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The road from 5G to 6G: Challenges ahead and potential approaches from the perspective of the 6G Research and Innovation Cluster

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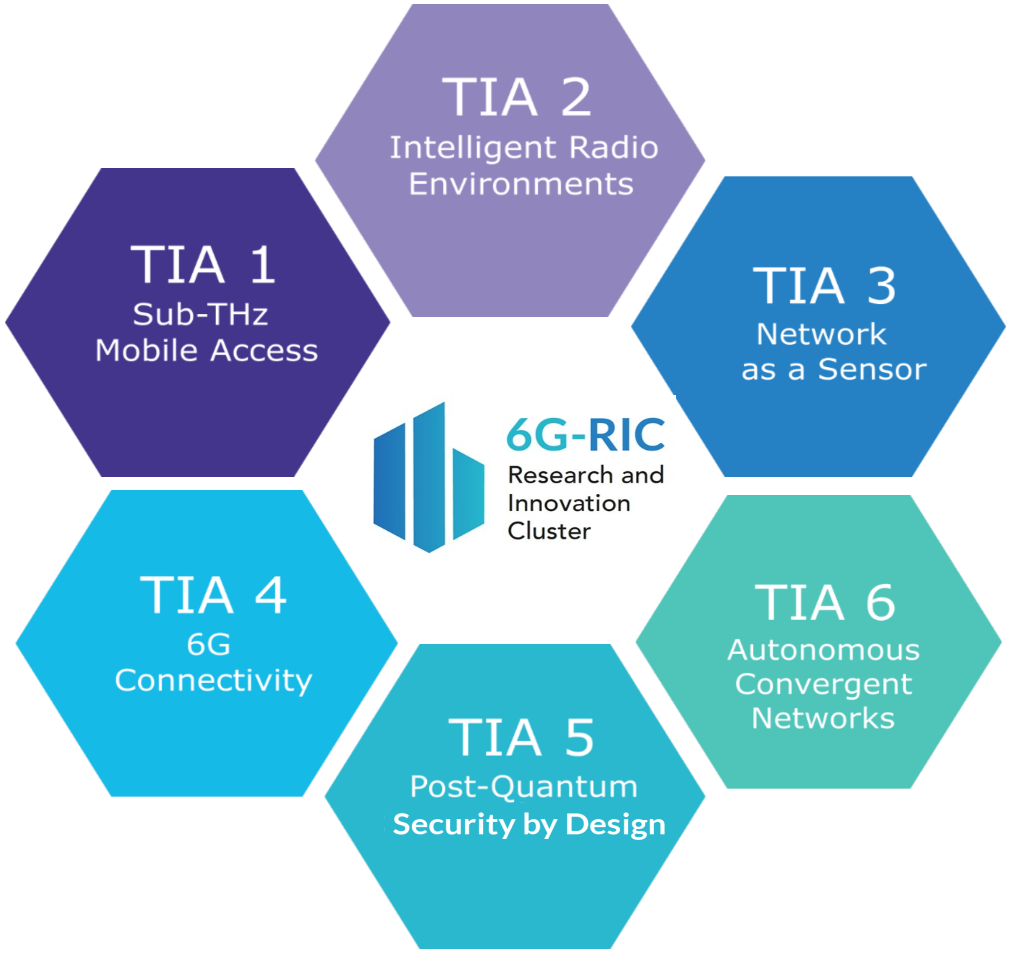
6G-RIC Research and Innovation Cluster

6G-RIC
Research and Innovation Cluster

- Duration: 1.8.2021-31.7.2025
- Funding: 70 Mio €

Technical Innovation Areas (TIA)



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Scoring the 100 Gbps goal

A Potential Energy Crunch

$$R = M \cdot B \cdot \log_2\left(1 + \frac{P \cdot G \cdot \mathrm{PL}}{B \cdot N_0}\right) \quad [\mathrm{bit}/s]$$

- Power (P)
- "Antenna" gain (G)
- Path loss (PL)
- Multiplexing gain (M)
- Bandwidth (B)

- How to increase throughput?
  1. Increase power, or reduce range
  2. Increase multiplexing gain (sub-6GHz focus)
  3. Increase bandwidth (sub-THz focus: 100-300GHz)
     - Higher noise and path loss
     - Requires more power, and high antenna gain

→ ***Problem #1:*** How to ensure high antenna gain with mobility?

- Energy efficiency
  - **Scaling of traditional designs leads to… disaster!**

$$\mathrm{EE} = \frac{R}{P + P_{\mathrm{hardware}}} \quad [\mathrm{bit}/J]$$

→ ***Problem #2:*** How to avoid excessive energy consumption?

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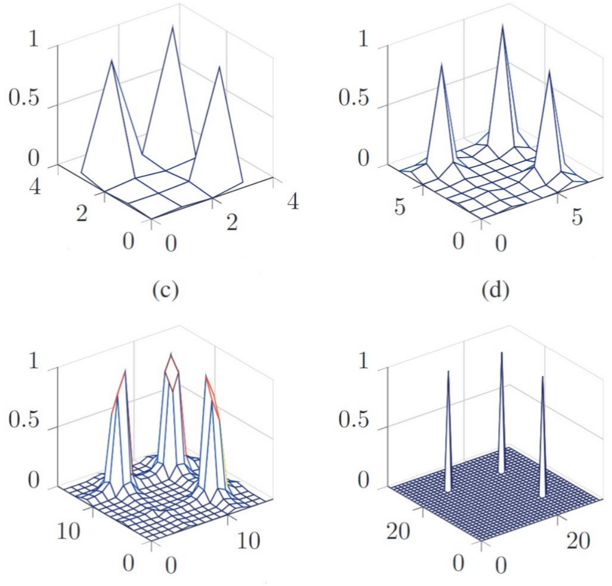
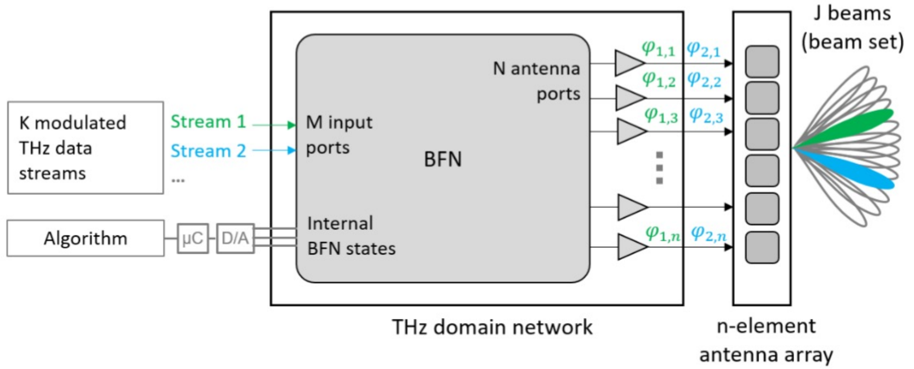
How to minimize energy consumption?

The 6G-RIC way

- Improve energy efficiency of each individual component is **<u>necessary</u>**, but **<u>not sufficient!</u>**
- We need **<u>sinergetic gains</u>** enabled by cross-domain analysis
- We identified:
  - Heterointegration of different hardware technologies
  - Communication theoretic analysis of relevant regimes, and mutual impact on hardware design (A/D conversion, PA, etc.)
  - Evaluation of channel unique features, and resulting opportunities for simplifying signal processing architectures
  - Digital-analog trade off





Thanks to Giuseppe Caire (top figure) and Thomas Merkle (Bottom figure)

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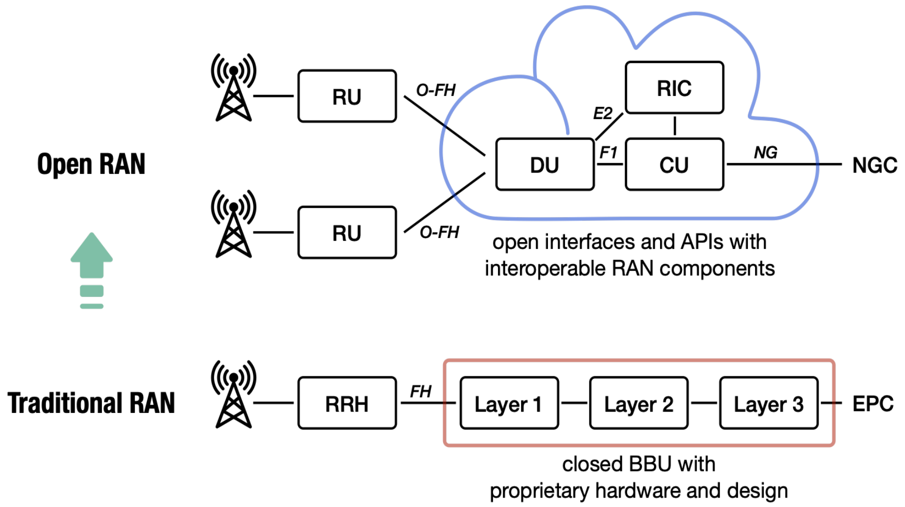
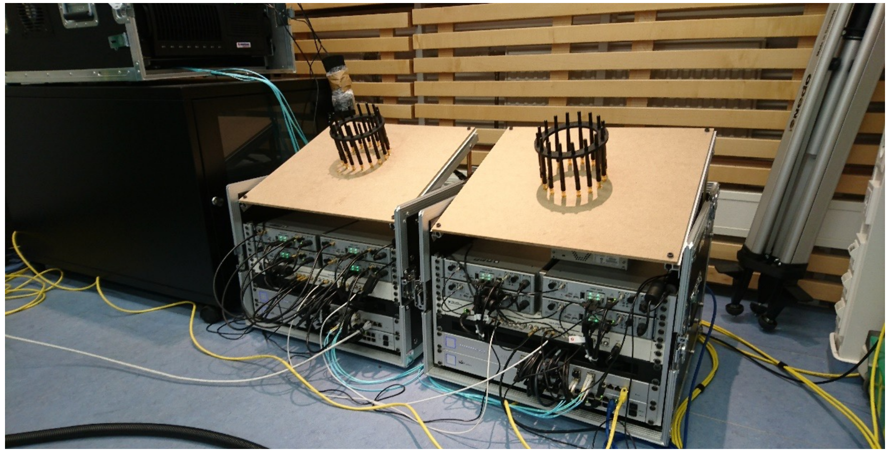
Virtualization and Cloudification

Computation challenge

- Central Unit (CU) can be easily virtualized
  - 5-10% of the processing requirements in the BBU
- Distributed Unit (DU)
  - provides the real-time functions of the lower layers
  - 90-95% of the processing requirements in the BBU
- Virtualizing the DU is challenging
  - already addressing this issue
  - https://youtu.be/dk-QWtYgZgY





Visit us at the IEEE 5G++ Summit in Dresden

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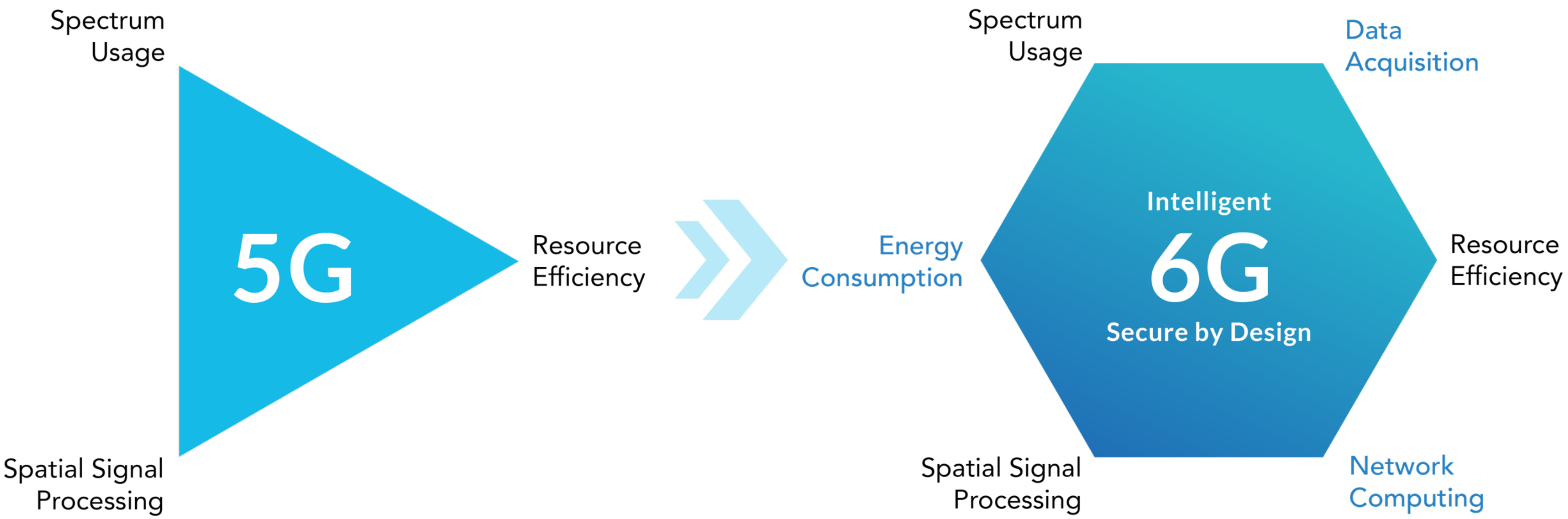
From 5G to 6G: Extended design dimensions



A 6G-RIC whitepaper coming soon

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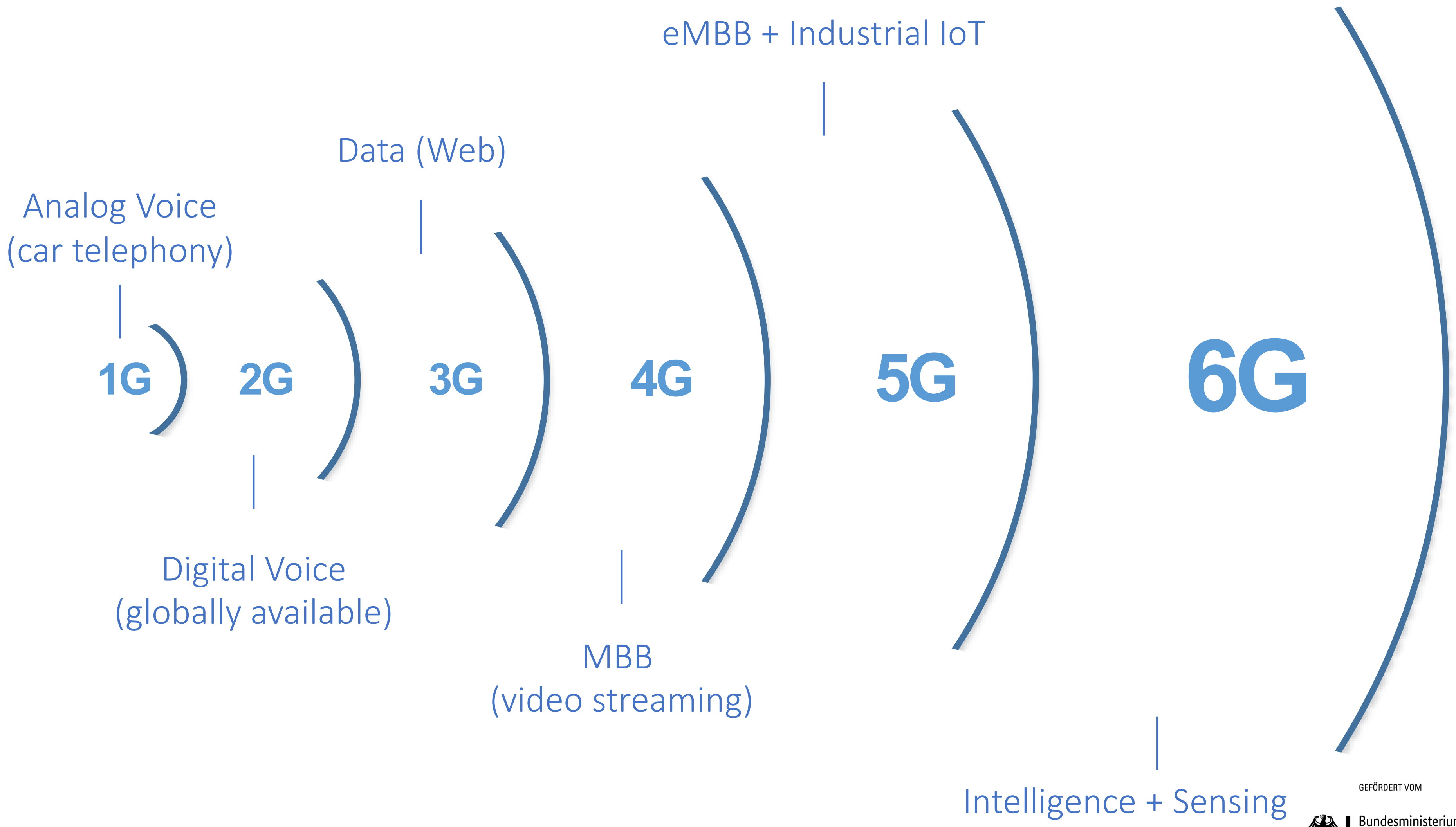
Evolution Towards 6G



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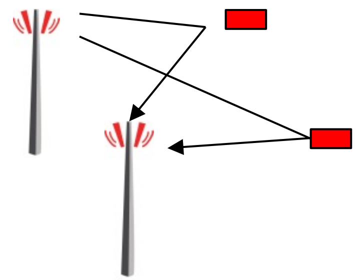
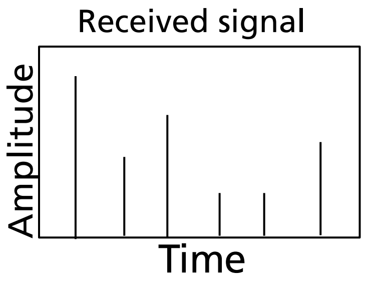
Use of ML Tools for Sensing

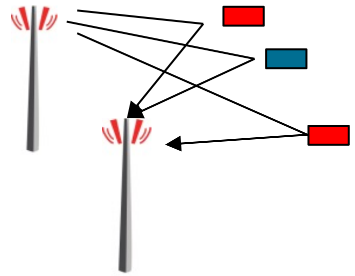
A Simple Illustrative Example

- The multipath profile might change significantly with changes in the environment
  - Learning techniques or statistical tools can be used for accurate source localization
  - Easy to detect changes in the environment (e.g., detect open windows, new scatters, etc.)

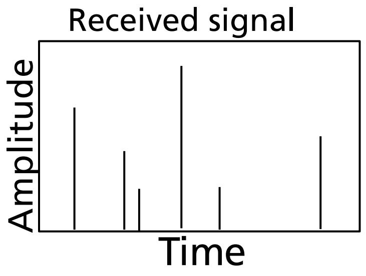


The static environment is observed by measuring the original (and the time-reversed) signal





The presence of a new scatter changes the statistics of the direct (and time-reversed) signals



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Wireless (MIMO) Channel
Radio Fingerprinting for Sensing

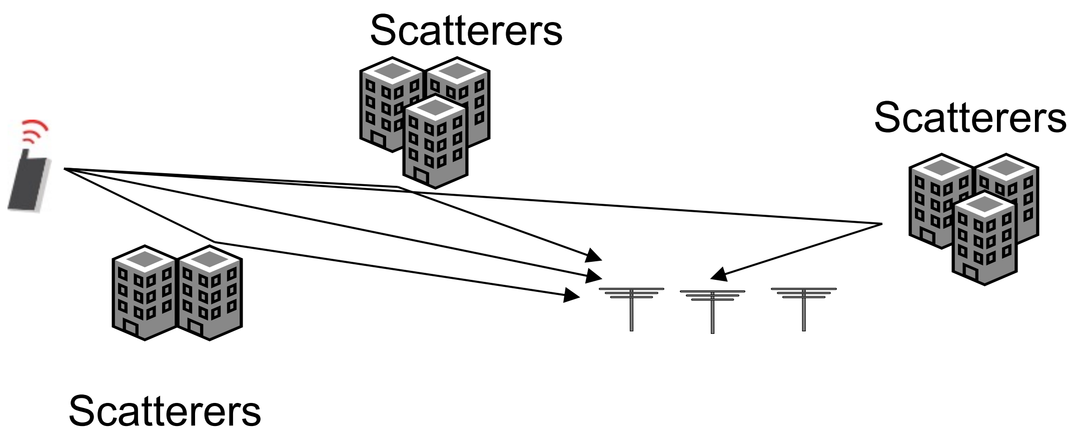
- Rich multipath environment is necessary (e.g. high frequencies)
  - Large bandwidth => High time resolution
  - Massive MIMO => High angle resolution

- Challenges:
  - Potential conflicting requirements of comm. and sensing
  - The wireless channel and its statistics are constantly changing

- Use ``invariant´´ features extracted from channels and context information as input to ML tools
  - increase the availability of training data, provide more time for training, etc.

Example: Positioning in Massive MIMO Systems

- Channel covariance matrix (CCM) is strongly related to the position of the users
- Advantages of the CCM
  - Approximately constant over milliseconds to seconds
  - In OFDM systems, almost invariant to the subcarrier index

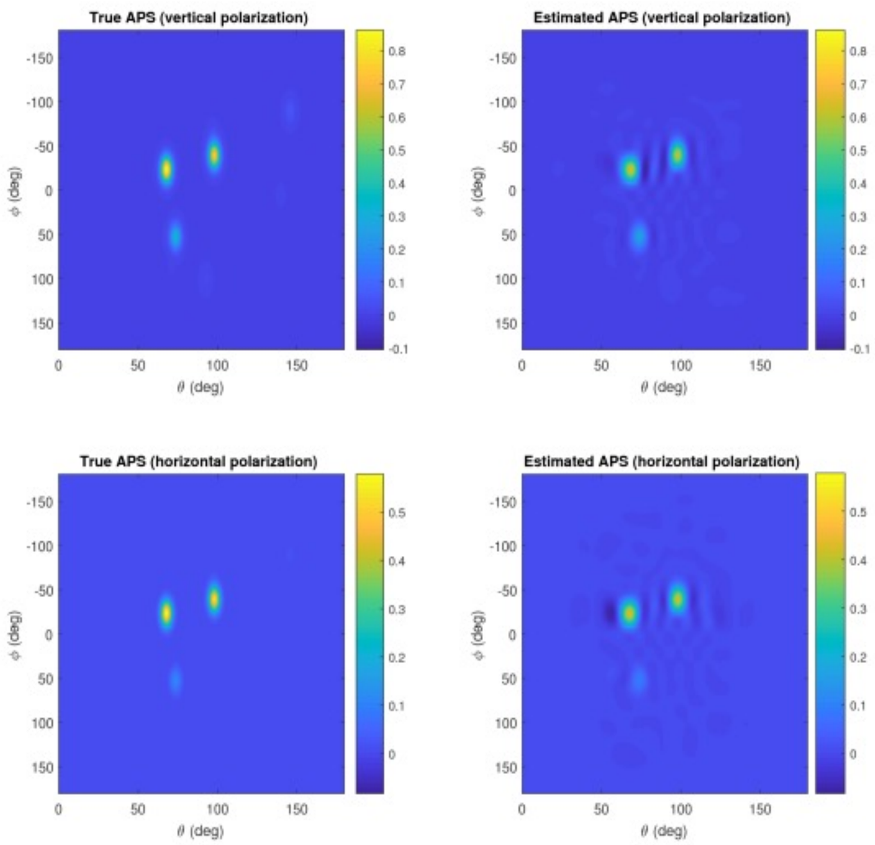


- However, the CCM is sensitive to changes in the frequency, transmit precoders, antenna array, etc.
  - Use the **angular power spectrum** instead of the channel covariance matrix

A. Decurninge, L. G. Ordonez, P. Ferrand, H. Gaoning, L. Bojie, Z. Wei, and M. Guillaud, "CSI-based Outdoor Localization for Massive MIMO: Experiments with a Learning Approach," in Proc. International Symposium on Wireless Communication Systems, 2018

The Angular Power Spectrum (APS)

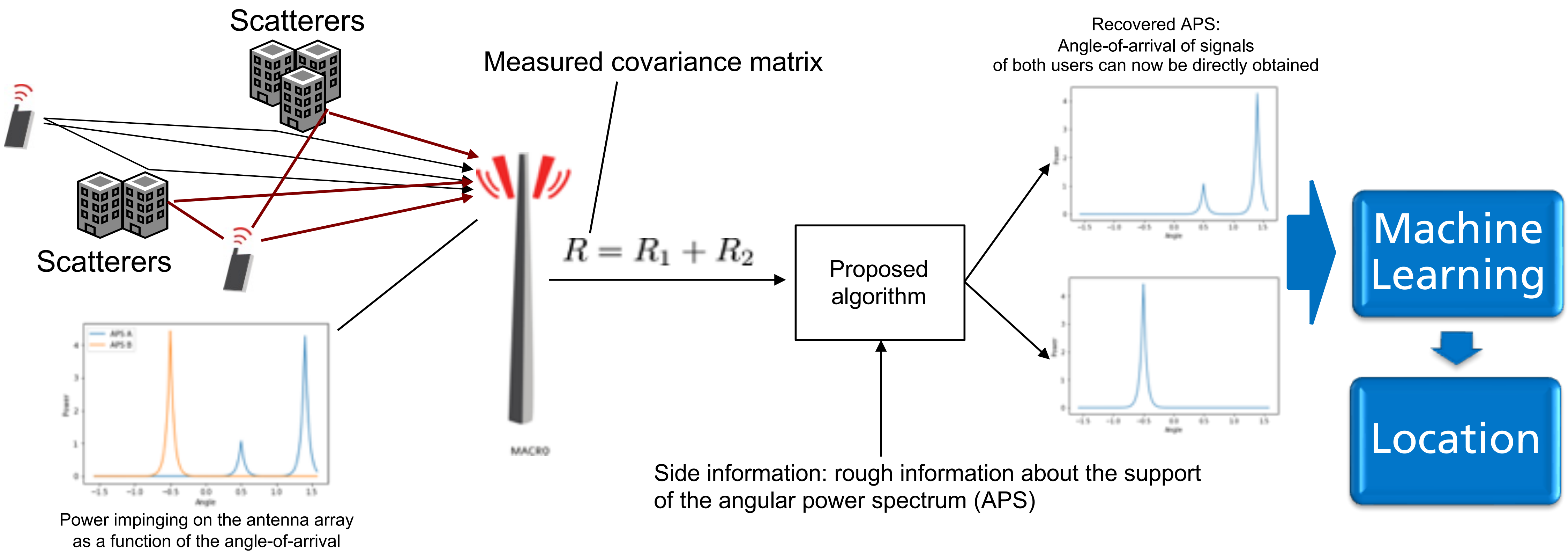
- The APS is the average power arriving at the array in a unit of angle
- Advantages in ML tools:
  - Constant over milliseconds to seconds
  - + Largely invariant with respect to changes in carrier frequency



- R. L. G. Cavalcante and S. Stańczak, "Hybrid data and model driven algorithms for angular power spectrum estimation," in Proc. IEEE Global Telecommunications Conference (GLOBECOM), Dec. 2020
- R. L. G. Cavalcante and S. Stańczak, "Channel covariance estimation in multiuser massive MIMO systems with an approach based on infinite dimensional Hilbert spaces," in Proc. IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), May 2020
- R. L. G. Cavalcante, L. Miretti, and S. Stańczak, "Error bounds for FDD massive MIMO channel covariance conversion with set-theoretic methods," in Proc. IEEE Globecom, Dec. 2018 - L. Miretti, R. L. G. Cavalcante, and S. Stańczak, "Downlink channel spatial covariance estimation in realistic FDD massive MIMO systems," in Proc. IEEE GlobalSIP, Nov. 2018
- L. Miretti, R. L. G. Cavalcante, and S. Stańczak, "FDD massive MIMO channel spatial covariance conversion using projection methods," in Proc. IEEE ICASSP, Apr. 2018

APS-based Localization

- Angular power spectrum (APS) may be unique to each position
  - ML can be used for localization based on APS (e.g. mmWave MIMO)



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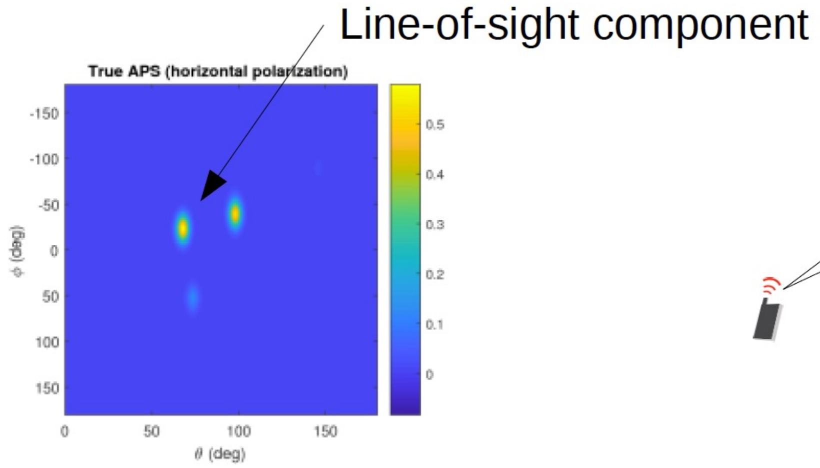
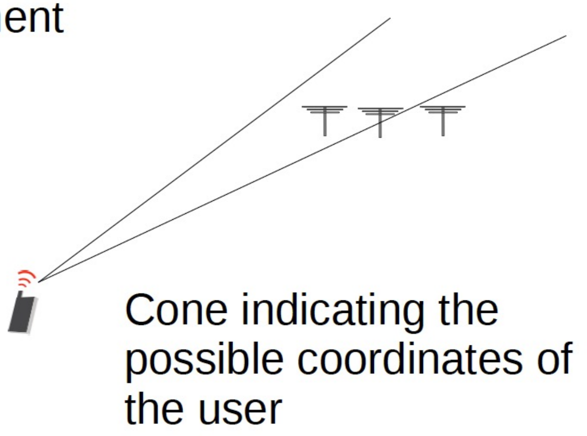
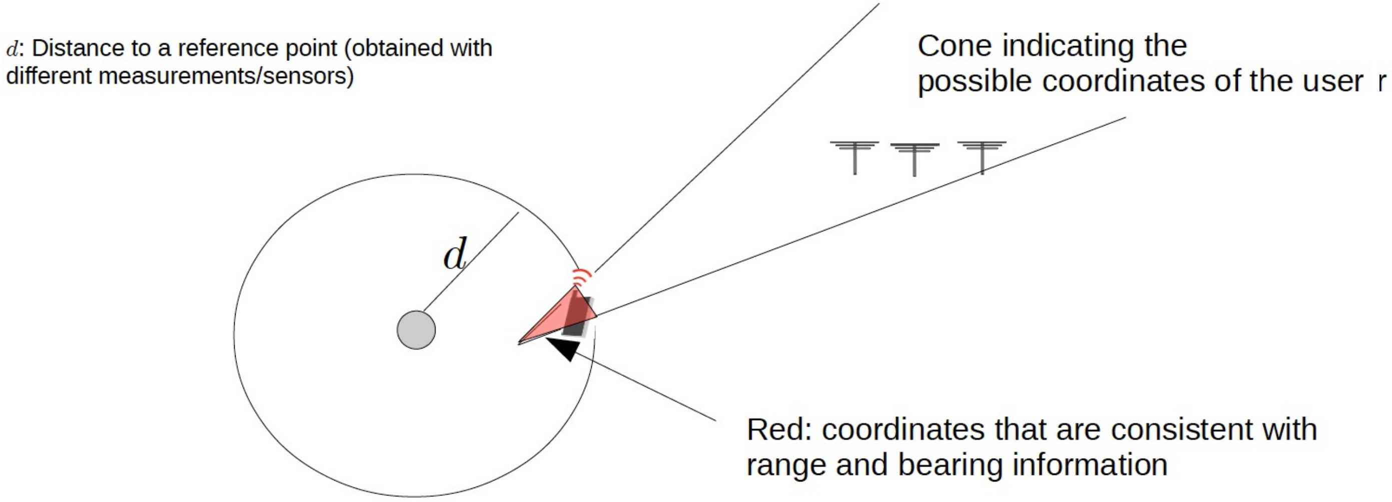
Extensions and Improvements

- Combine APS information from multiple base stations
  - new interfaces needed!
- Fuse information provided by the APS with other data and measurements
- E.g. use set-theoretic methods and fixed-point algorithms







- J. Fink, D. Schaufele, M. Kasparick, R. L. G. Cavalcante, and S. Stańczak, "Cooperative localization by set-theoretic estimation," in Proc. Workshop on Smart Antennas (WSA), April 2019

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But what will be the impact of emerging 6G technologies on the network management and operation?

- 6G-RIC technologies
  - Sub-THz Communication
  - IRS: Intelligent reflecting surfaces
  - ICAS: Integrated Communication and Sensing
  - Semantic-enhanced and goal-oriented communication
  - PHY-/Post-Quantum Security

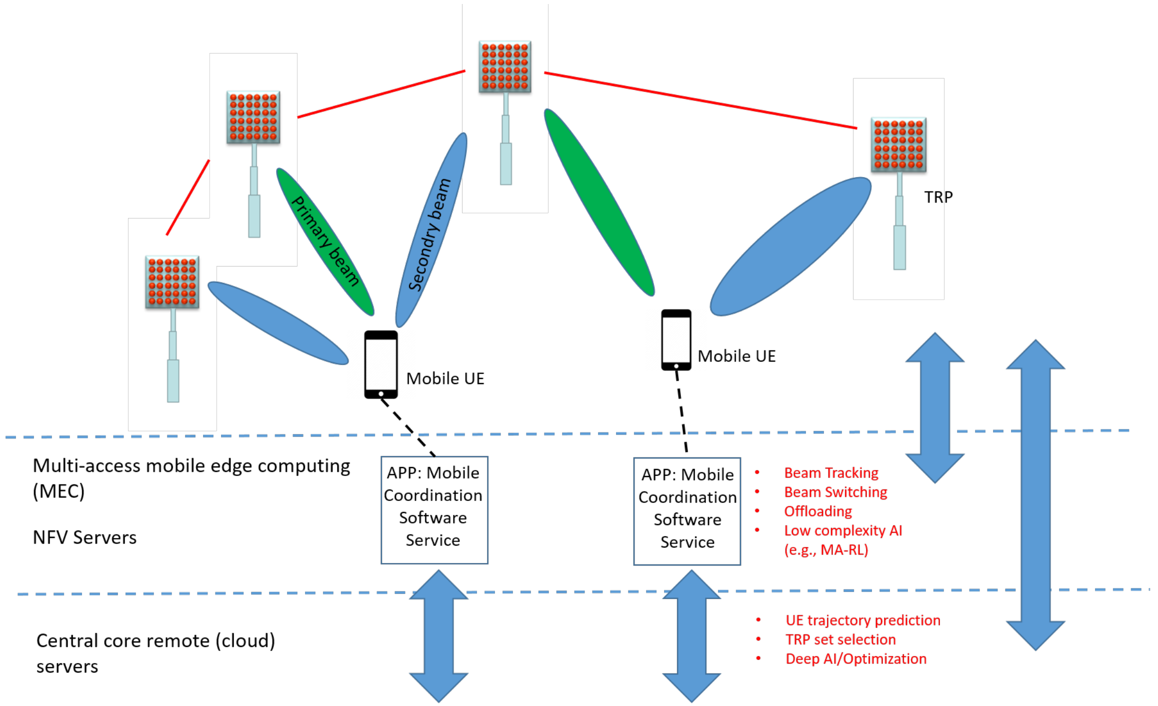
Autonomous (sub-THz) Networking

AI-based Optimization and Resource Allocation

- Challenge: Large disaggregated networks
  - Disaggregated network
    → Disaggregated data
  - Avoid large data/control transport
  - Predict local changes in the network

- Approach: Distributed AI Placement
  - Edge AI : Fast algorithms with local view
  - Core AI : Deep AI with global view

How to ensure sub-THz connectivity under mobility?



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Reactive vs. Proactive Mobile Networks

- Today's mobile networks are mostly **reactive**
  1. Detect a problem (e.g. outage, poor performance, anomaly)
  2. Respond to the problem by taking appropriate action

- Future networks must be **proactive**
  1. Anticipate a problem (robust prediction required)
  2. Act proactively to avoid the problem

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ML/AI-Enabled Proactive Networking

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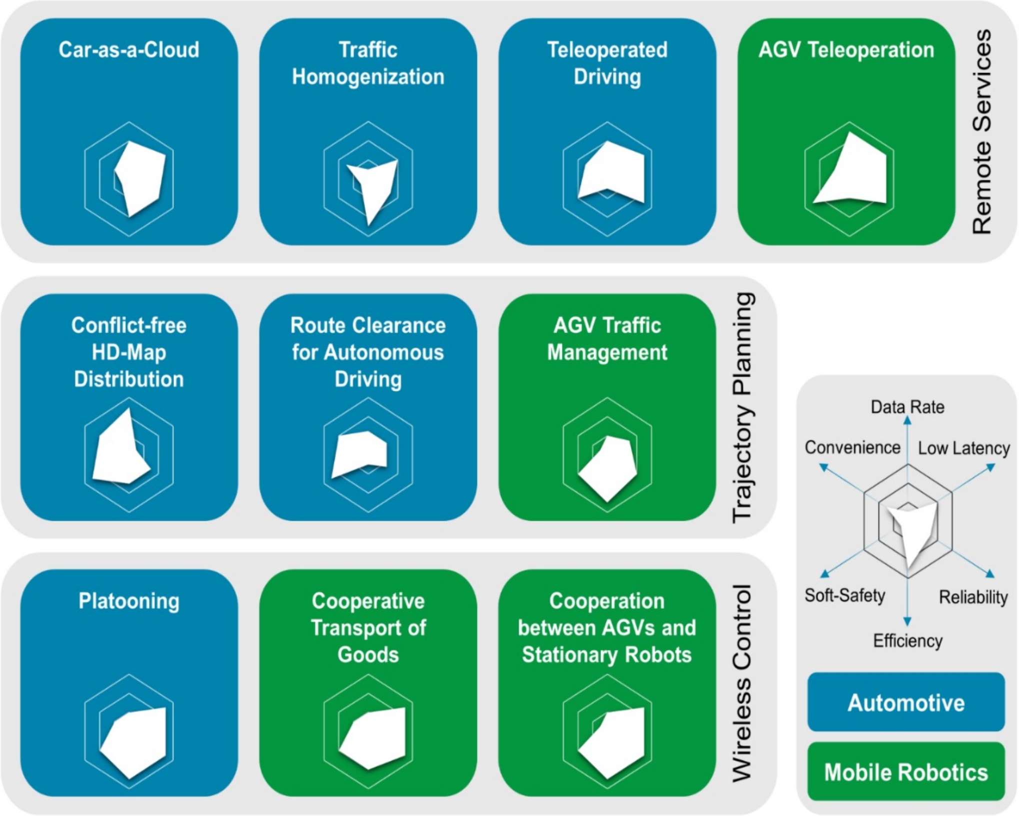
- **Robust E2E prediction of QoS** parameters using a variety of data sources
- Mechanisms for **pro-active network optimization** and dynamic adaptation
- Increased use of **ML/AI**
  - Insufficient network models
  - Virtualization & openness
  - In-memory computation



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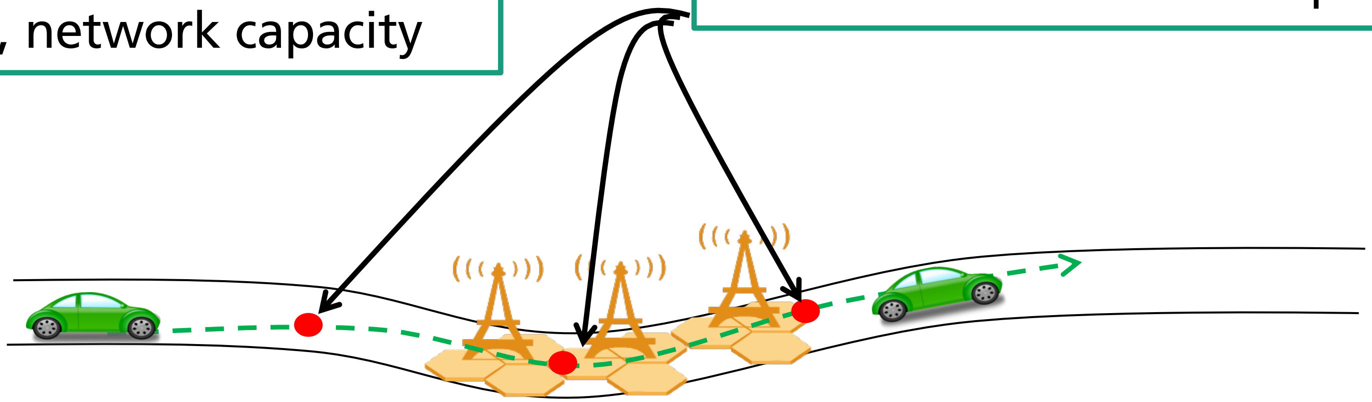
QoS Prediction and Proactive Resource Allocation in V2X

By predicting radio conditions, network provides to cars:

1. Future resource allocation decisions
2. Predicted link quality, network capacity

e.g. coverage holes or **strong inter-cell interference** need to be predicted



Robust real-time tracking of link quality required
(based on radio and context information)

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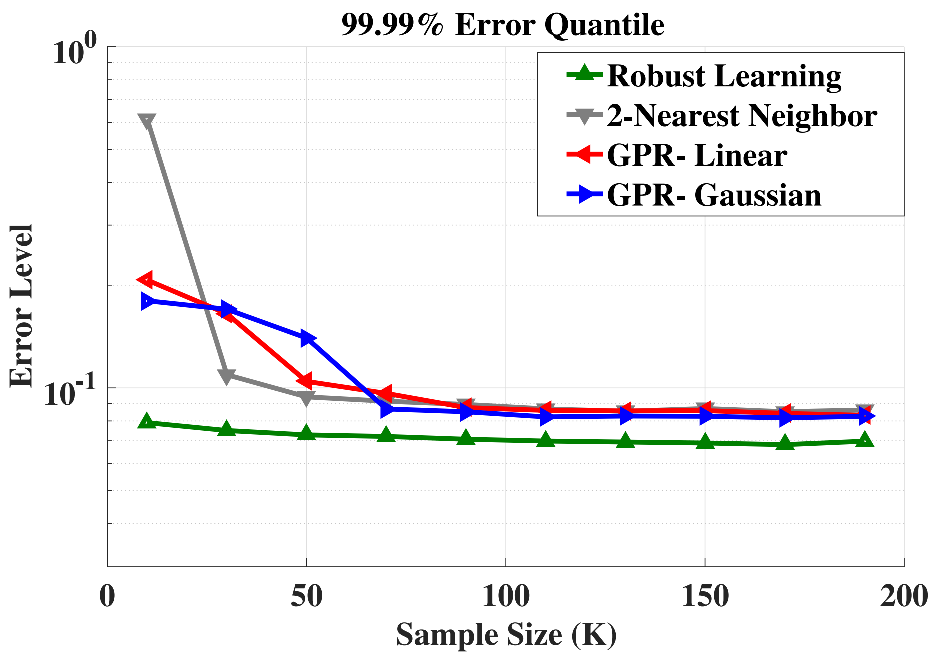
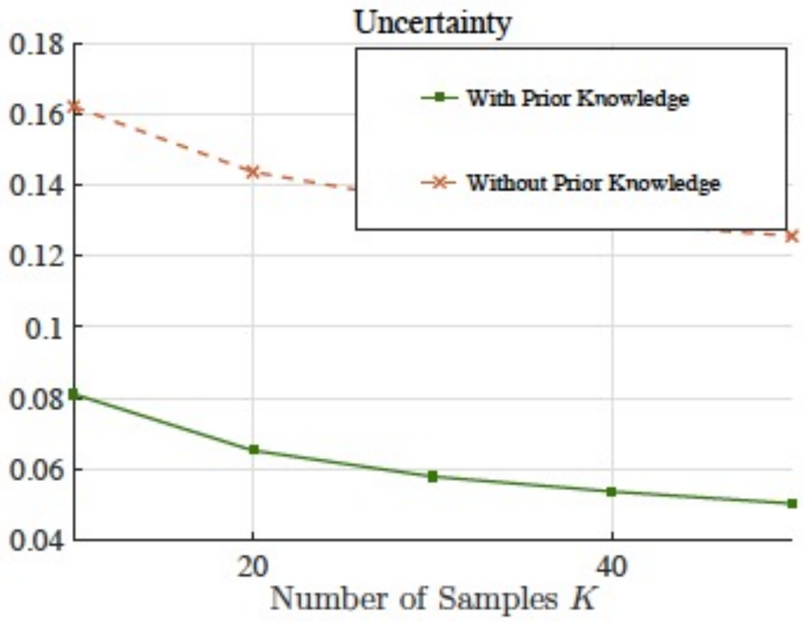
Impact of Domain Knowledge

- New hybrid-driven methods based on robust approx. in uncertain environments
- Domain knowledge: monotonicity and Lipschitz continuity





D. A. Awan, R.L.G. Cavalcante and S. Stanczak. “Robust Cell-Load Learning with a Small Sample Set“, IEEE Trans. On Signal Processing, vol. 68, pp. 270-283, 2020

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All major measurement campaigns finished

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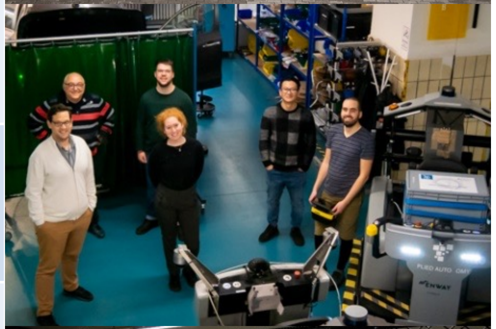
Data set	Scenario	Status
Motorway A9 5G-ConnectedMobility	Outdoor (highway, suburban, rural), cellular	Measurements finished, First publications available
Berlin V2I	Outdoor (city), cellular	Measurements finished, Processing ongoing
Berlin V2V	Outdoor (city), cellular	Measurements finished, Processing ongoing
Enway Campus data set	Indoor (AGV), cellular	Measurements finished, Processing started
Bosch Campus data set	Indoor (AGV), V2V, cellular	Measurements finished, Processing to be started



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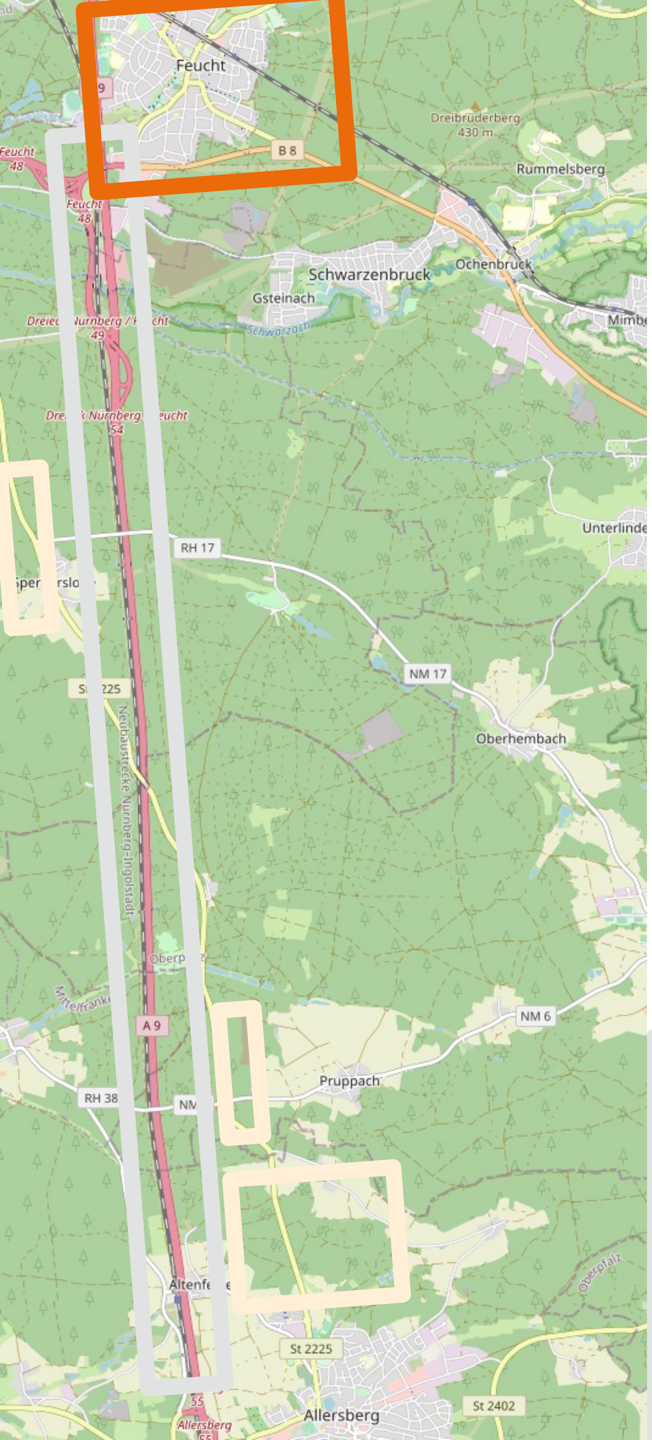


Measurement Campaign on Highway

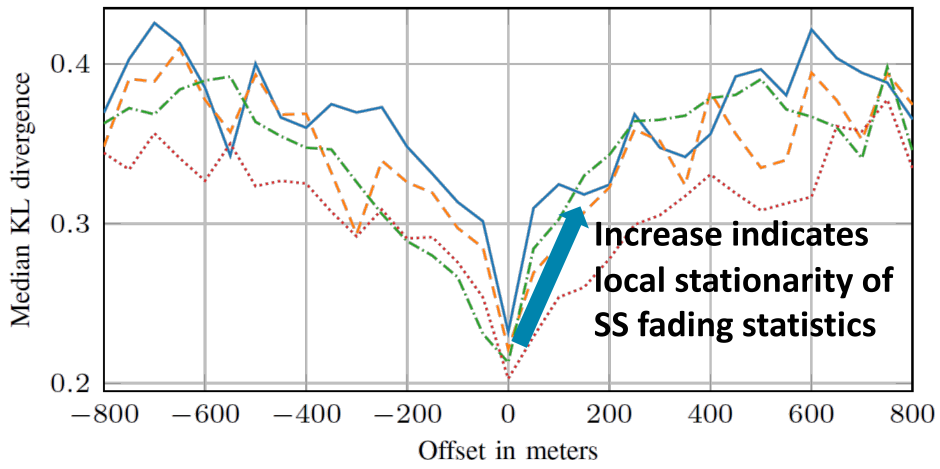
- 1 week of measurements
- 9 people measuring (+ back-office support)
- 12 UEs in 4 cars
- 3300+km driven
- A large dataset that is richer than a typical datasets used in literature.

- We split the following coverage area into the following propagation zones.
  - A9 highway (30km segment), speed limit to some segments only.
  - Rural zones, up to 50-70 km/h (only few examples in the map)
  - Suburban city, maximum of 30km/h inside the city.

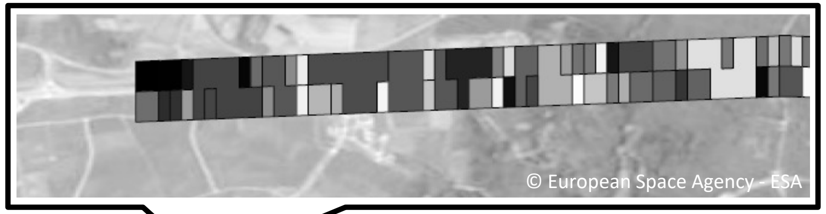
CDI Maps – Predicting Channel Statistics

- Fading statistics are stationary in bounded regions
  - Channel distribution information (CDI) maps

- Measure RSRP with 100 Hz in two equally-equipped vehicles driving the same route time-delayed



Impact of offset between two vehicles' distribution series for four highway runs.



RSRP measurements → Small-scale (SS) fading extraction → Distribution estimation → Heuristic to find stationary regions → CDI Maps → Proactive Resource Allocation

D. F. Külzer, S. Stańczak, and M. Botsov, "CDI maps: Dynamic Estimation of the Radio Environment for Predictive Resource Allocation," in *Proc. IEEE PIMRC*, Sep. 2021, pp. 1–7.

A. Palaios, P. Geuer et al., "Network under control: Multi-vehicle E2E Measurements for AI-based QoS Prediction," in *Proc. IEEE PIMRC*, Sep. 2021, pp. 1–7.

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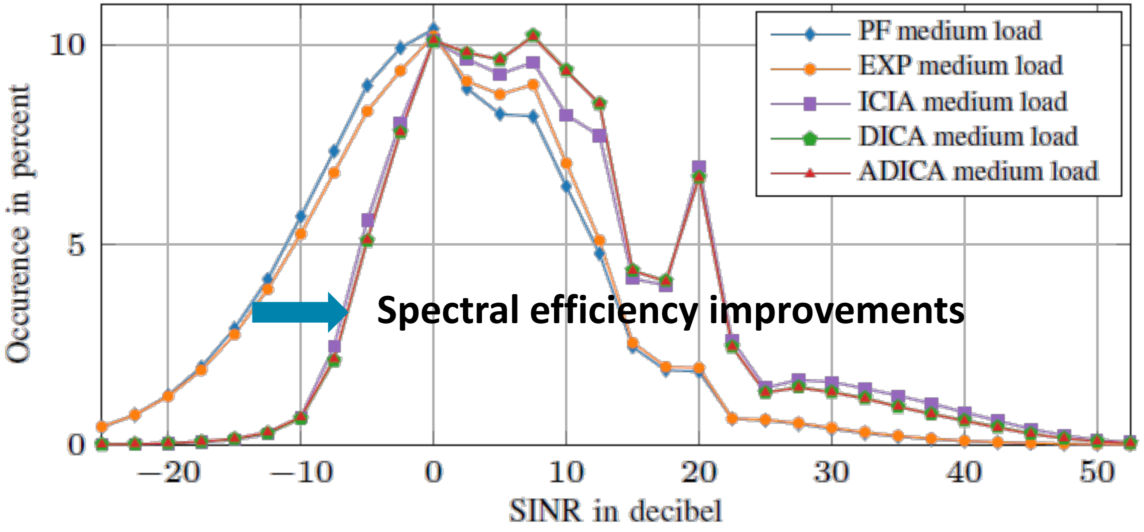
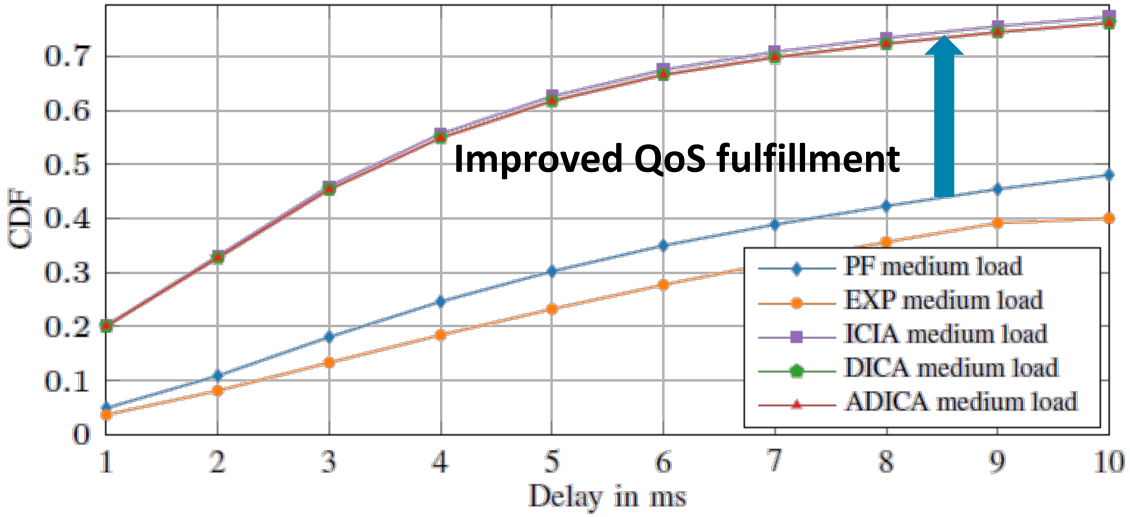
Leveraging CDI Maps for Network Optimization

- Automotive service coexistence: delay-constrained services, video-streaming and HD map distribution

Discretized PDF of the SINR per transmission.



Delay-constrained services' packet delay CDF for successfully transmitted packets.



RSRP measurements → Small-scale (SS) fading extraction → Distribution estimation → Heuristic to find stationary regions → CDI Maps → Proactive Resource Allocation

D. F. Külzer, S. Stańczak et al., "Predictive Resource Allocation for Automotive Applications Using Interference Calculus," *IEEE GLOBECOM*, 2020

D. F. Külzer, S. Stańczak, and M. Botsov, "Interference-aware Distributed Predictive Resource Allocation for Automotive Applications," *ISWCS*, 2021

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