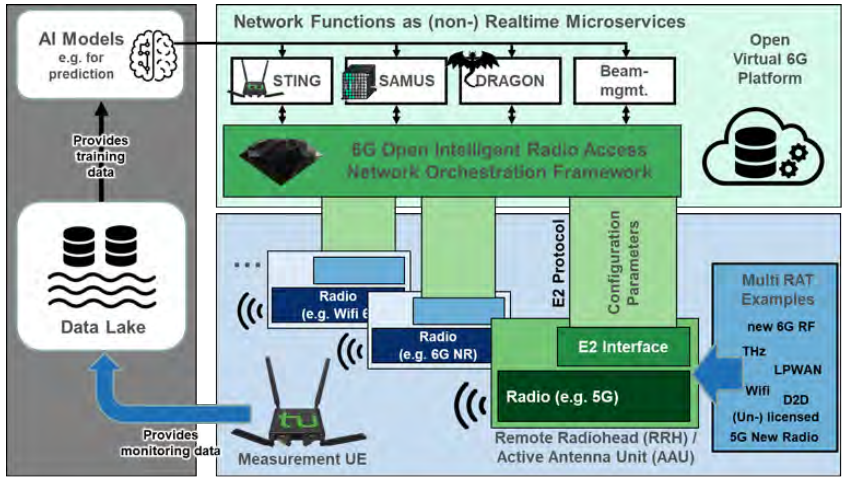

Resource-efficiency

Energy **Spectrum**

Proposed solution approaches

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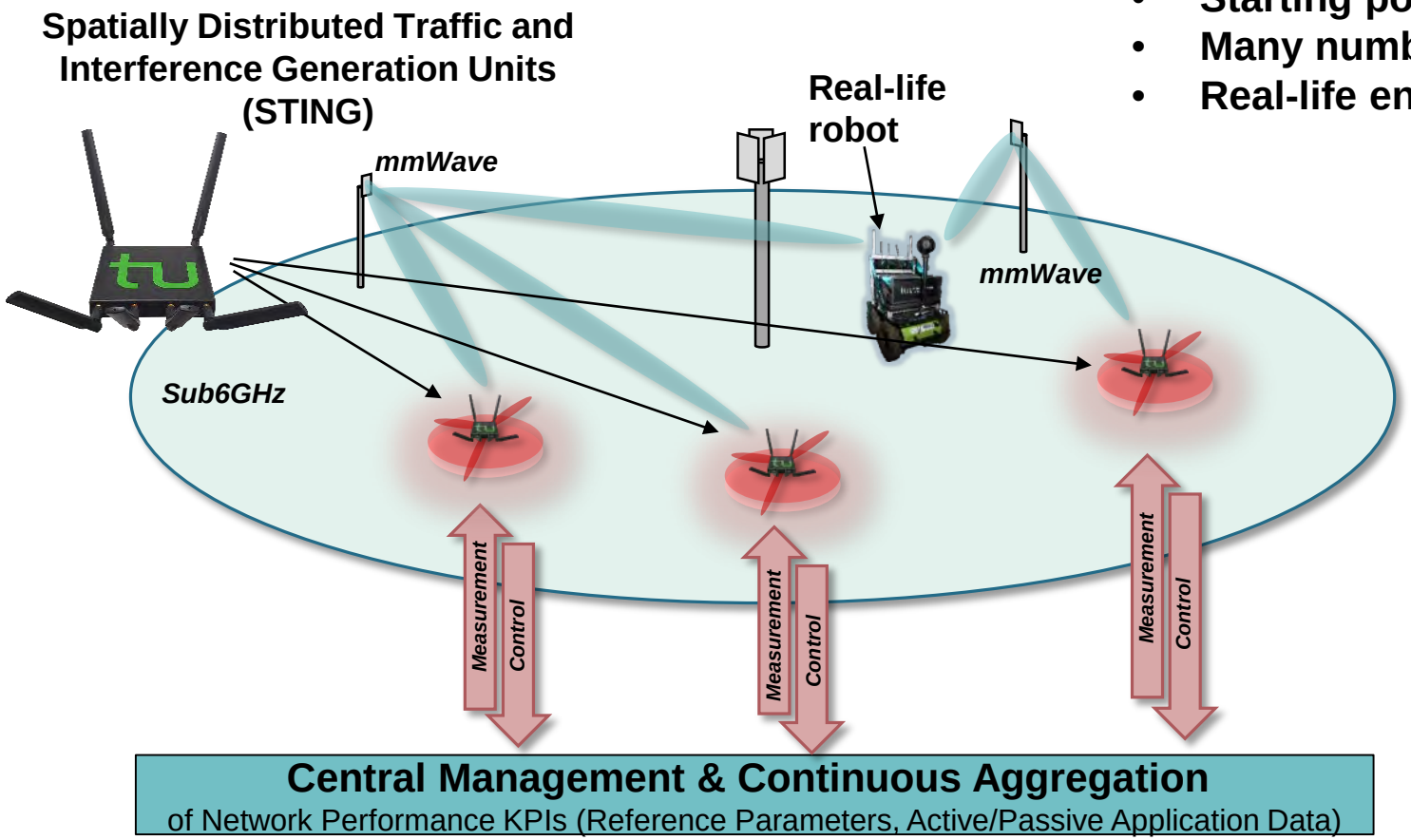
HELIOS

Ground Truth KPI monitoring and control

→ Scale the system to the max in an early stage



- **Starting point: few real-life users**
- **Many numbers of users emulated by STING**
- **Real-life environments**

production

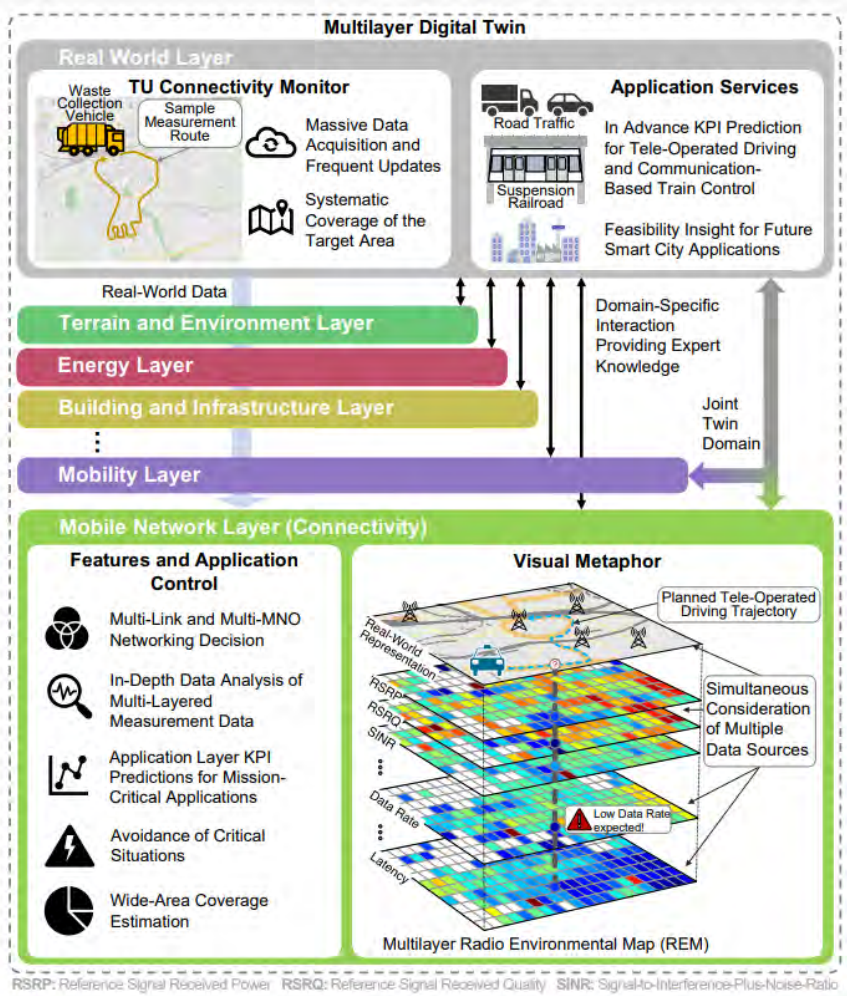
logistics

in cooperation with Fraunhofer IML flw

C. Arendt, S. Böcker, C. Bektas, C. Wietfeld, **Better Safe Than Sorry: Distributed Testbed for Performance Evaluation of Private Networks**, In IEEE FNWF, Montreal, Canada, October 2022.

Ground Truth KPI monitoring & prediction:

→ *Gathering data in the field*



H. Schippers, S. Böcker, C. Wietfeld, "**Data-Driven Digital Mobile Network Twin Enabling Mission-Critical Vehicular Applications**", *In 2023 IEEE 97th Vehicular Technology Conference (VTC-Spring),* Florence, Italy, June 2023.

Selected research approaches for data-driven, multi-dimensional networks

Specific Methods

Ground Truth KPI Monitoring & Prediction

STING

6G Open Intelligent Radio Access Network Orchestration Framework

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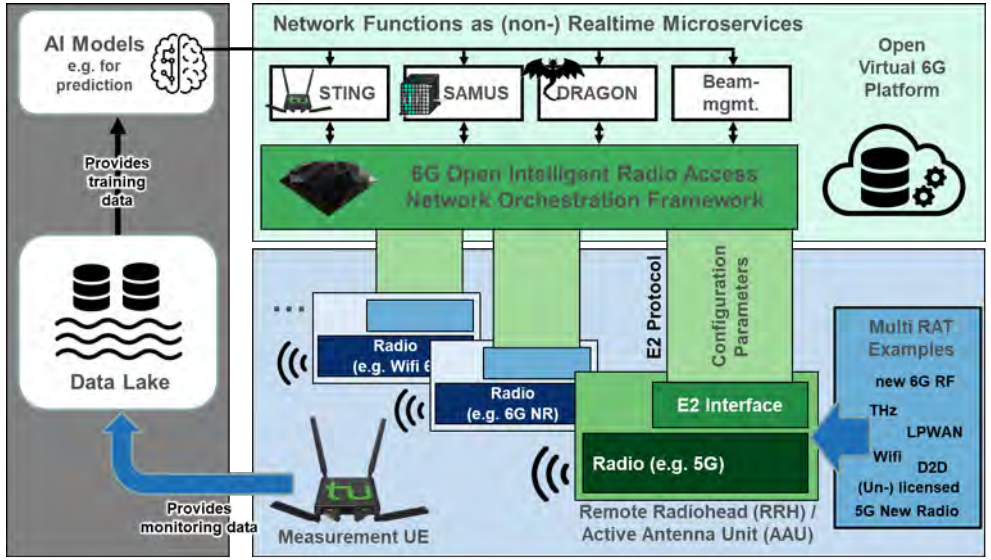

Resource-efficiency

Proposed solution approaches

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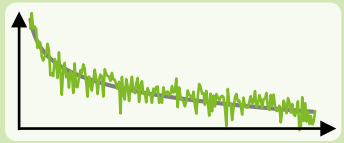
Data-driven Accurate Channel Prediction
Limitations of Classic Radio Propagation Modeling

Empirical Models

- Computationally simple
- Fast
- Satisfactory accuracy

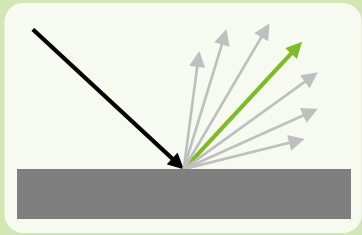


- Not able to mimic complex real world characteristics

Inaccurate

Raytracing Models

- Models physical effects
- Accurate prediction

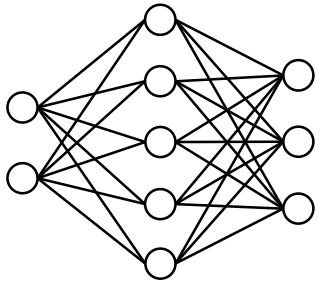


- Computationally expensive
- Time consuming
- Geographical data exhaustive

High effort

New approach

Machine Learning based Propagation Modeling



DRaGon:
Deep Radio Channel Modeling from Geoinformation

J. Thrane, et. al.: „Model-Aided Deep Learning Method for Path Loss Prediciton in Mobile Communication Systems at 2.6 GHz“ in IEEE Access, 2020

DRaGon: Data-driven Accurate Channel Prediction

Leveraging channel measurements and open geo models

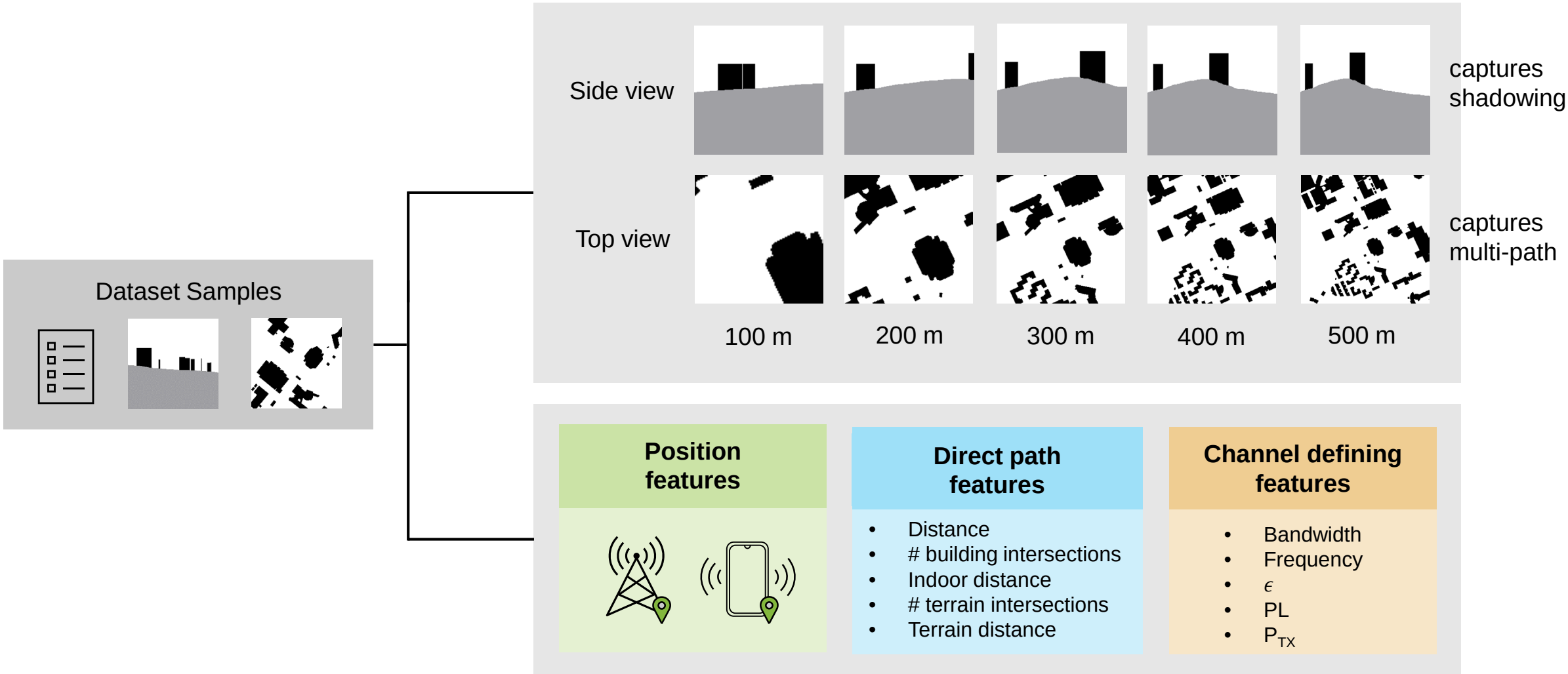
Deep **Ra**dio Channel Modeling
from **Geo**information

OSM – Open Street Map
DEM – Digital Elevation Map
eNB – evolved node B
LIMoSim – Lightweight ICT-centric Vehicle Mobility Simulation
RSRP – Reference Signal Received Power

[1] https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1/view
[2] https://pytorch.org/

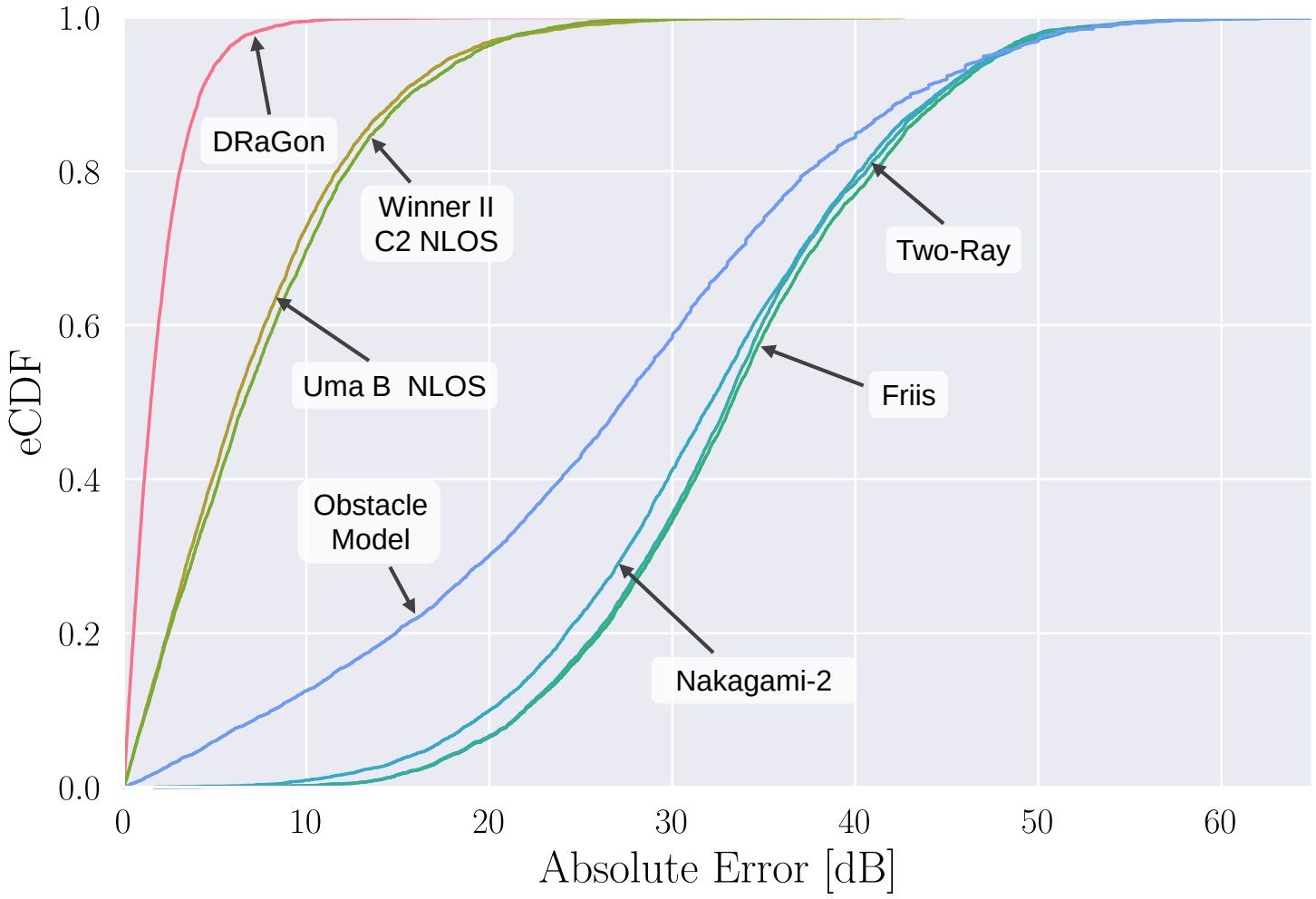
DRaGon: Data-driven Accurate Channel Prediction

Feature Extraction from 3D geo data & wireless network system parameters



DRaGon: Data-driven Accurate Channel Prediction

DraGon outperforms empirical models

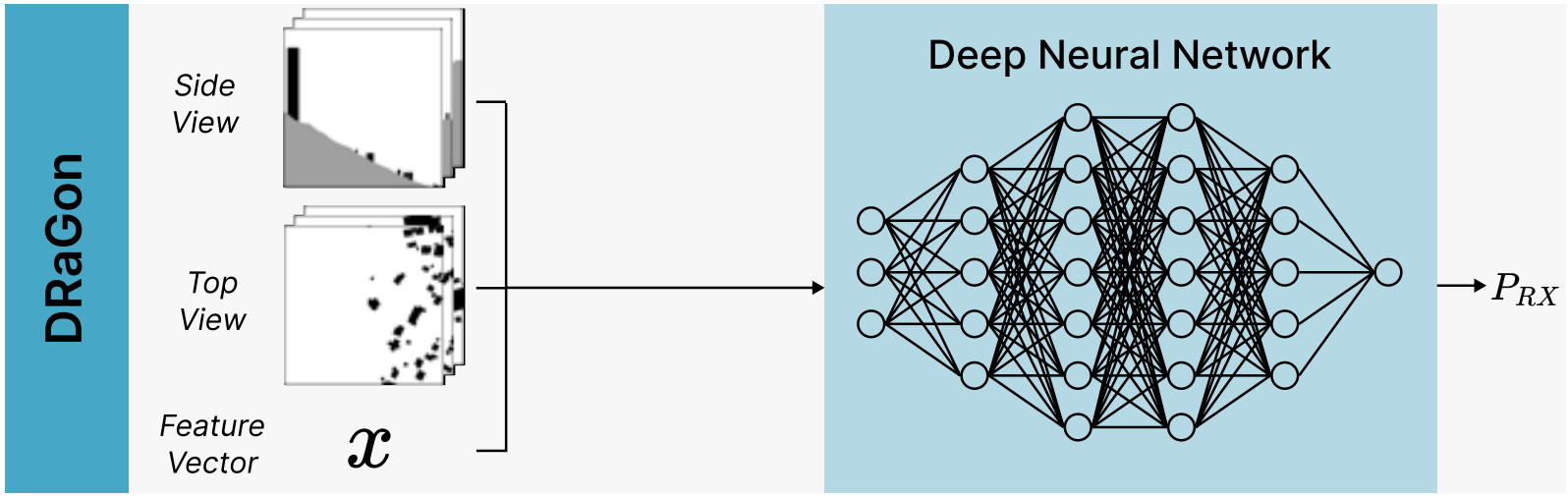


Model	RMSE [dB]
DRaGon	2.70
Uma B NLOS	9.33
Winner II C2 NLOS	9.61
Obstacle Model	29.49
Nakagami-2	33.52
Two-Ray	34.17
Friis	34.49

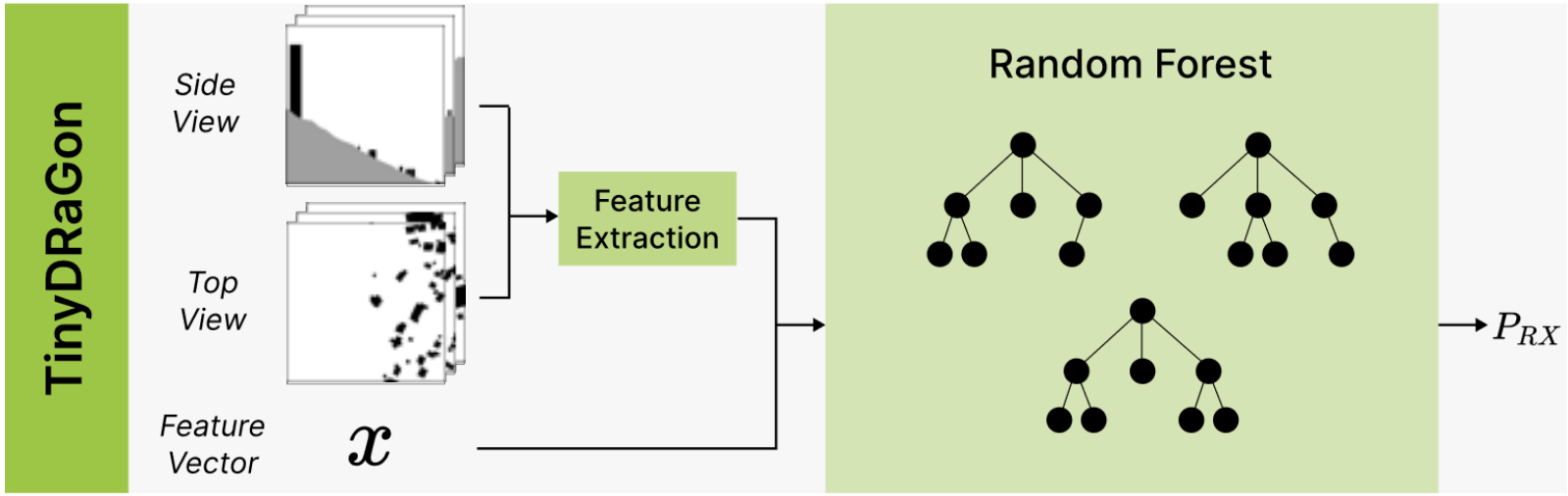
RMSE – Root Mean Square Error
eCDF – empirical Cummulative Distribution Function

DRaGon: Data-driven Accurate Channel Prediction

Reducing complexity by alternative ML methods and further feature extraction



Complex Deep Learning Pipeline due Image Inputs

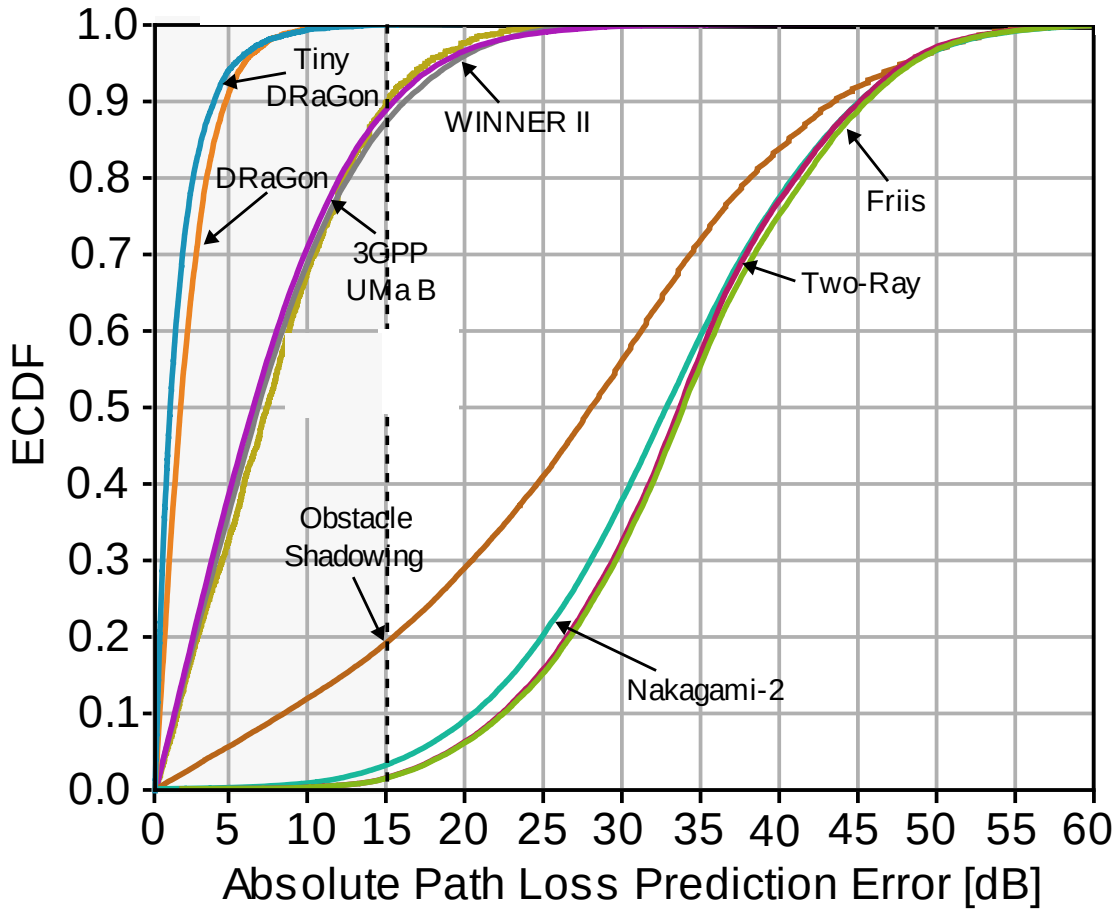


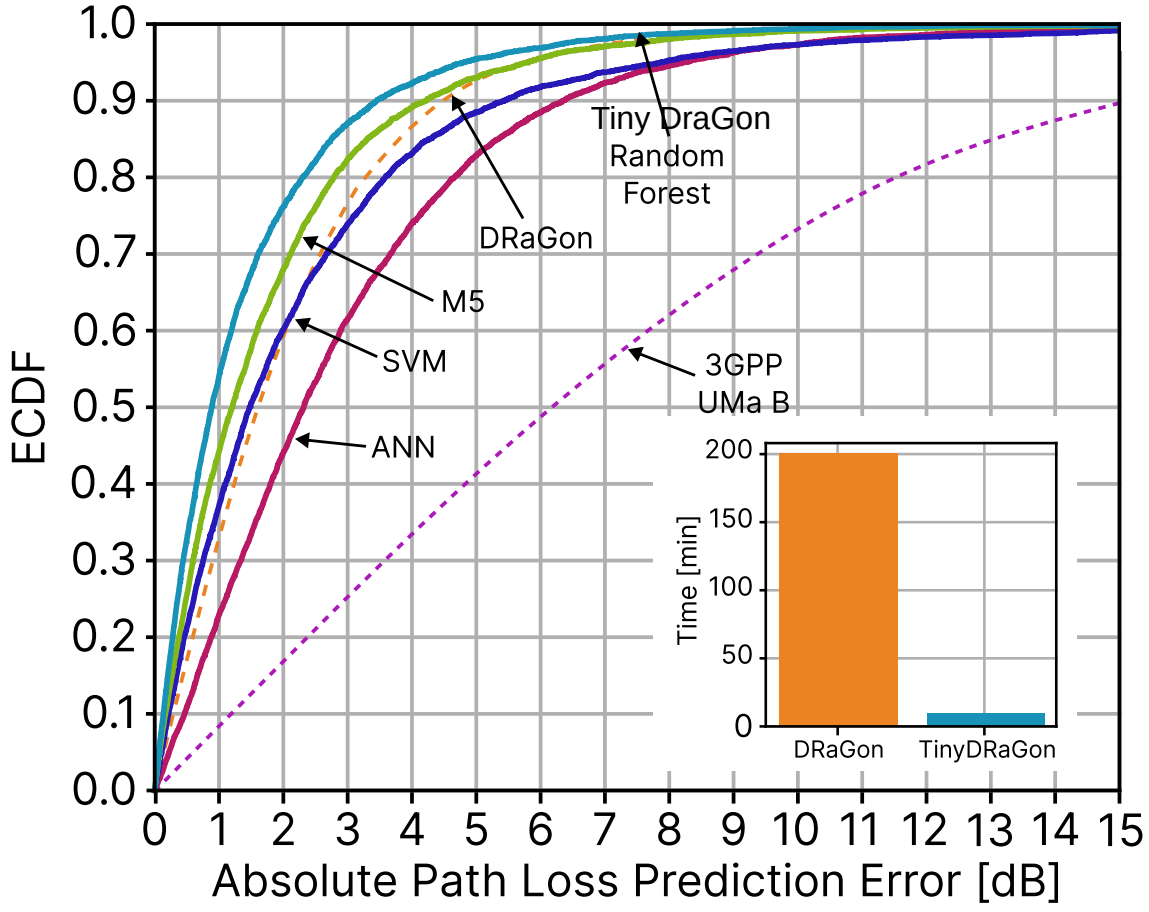
Elimination of Image Inputs results in Reduced Model Complexity

DRaGon: Data-driven Accurate Channel Prediction

Deep learning is not always the best choice

Best Paper IEEE Future Networks WORLD FORUM · 2022



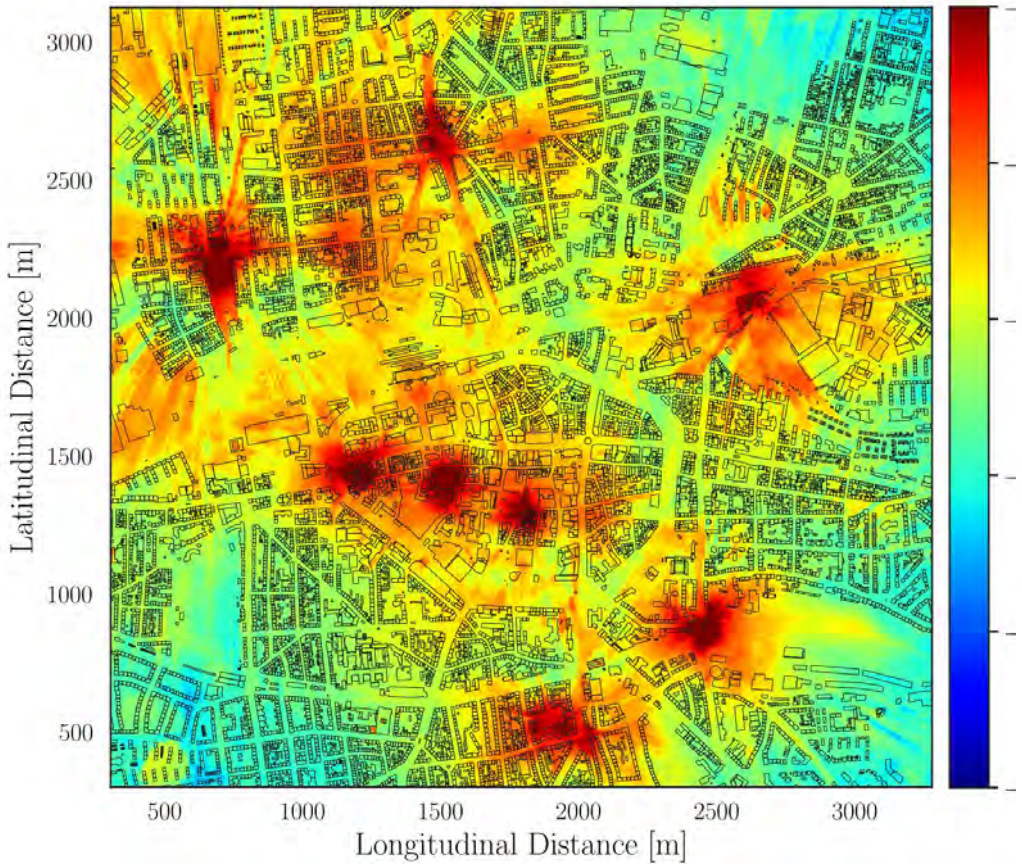


RMSE – Root Mean Square Error **ECDF** – Empirical Cumulative Distribution Function

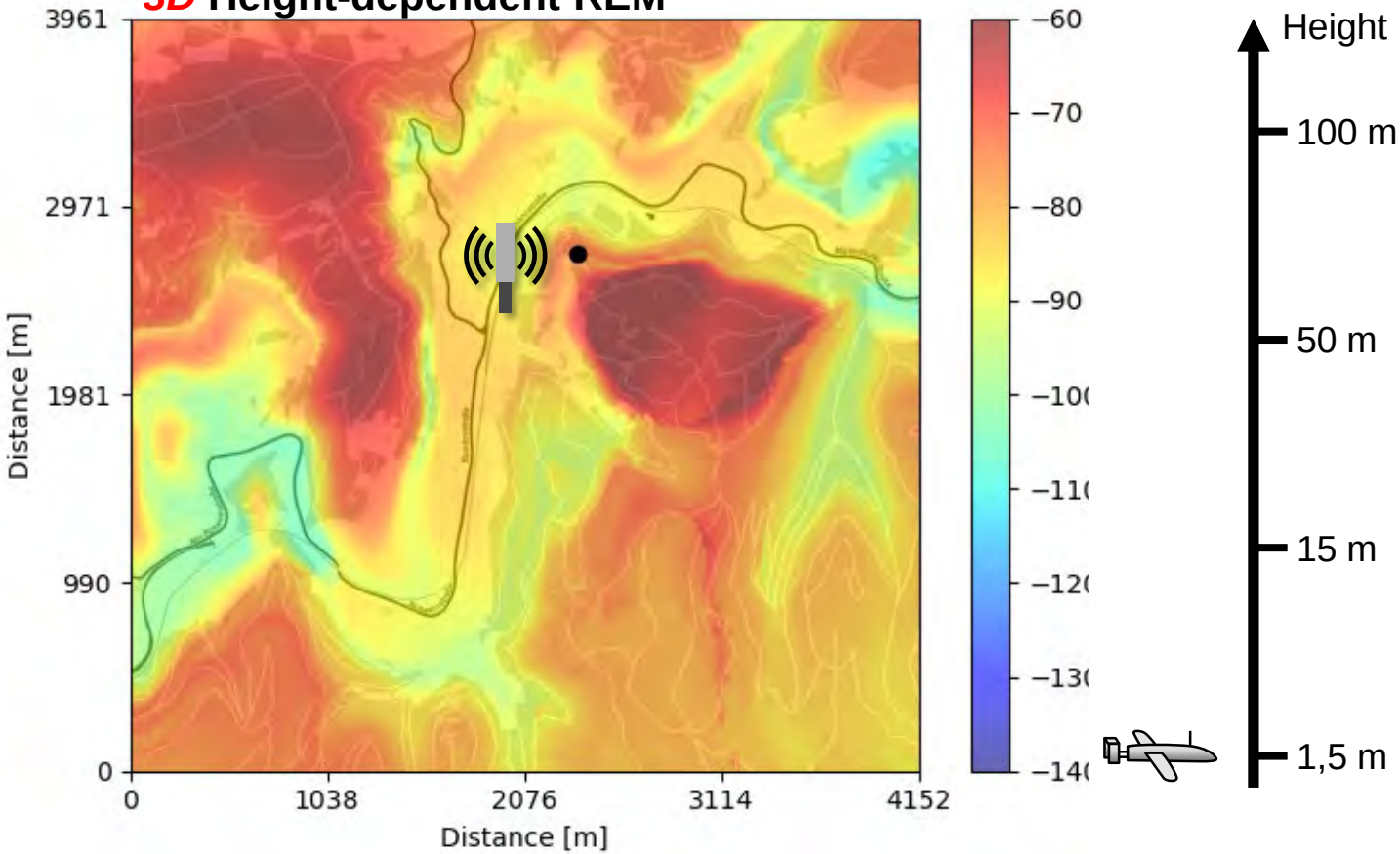
DRaGon: Data-driven Accurate Channel Prediction

Derivation of Radio Environmental maps based on available geo models

2D REM



3D Height-dependent REM



Bundesministerium für Bildung und Forschung
LARUS PRO

Selected research approaches for data-driven, multi-dimensional networks

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Ground Truth KPI Monitoring & Prediction

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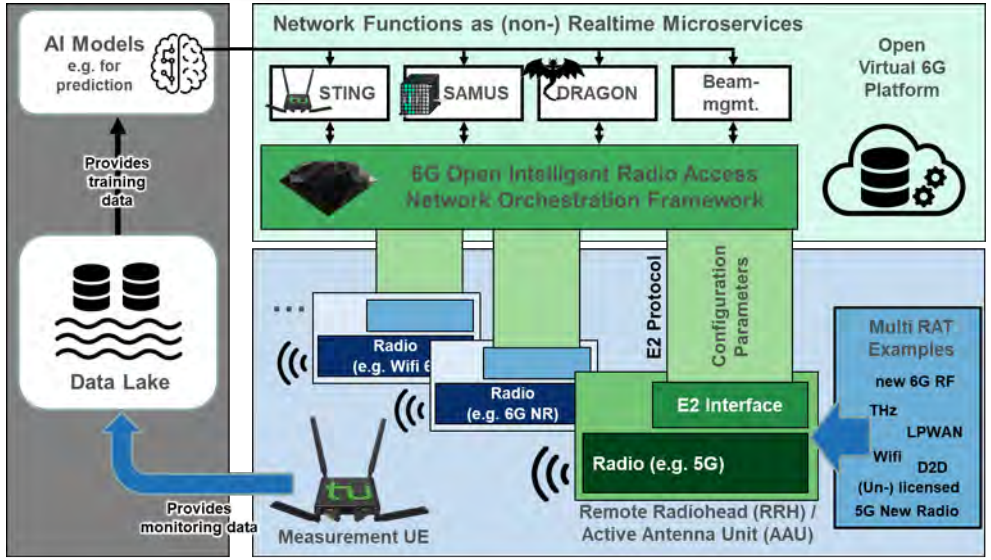
Low Latencies



Resource-efficiency

Proposed solution approaches

Data-driven Accurate Channel Prediction

DraGon

AI-enabled resource awareness and scheduling

SAMUS

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HELIOS

AI-enabled resource awareness and scheduling on ***Client-side:***

CAT: Channel-Aware Transmission

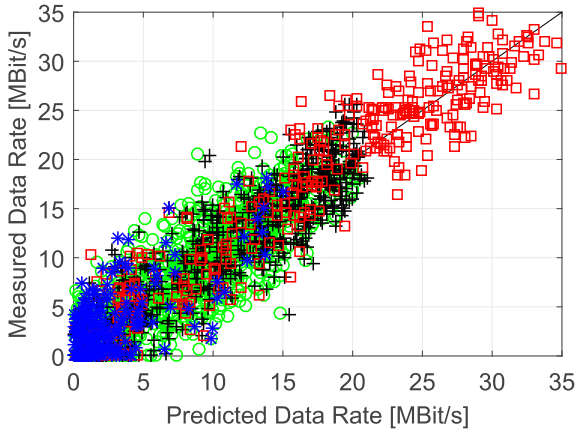
SFB 876

DFG

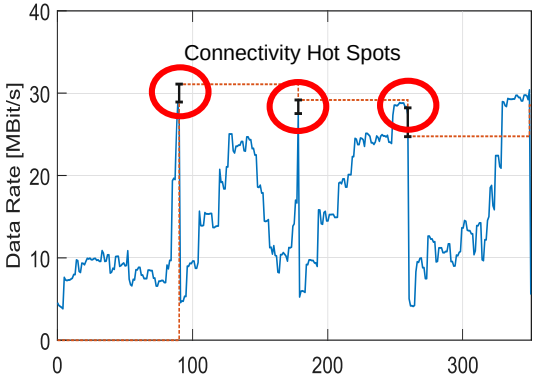
ML-enabled opportunistic scheduling decisions

Learning the complex behaviour of mobile networks

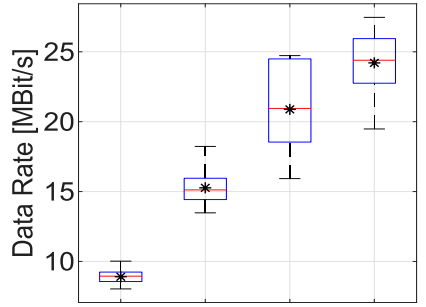
Datarate predicition with passive indicators *using Random Forests*



Opportunistic choice of application-level scheduling *using Reinforcement Learning*

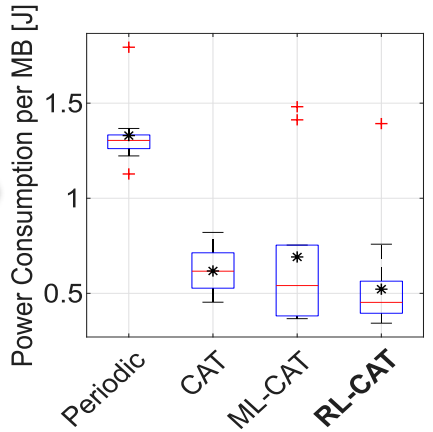


Flexible scheduling leads to **higher data rates**



+171%

Additionally **lower battery conspumption**



-80%

Usable not only for Smart Phones, but also **tiny IoT devices**

LIMITS

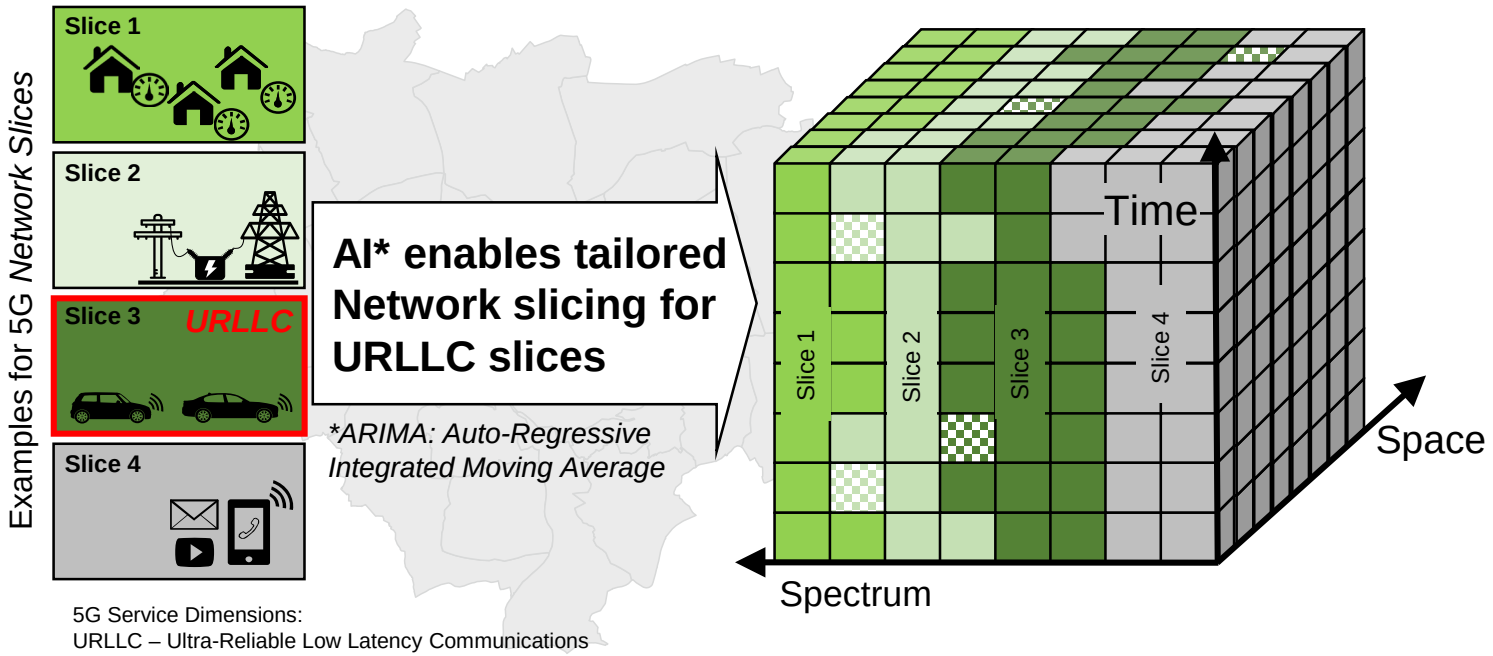
Best Paper IEEE ICC

B. Sliwa, C. Wietfeld, "**A Reinforcement Learning Approach for Efficient Opportunistic Vehicle-to-Cloud Data Transfer**", In *2020 IEEE Wireless Communications and Networking Conference (WCNC)*.

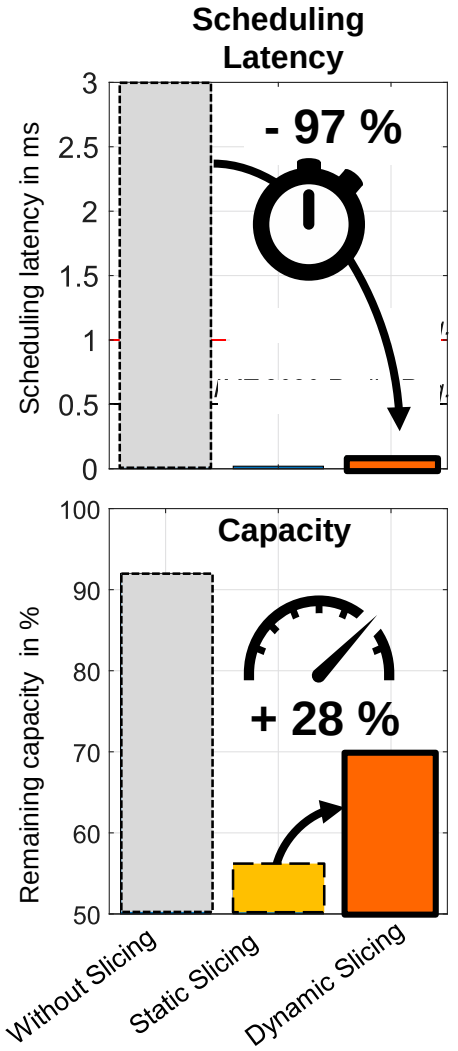
B. Sliwa, N. Piatkowski, C. Wietfeld, "**LIMITS: Lightweight Machine Learning for IoT Systems with Resource Limitations**", In *2020 IEEE International Conference on Communications (ICC)*, ***(Best Paper Award).***

AI-enabled resource awareness and scheduling on *Network-side*
SAMUS: Slice-Aware Machine Learning-based Ultra-Reliable Scheduling

Dynamic Mixed-Critical Network Slicing



5G Service Dimensions:
URLLC – Ultra-Reliable Low Latency Communications
eMTC – evolved Machine-Type Communication
eMBB - enhanced Mobile Broadband



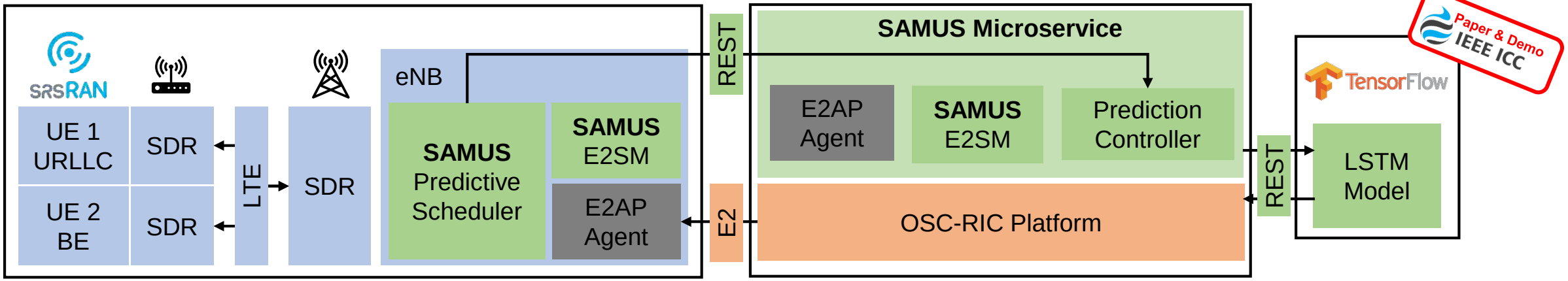
Without Slicing:
Latency requirement violated

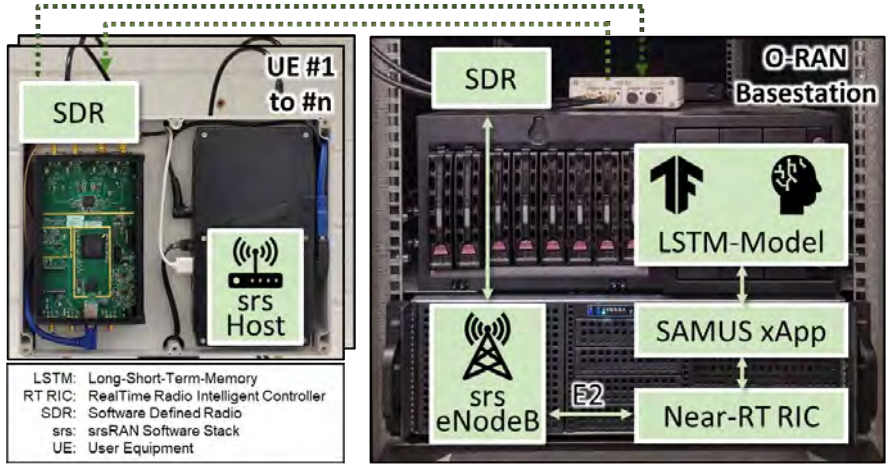
With static slicing:
Latency requirement fullfilled, yet inefficient

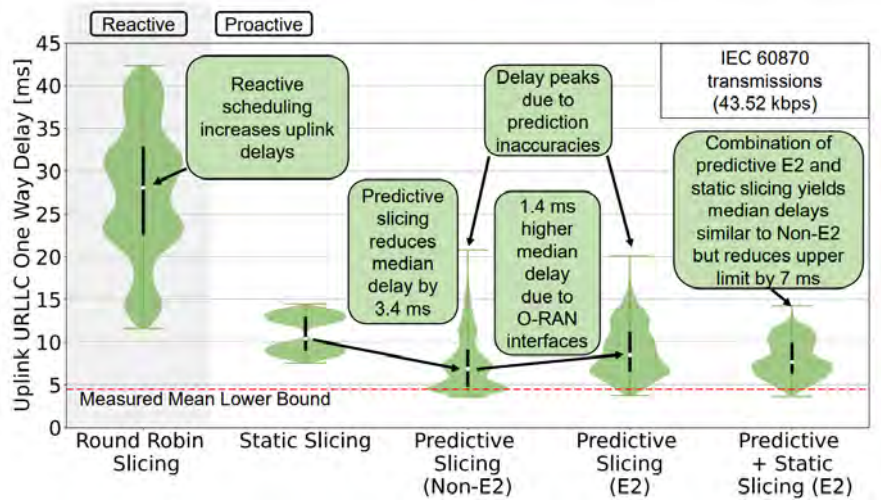
Dynamic Slicing with AI:
Latency requirement fullfilled, yet more efficient

C. Bektas, D. Overbeck, C. Wietfeld, **SAMUS: Slice-Aware Machine Learning-based Ultra-Reliable Scheduling**, *IEEE International Communications Conference ICC 2021.*

AI-enabled resource awareness and scheduling on the network *side:*
openSAMUS: Realization as microservice on top of open platform







R. Wiebusch, N. A. Wagner, D. Overbeck, F. Kurtz, C. Wietfeld, "Towards Open 6G: Experimental O-RAN Framework for Predictive Uplink Slicing,"
In 2023 IEEE International Conference on Communications (ICC), Rome, Italy, May 2023.

Selected research approaches for data-driven, multi-dimensional networks

Specific Methods

Ground Truth KPI Monitoring & Prediction

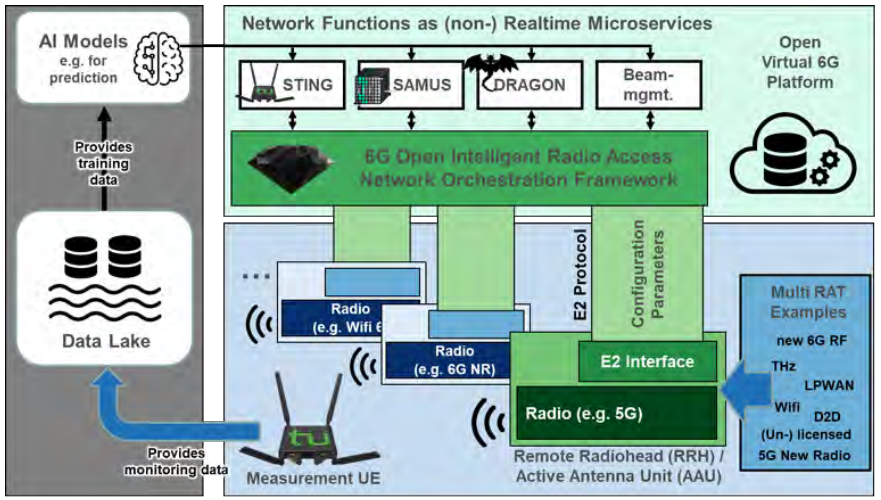
STING

6G Open Intelligent Radio Access Network Orchestration Framework

6G-evolved RIC

High reliability

Low Latencies



Resource-efficiency

Proposed solution approaches

Data-driven Accurate Channel Prediction

DraGon

AI-enabled resource awareness and scheduling

SAMUS

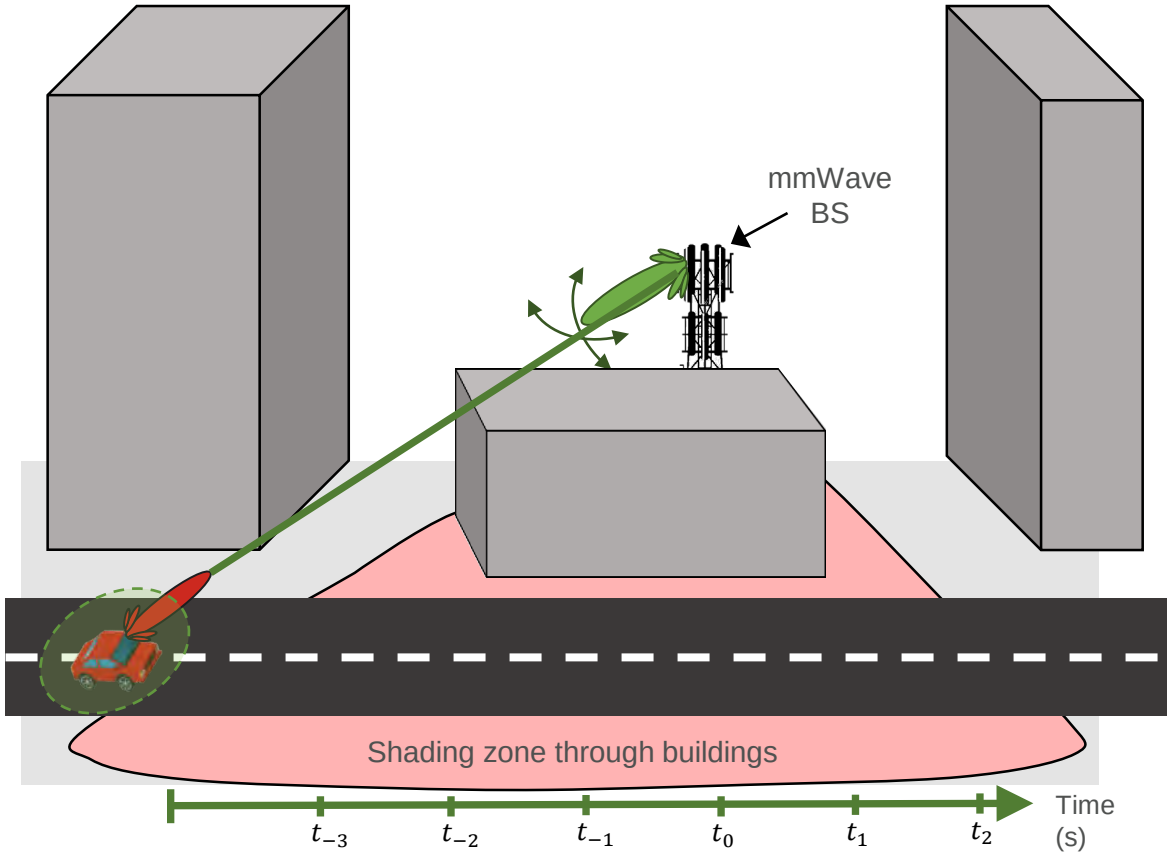
Programmable mmWave Radio Environments

HELIOS

Programmable mmWave Radio Environments

Introducing intelligent surfaces as new network components

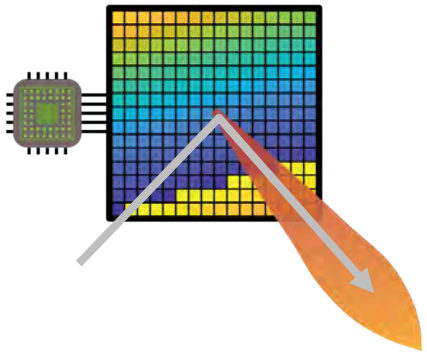
Problem: *Controllable antennas for high frequencies (mmwaves) allow tracking, but require line-of-sight*



Different approaches to solutions under discussion

Additional base station(s)

Reconfigurable Intelligent Surfaces (RIS)

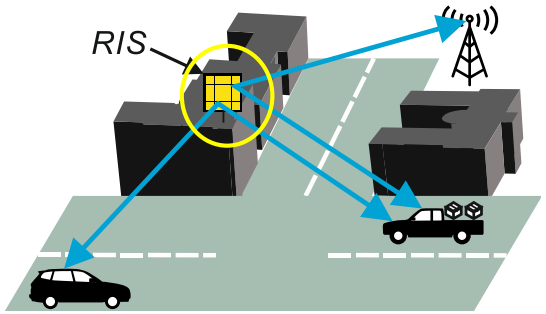


**S. Häger, K. Heimann, S. Böcker, C. Wietfeld, "Holistic Enlightening of Blackspots with Passive Tailorable Reflecting Surfaces for Efficient Urban mmWave Networks," In IEEE Access, April 2023. [Online via IEEE Xplore].*

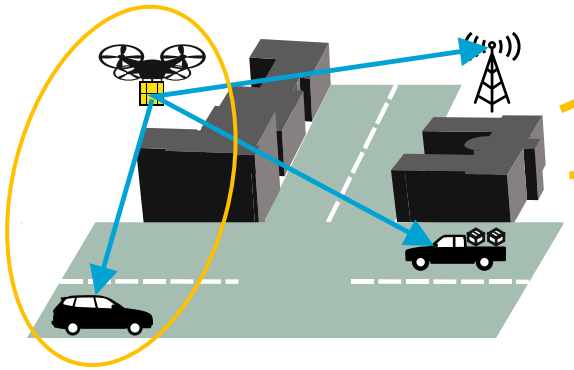
Programmable mmWave Radio Environments

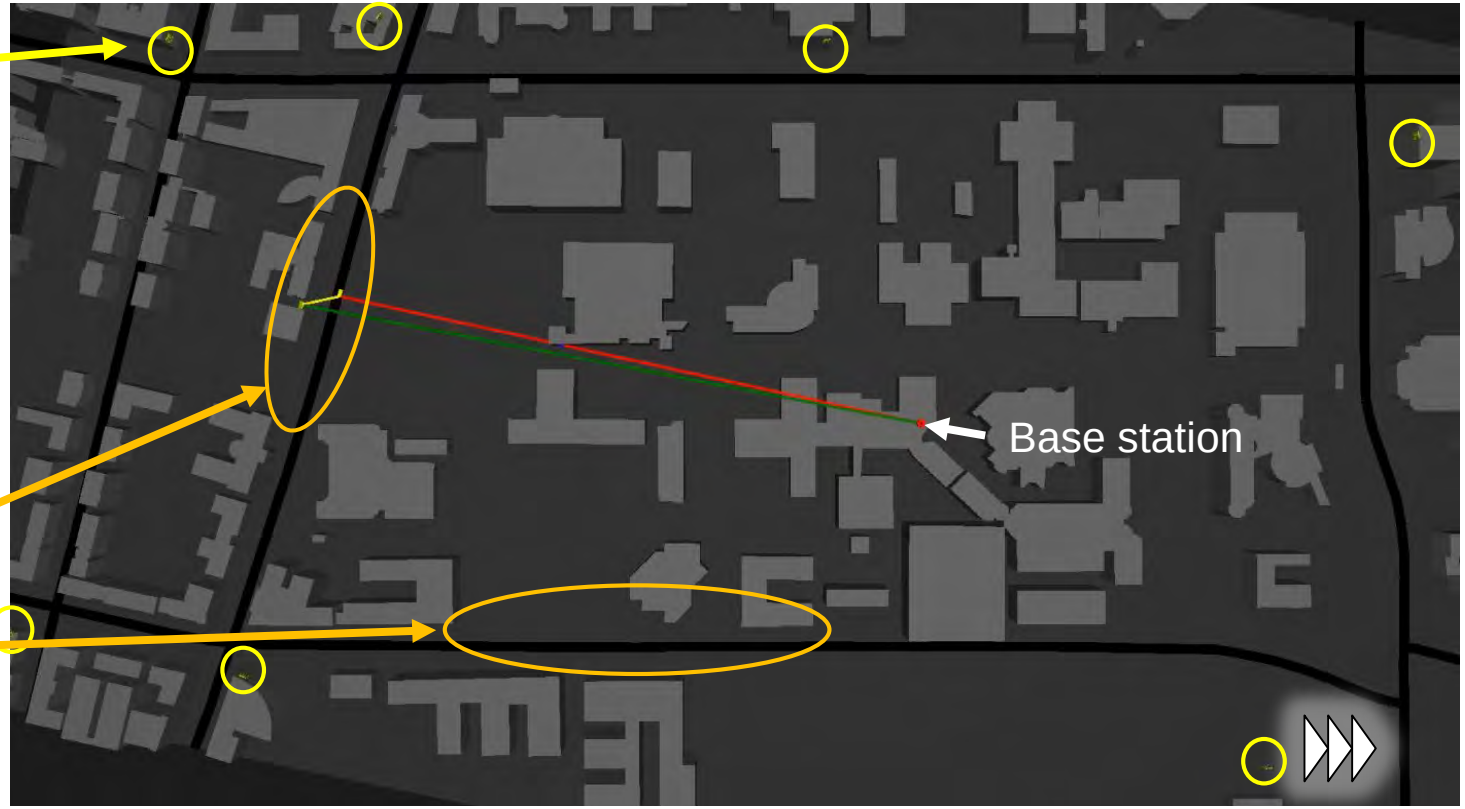
Analysing the potential of RIS in a simulation study

Static RISs



Dynamic RIS (UAV)

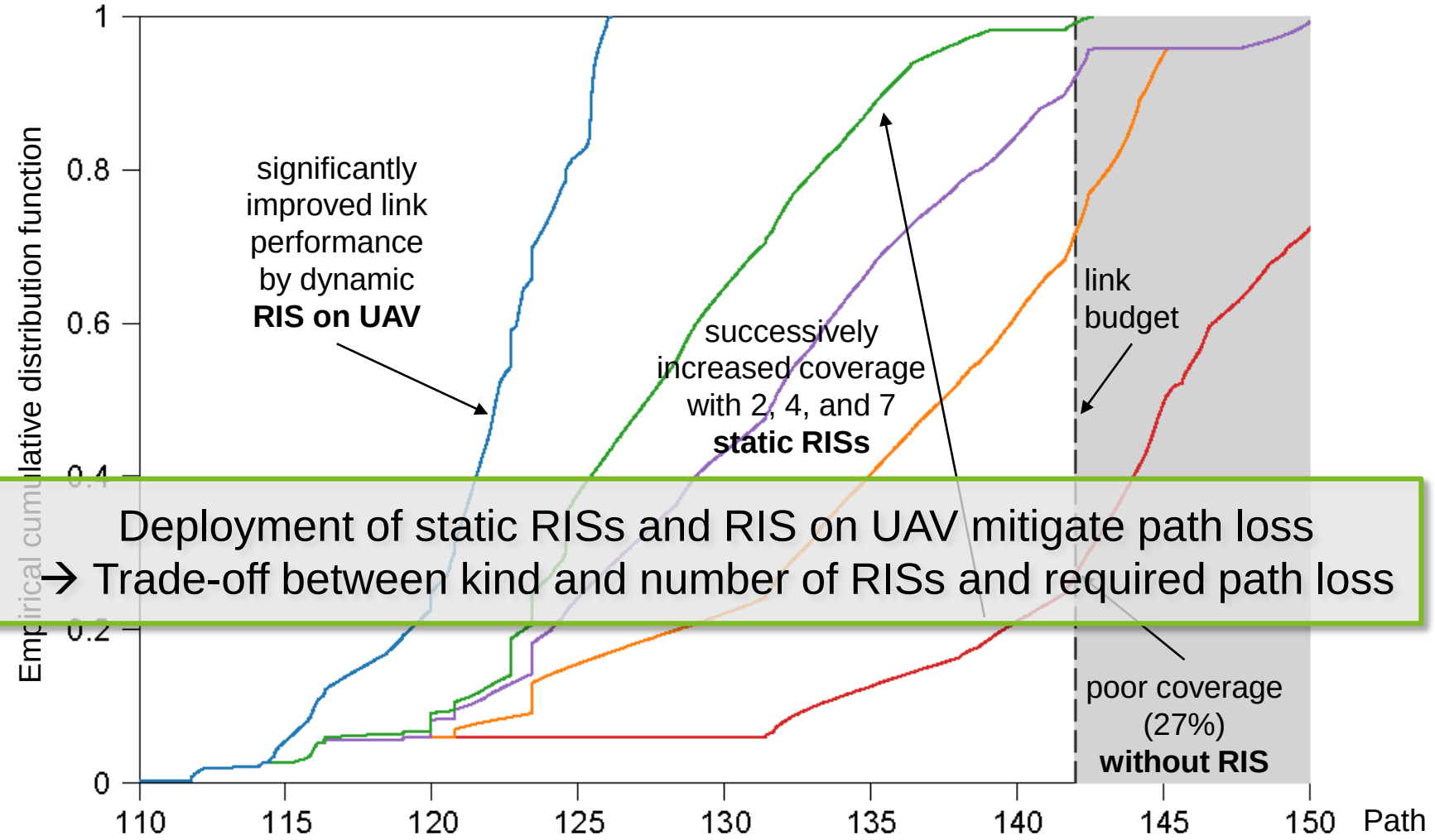




K. Heimann, B. Sliwa, M. Patchou, C. Wietfeld, "Modeling and simulation of reconfigurable intelligent surfaces for hybrid aerial and ground-based vehicular communications", In Proceedings of the 24th International ACM Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems, Association for Computing Machinery, Alicante, Spain (Virtual Event), pp. 67–74, November 2021.

Programmable mmWave Radio Environments

Analysing the potential of RIS in a simulation study

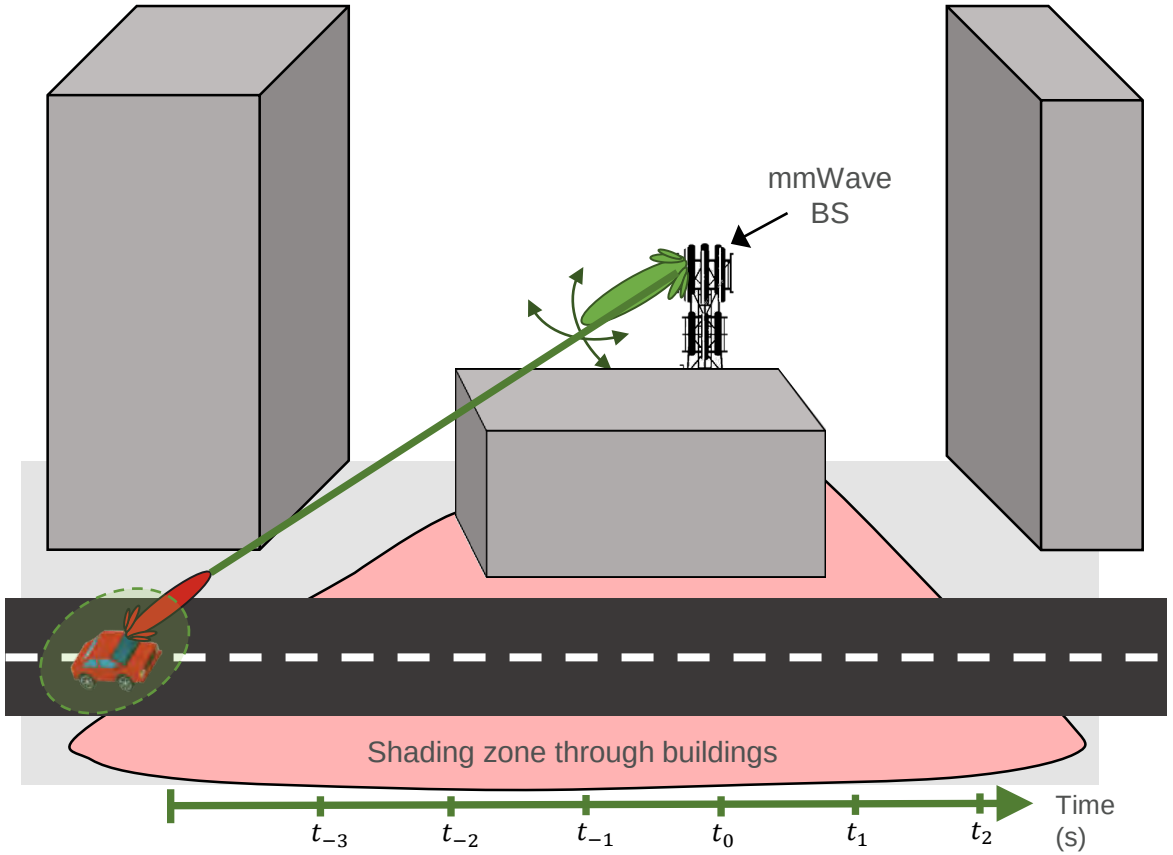


Deployment of static RISs and RIS on UAV mitigate path loss
→ Trade-off between kind and number of RISs and required path loss

K. Heimann, B. Sliwa, M. Patchou, C. Wietfeld, "Modeling and simulation of reconfigurable intelligent surfaces for hybrid aerial and ground-based vehicular communications", In Proceedings of the 24th International ACM Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems, Association for Computing Machinery, Alicante, Spain (Virtual Event), pp. 67–74, November 2021.

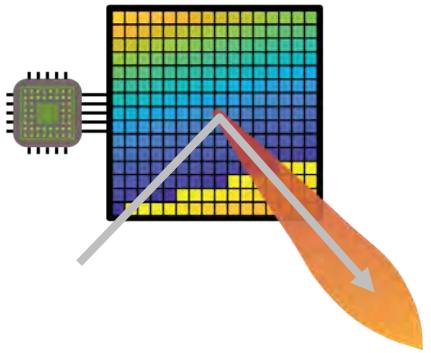
Programmable mmWave Radio Environments

Adding a new category of intelligent reflecting surfaces: HELIOS



Additional base station(s)

Reconfigurable Intelligent Surfaces (RIS)



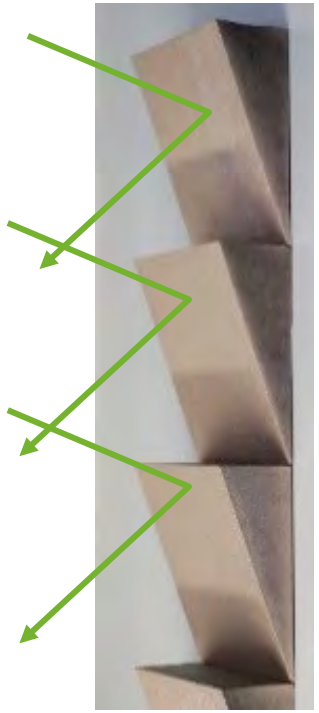
NEW: Passive reflectors from additive manufacturing

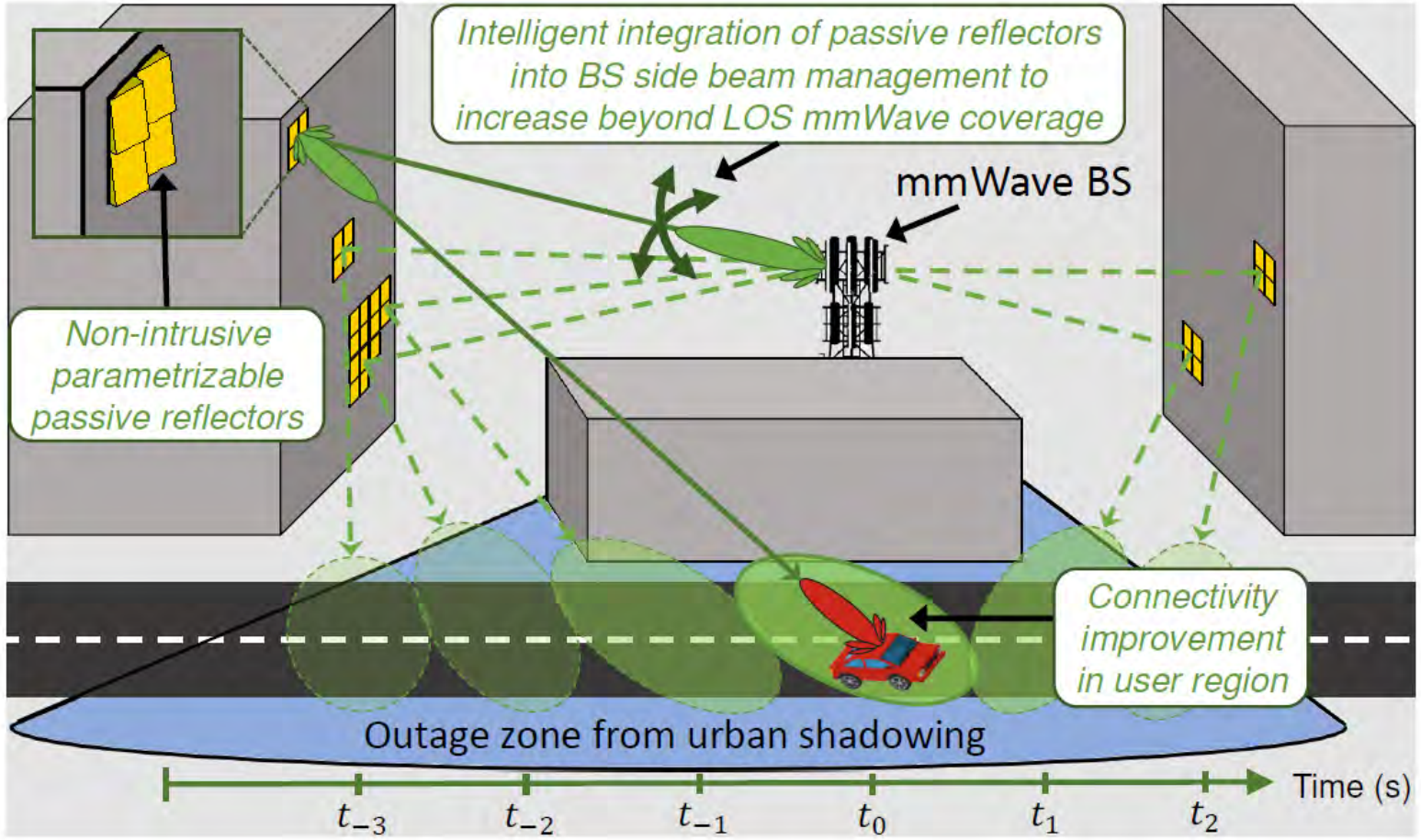
HELIOS

**S. Häger, K. Heimann, S. Böcker, C. Wietfeld, "Holistic Enlightening of Blackspots with Passive Tailorable Reflecting Surfaces for Efficient Urban mmWave Networks," In IEEE Access, April 2023. [Online via IEEE Xplore].*

Programmable mmWave Radio Environments

Adding a new category of intelligent reflecting surfaces: HELIOS





S. Häger, K. Heimann, S. Böcker, C. Wietfeld, "Holistic Enlightening of Blackspots with Passive Tailorable Reflecting Surfaces for Efficient Urban mmWave Networks," In IEEE Access, April 2023.

Programmable mmWave Radio Environments

Adding a new category of intelligent reflecting surfaces: HELIOS

Tailored design and low cost production process

(a) Network planning and reflector parametrization aided by simulations.

(b) Prototype production process with 3D printing and conductive coating. Subsequent piecewise mounting of modules.

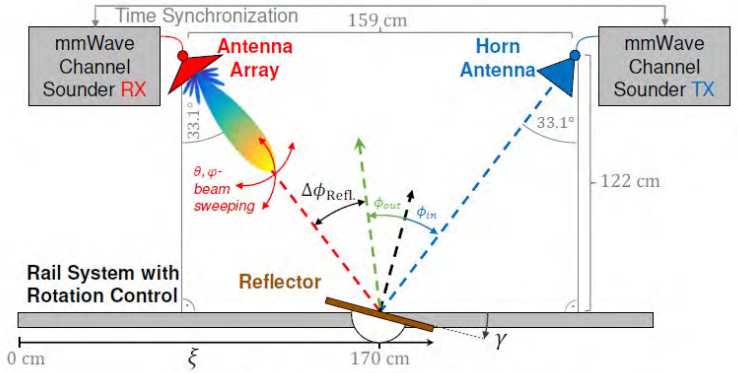
(c) Lab and field validation of various target reflection characteristics.

S. Häger, K. Heimann, S. Böcker, C. Wietfeld, "Holistic Enlightening of Blackspots with Passive Tailorable Reflecting Surfaces for Efficient Urban mmWave Networks," In IEEE Access, April 2023.

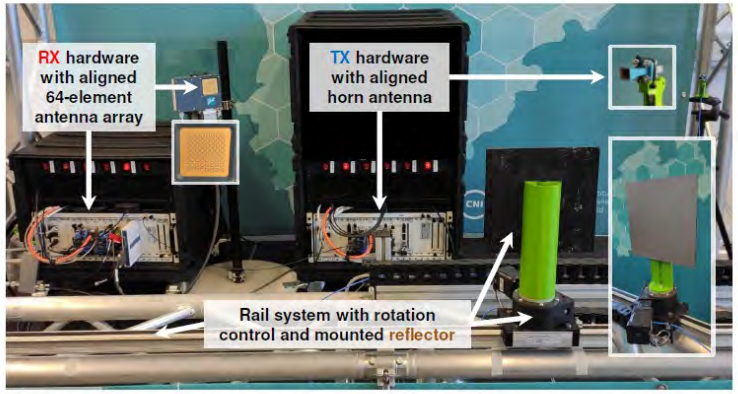
Programmable mmWave Radio Environments

Adding a new category of intelligent reflecting surfaces: HELIOS

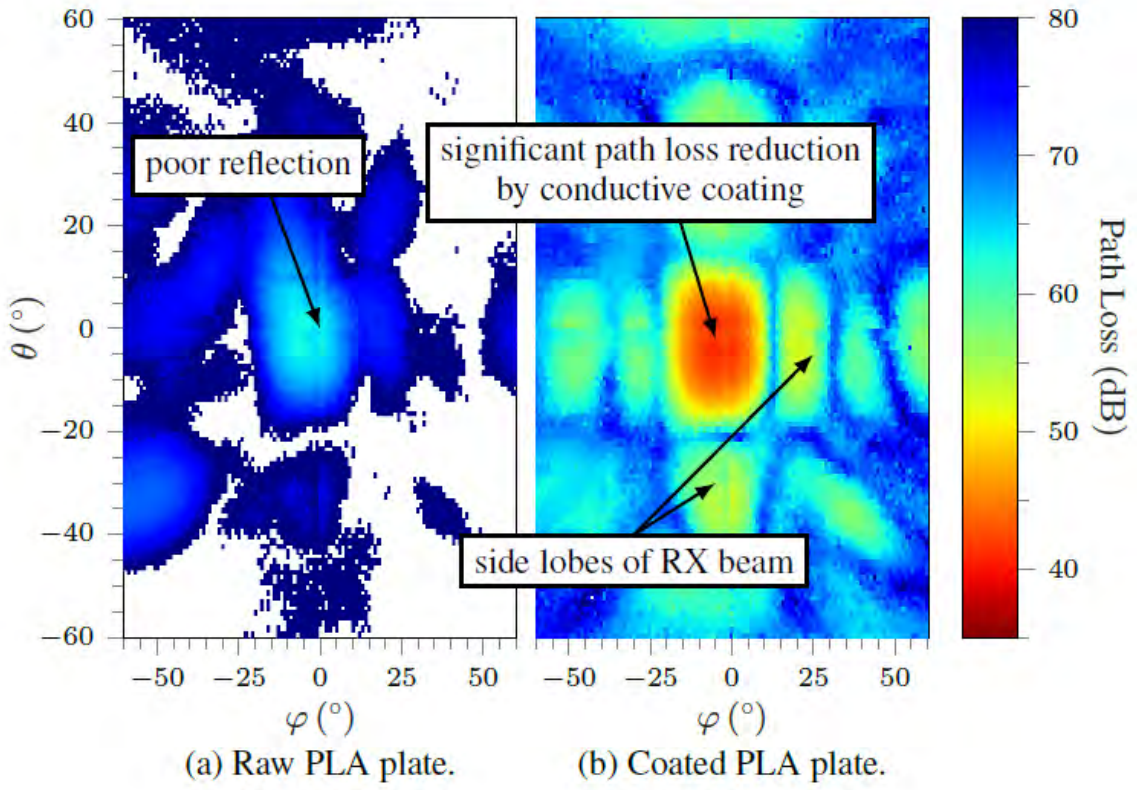
Feasibility of HELIOS reflectors confirmed in lab experiments



(a) Sketch of the laboratory setup in top view.



(b) Photo of reflectivity study of a spray coated PLA plate, cf. Fig. 7b.



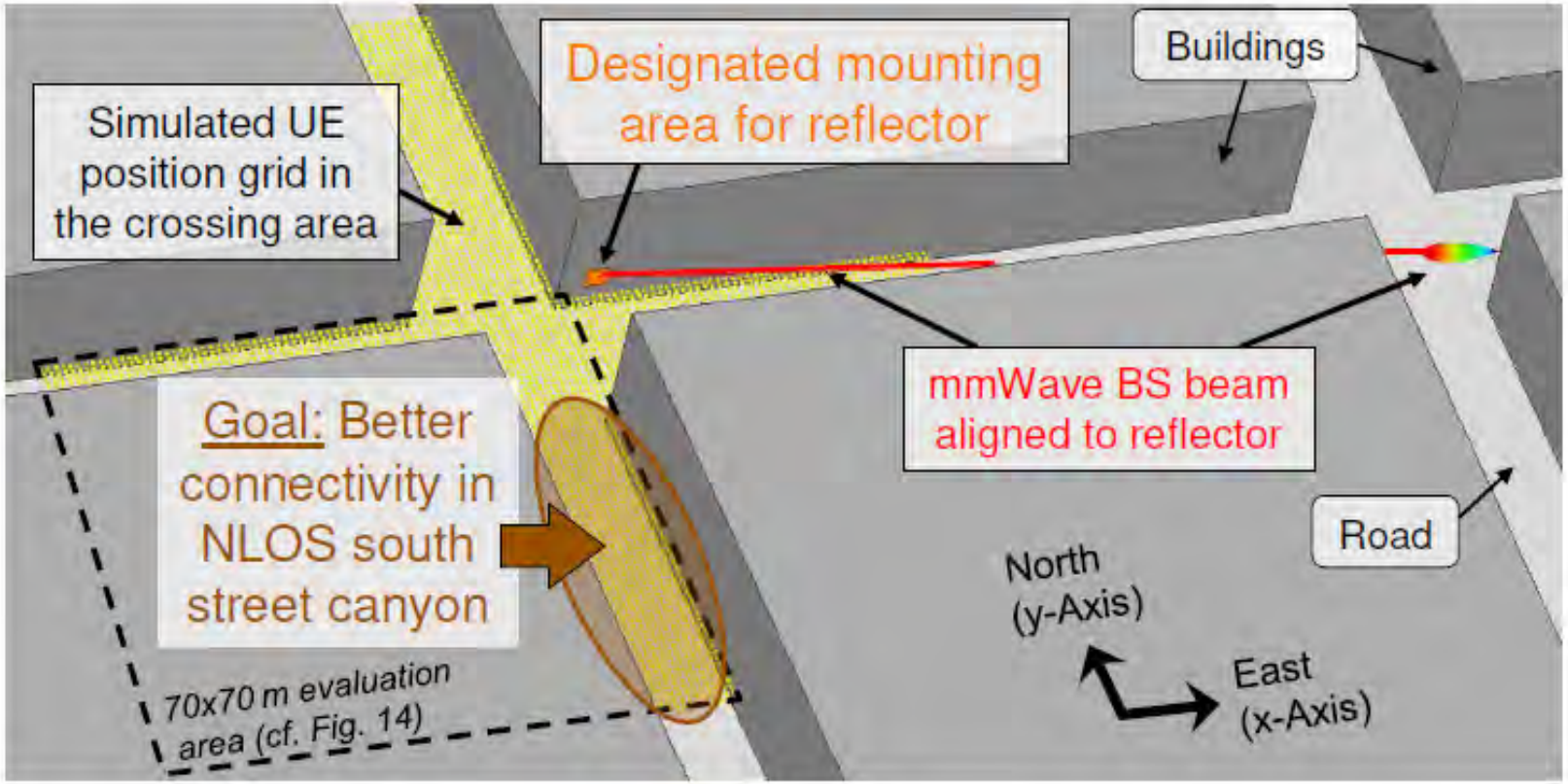
(a) Raw PLA plate. (b) Coated PLA plate.

S. Häger, K. Heimann, S. Böcker, C. Wietfeld, "Holistic Enlightening of Blackspots with Passive Tailorable Reflecting Surfaces for Efficient Urban mmWave Networks," In IEEE Access, April 2023.

Programmable mmWave Radio Environments

Adding a new category of intelligent reflecting surfaces: HELIOS

Case study: illuminating a NLOS area



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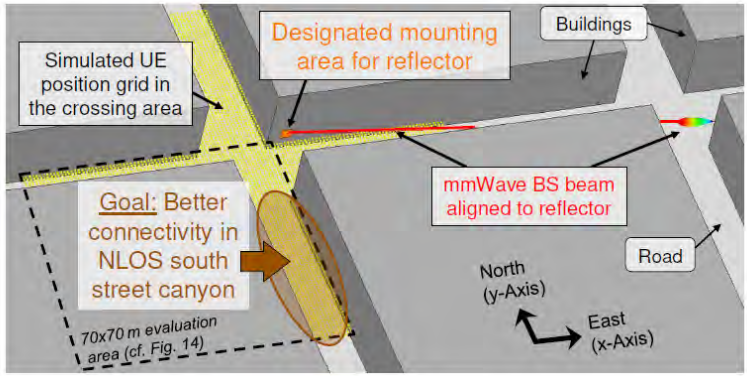
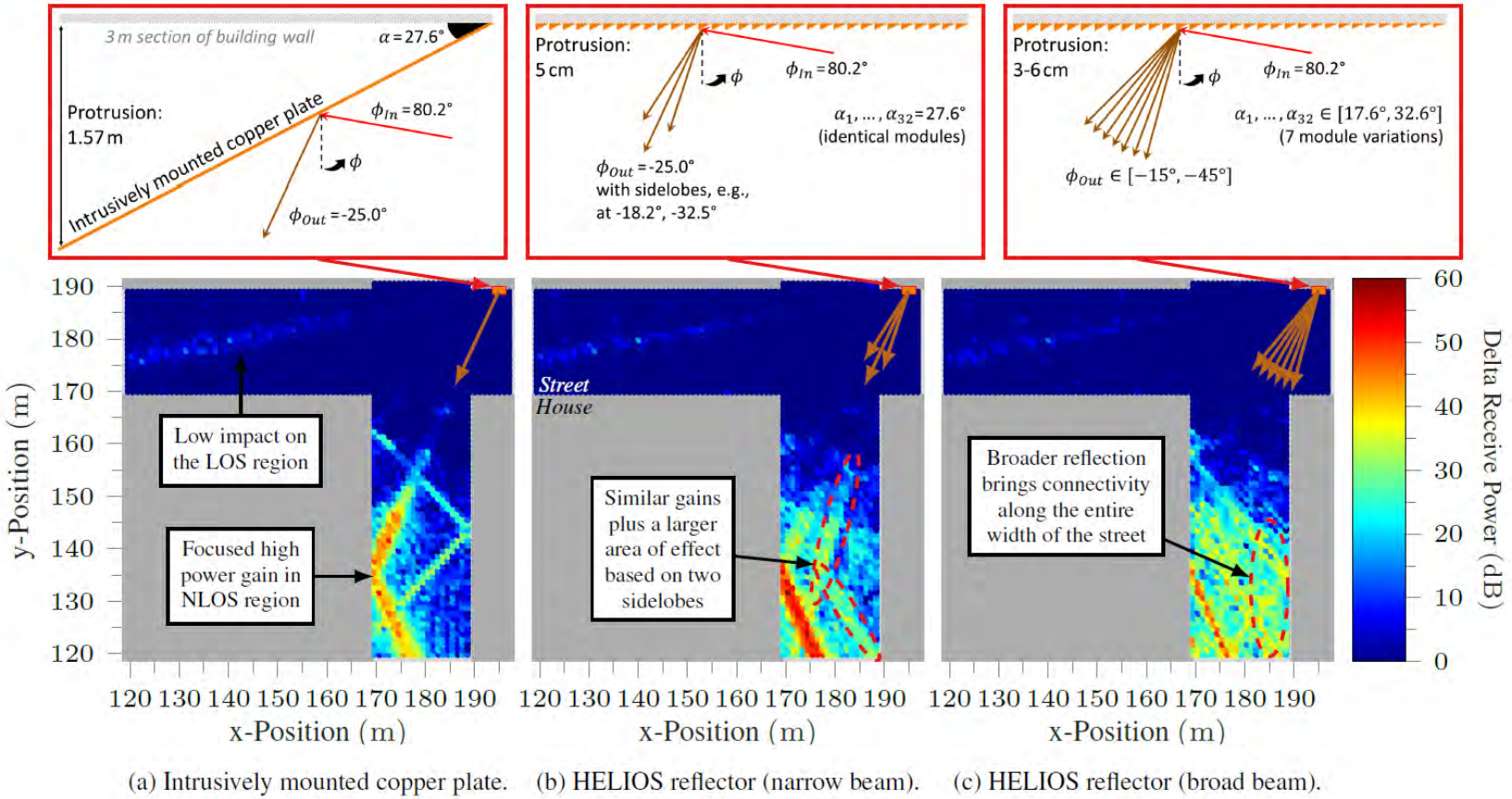
Programmable mmWave Radio Environments

Adding a new category of intelligent reflecting surfaces: HELIOS

Case study: illuminating a NLOS area





(a) Intrusively mounted copper plate. (b) HELIOS reflector (narrow beam). (c) HELIOS reflector (broad beam).

S. Häger, K. Heimann, S. Böcker, C. Wietfeld, "Holistic Enlightening of Blackspots with Passive Tailorable Reflecting Surfaces for Efficient Urban mmWave Networks," In IEEE Access, April 2023.

Programmable mmWave Radio Environments

Much more research is needed to find the „right“ solutions to solve the NLOS problem of mmWave and even THz

Recent Journal IEEE Access

Metrics / Categories/Features \ Approaches / Generic/Specific		Extra BS	Relay	Repeater	RIS/IRS		Passive Reflector		
					Active	Passive	Proposed HELIOS Concept	Mechanical Steerable Surface	Simple Plate/ Foil
Power Consumption	Full Stack	●	○	○	○	○	○	○	○
	Decoding/Channel Estimation	●	●	◐	◐	○	○	○	○
	Amplification	●	●	●	●	○	○	○	○
	Steering (Electronical or Mechanical)	●	◐	◐	●	●	○	●	○
	Control Link	◐	◐	◐	●	●	○	●	○
	None/Passive	○	○	○	○	○	●	○	●
Coverage Type	New Cell	●	○	○	○	○	○	○	○
	Active Antennas	●	●	●	●	○	○	○	○
	Generalized Snell's Law of Reflection [9]	○	○	○	●	●	◐	○	○
	Snell's Natural Law of Reflection	○	○	○	◐	◐	●	●	●
Signal Forwarding	Full Stack	●	○	○	○	○	○	○	○
	Decode & Forward	◐	●	○	○	○	○	○	○
	Amplify & Forward	○	○	●	●	○	○	○	○
	Real-time Control of Reflection	○	○	○	●	●	○	●	○
	None/Predefined	○	○	○	○	○	●	○	●
Control	Backhaul (Wired or Wireless)	●	●	●	○	○	○	○	○
	Control Signaling	●	◐	◐	●	●	○	●	○
	None/Predefined	○	◐	◐	○	○	●	○	●
Material and Equipment	Radio Unit (Transmit and/or Receive)	●	●	◐	◐	○	○	○	○
	Active Antennas	●	●	●	●	○	○	○	○
	Passive Antennas	○	○	○	◐	●	◐	○	○
	Metamaterial	○	○	○	●	●	◐	◐	○
	Tailorable Reflection	○	○	○	●	●	●	●	○
	Reflective Material	○	○	○	●	●	●	●	●
Deploy-ment	Rooftop/Pole Mount	●	●	●	○	○	●	●	○
	Wall/Ceiling Mount	●	●	●	●	●	●	●	●
	Arbitrary Surface	○	○	○	●	●	◐	○	●
	References	[10–12]	[12–18]	[14–18]	[6, 15–20]	[6, 14–19, 21, 22]	*This Work*	[6, 19, 22, 23]	[6, 18, 24–26]

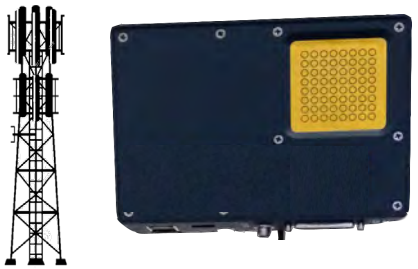
Feature Classification: ● – Typical feature. ◐ – Applies in selected realizations or system states. ○ – Does not apply.

S. Häger, K. Heimann, S. Böcker, C. Wietfeld, "Holistic Enlightening of Blackspots with Passive Tailorable Reflecting Surfaces for Efficient Urban mmWave Networks," In IEEE Access, April 2023.

Programmable mmWave Radio Environments

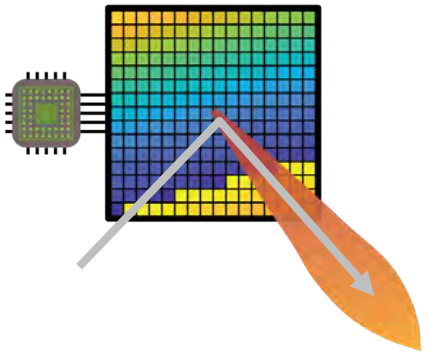
Much more research is needed to find the „right“ solutions to solve the NLOS problem of mmWave and even THz

More base stations



- ✚ Full range of functions
- ✚ Largest capacity
- ▬ Complex installation (regulatory, technical)
- ▬ Comparatively high energy demand

RIS



- ✚ Controllable features for flexible radio field extension
- ✚ Less effort in terms of installation and operation
- ▬ Electronic system with power and communication needs

Passive HELIOS reflectors

- ✚ Cheaper manufacturing (additive)
- ✚ Self-sufficient (passive)
- ✚ Potential additional benefit
- ▬ Form factor: the more flexibility, the more modules are needed

Summary

- The **solution space of wireless networking solutions gets ever more complex and multi-dimensional.**
- **Data-driven solution** supported by machine-learning delivers **deep insights in the performance of different solution and helps to make the proper choices**.
- Today‘s 6G-related networking research can go beyond mathematical modelling and simulation: **validation of selected networking concepts in the target environment** is enabled by **software-defined solutions** and **open interfaces**
- **Selected networking solution approaches** show their potential for resource-efficient support of highly reliable wireless communications: **STING, SAMUS, DraGon & HELIOS**

Website

Thank you very much for your attention!

YouTube

Acknowledgement: The work presented in the slides has been realized by the CNI team within various collaborative projects funded by DFG, BMBF, BMWi, BMVD, 5G.NRW. Special thanks go to Stefan Böcker, Fabian Kurtz, Dennis Overbeck, Robin Wiebusch, Caner Bektas, Melina Geis, Karsten Heimann, Simon Häger, Manuel Patchou, Christian Arendt, Hendrik Schippers, Tim Gebauer; Benjamin Sliwa.