Towards Environment-Aware RRM for 6G:
The Devil's in the Data

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20th August 2025 | KTH, Stockholm

6GEM

iNETS Institute for Networked Systems | RWTH AACHEN UNIVERSITY

MCC Mobile Communications and Computing | RWTH AACHEN UNIVERSITY

Mobile wireless network evolution

1980	1990	2000	2010	2020	2030
1G	2G	3G	4G	5G	6G

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Mobile wir

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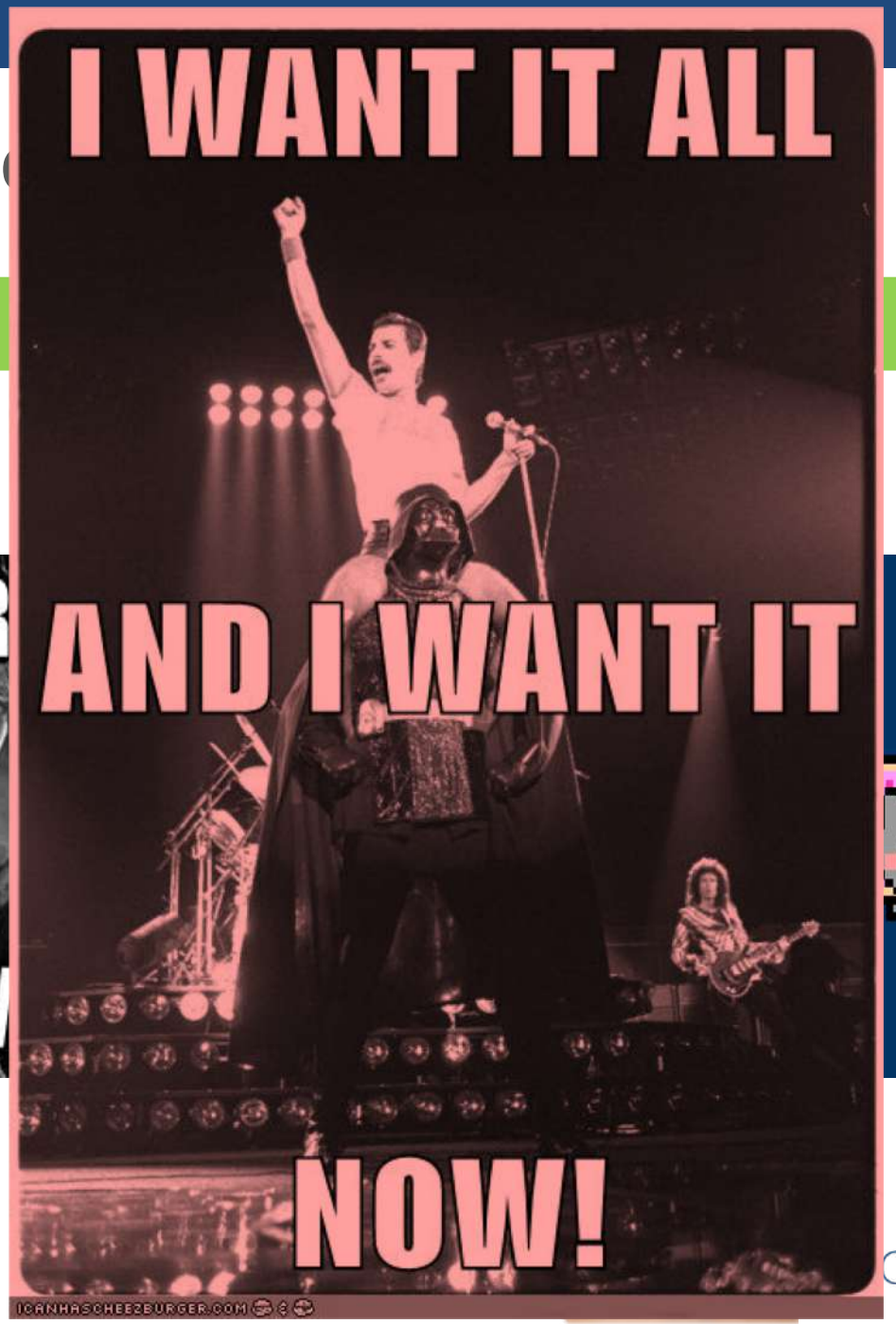
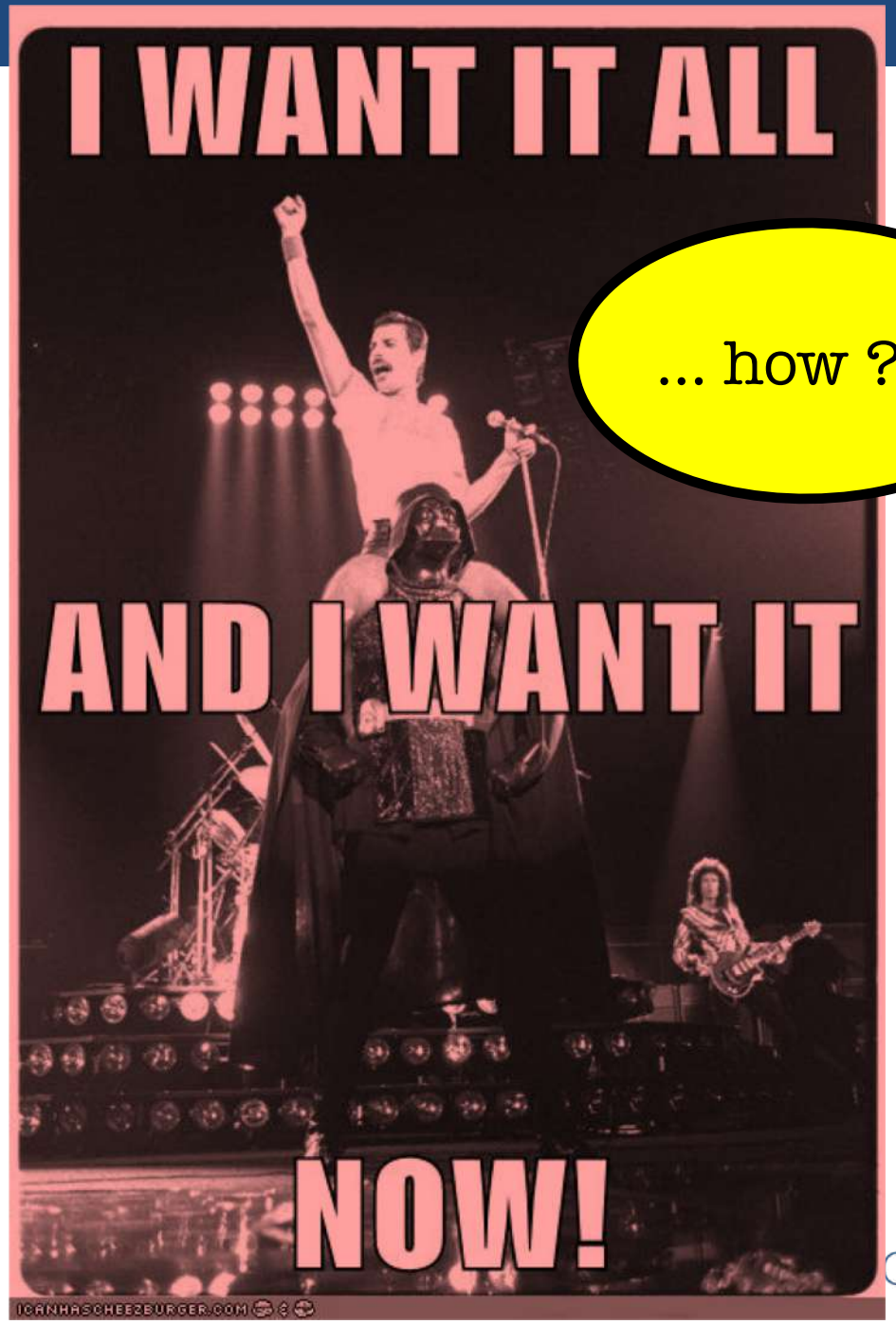
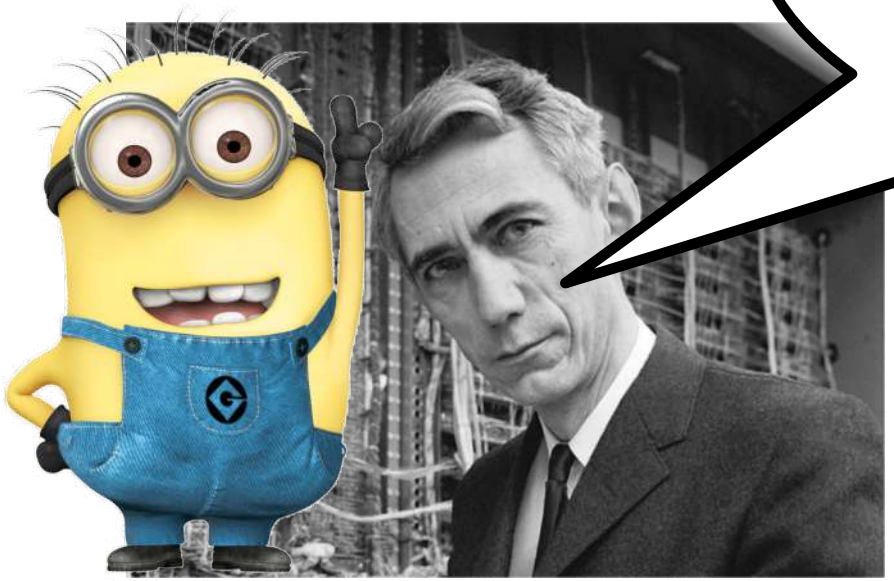



I WANT IT ALL
AND I WANT IT
NOW!
ICANHASCHEEZBURGER.COM

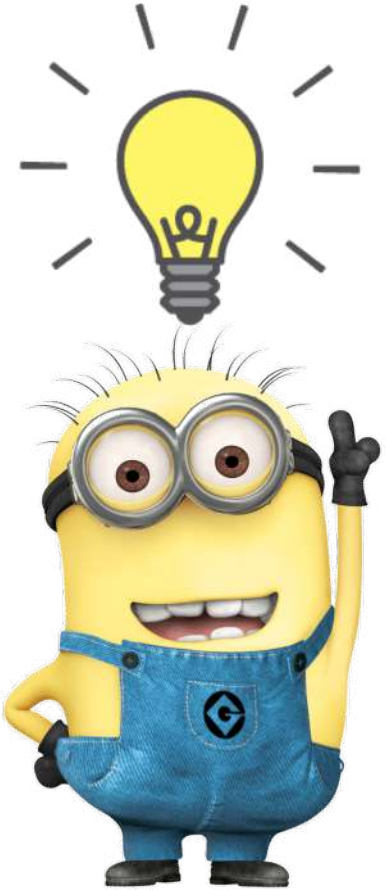
... how ??

How to satisfy wireless need for speed?

$$C = B \log_2 \left(1 + \frac{S}{I+N}\right)$$



High frequency bands are “spectrum-rich”!



(+ FR3 for 6G?)

FR1 **FR2 (mm-wave) for 5G-and-beyond**

BUT high frequencies can’t reach far!

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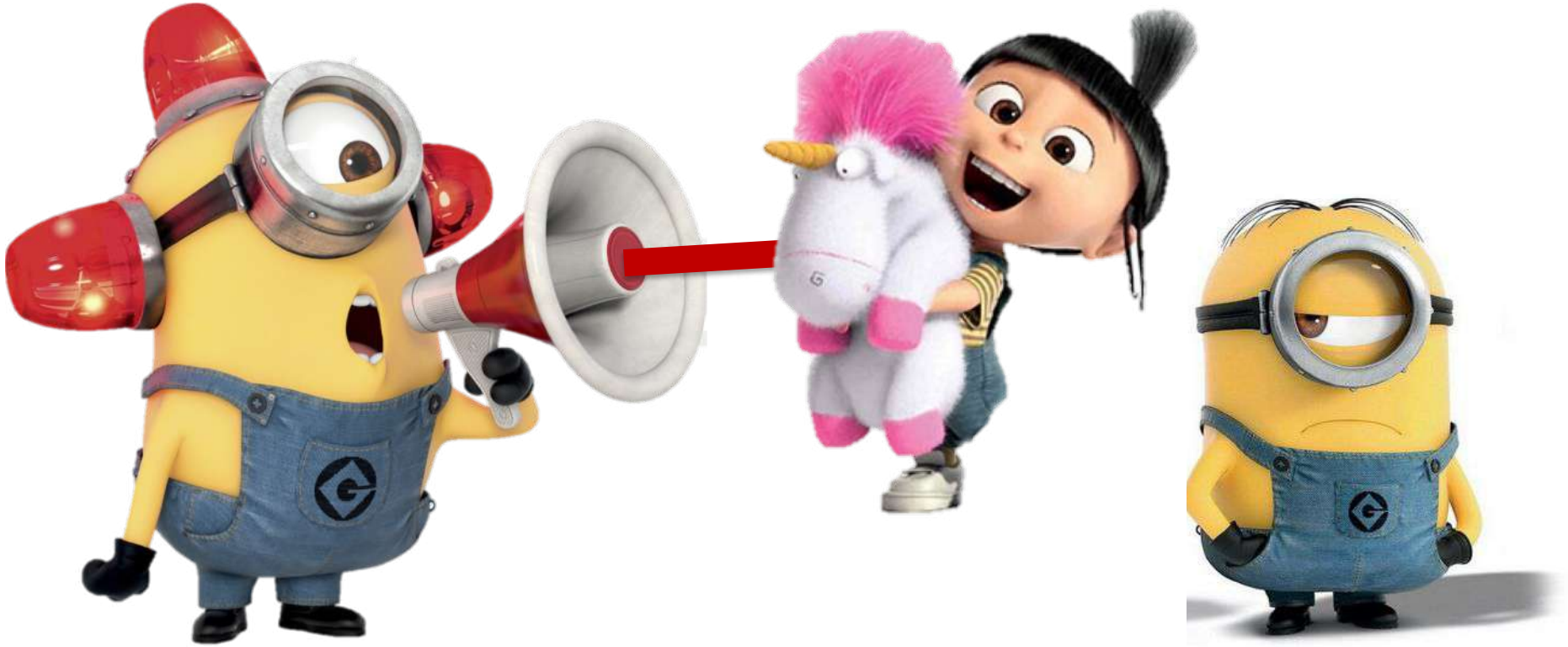
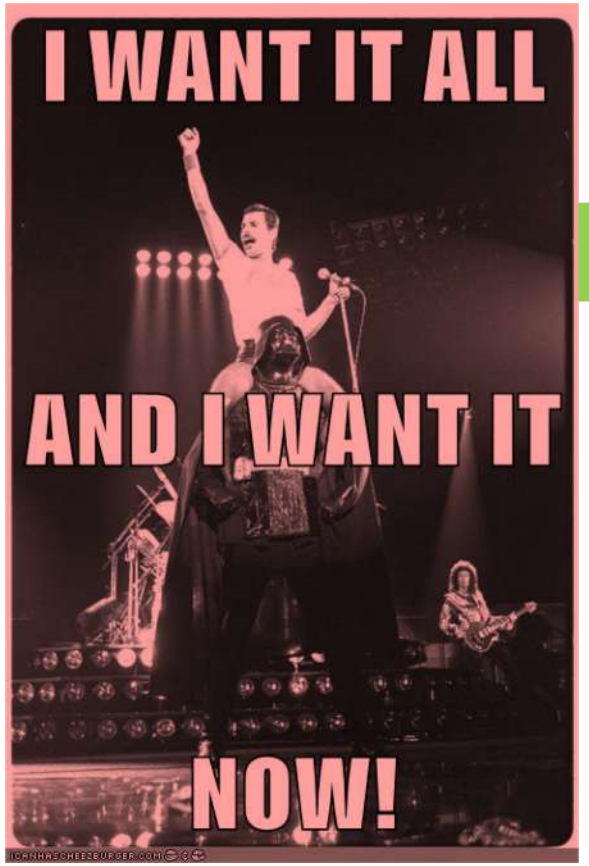
… unless we use beamforming for
directional antenna beams!

BUT high frequencies can’t reach far!

… even then, **easily blocked!**





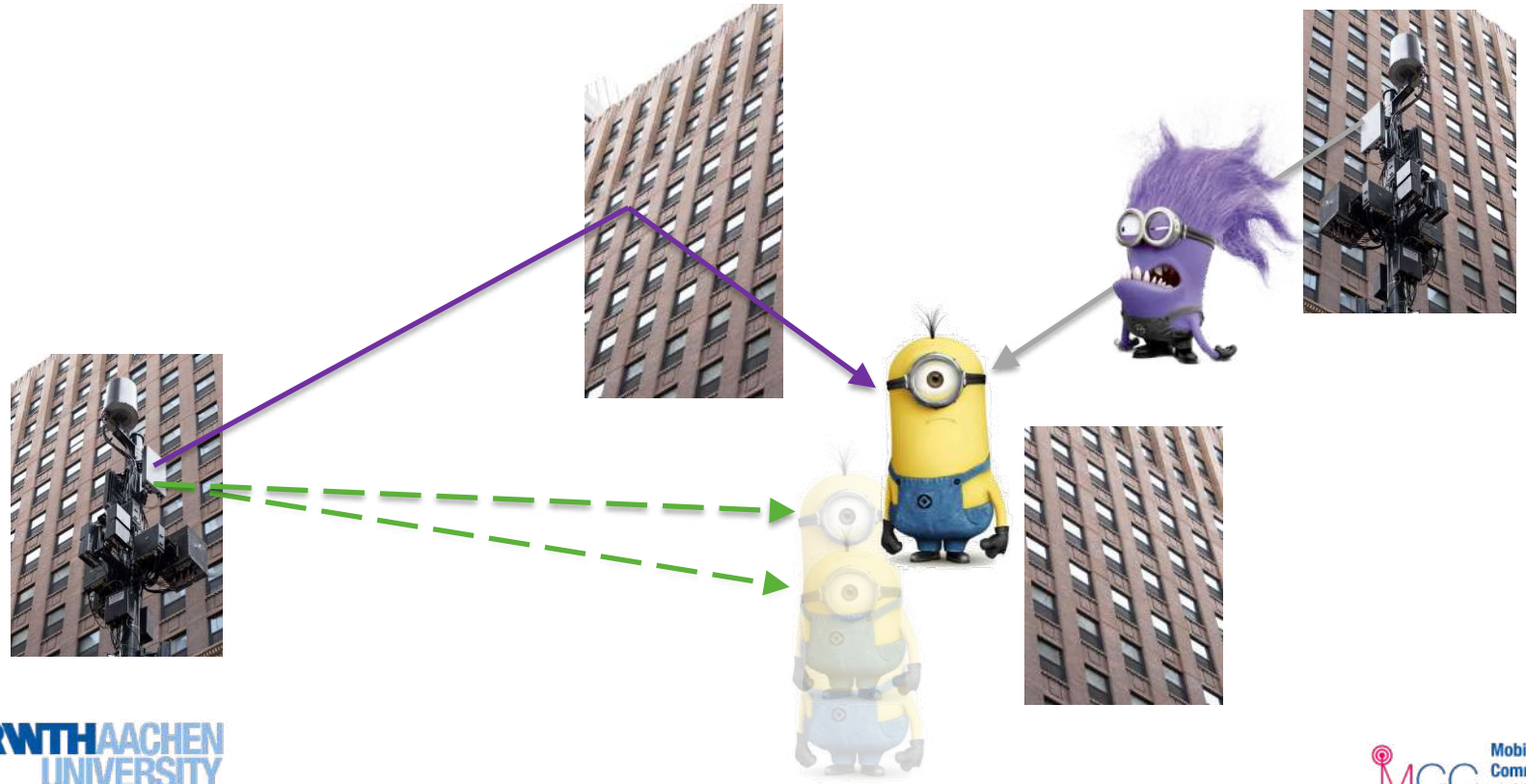
2020

5G & beyond

… so does it work for **mobile**?

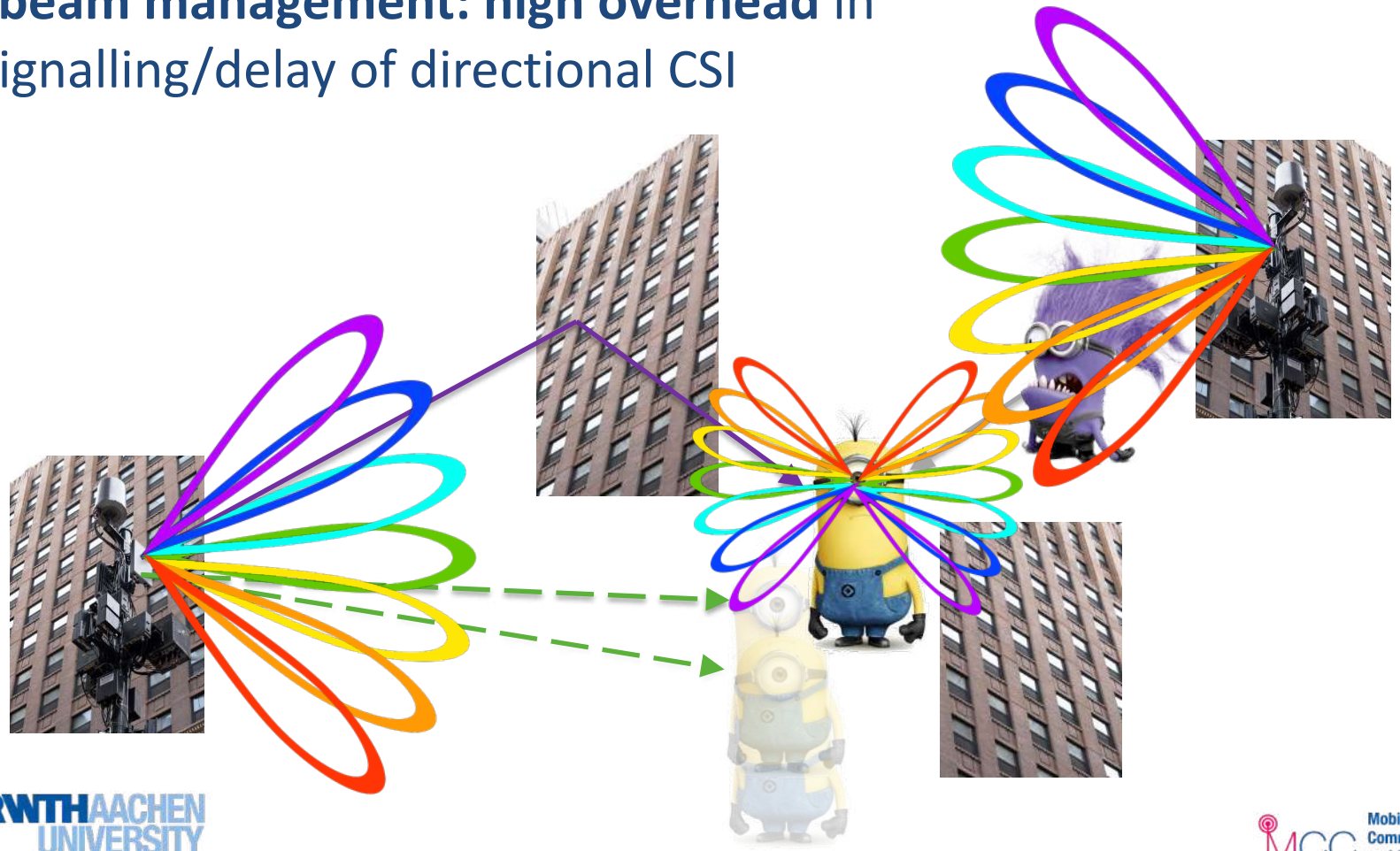
Agile beam management is key mm-wave networking problem

- **site-specific** sparse multipath channel
- blockage by static & dynamic obstacles



Agile beam management is key mm-wave networking problem

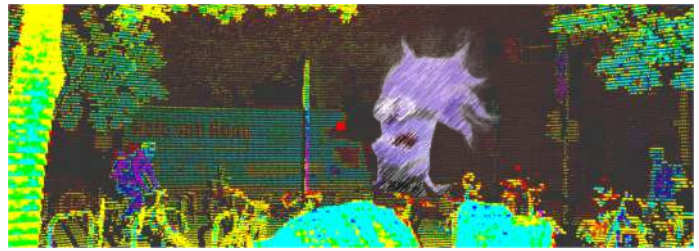
- **RF-based beam management: high overhead** in terms of signalling/delay of directional CSI

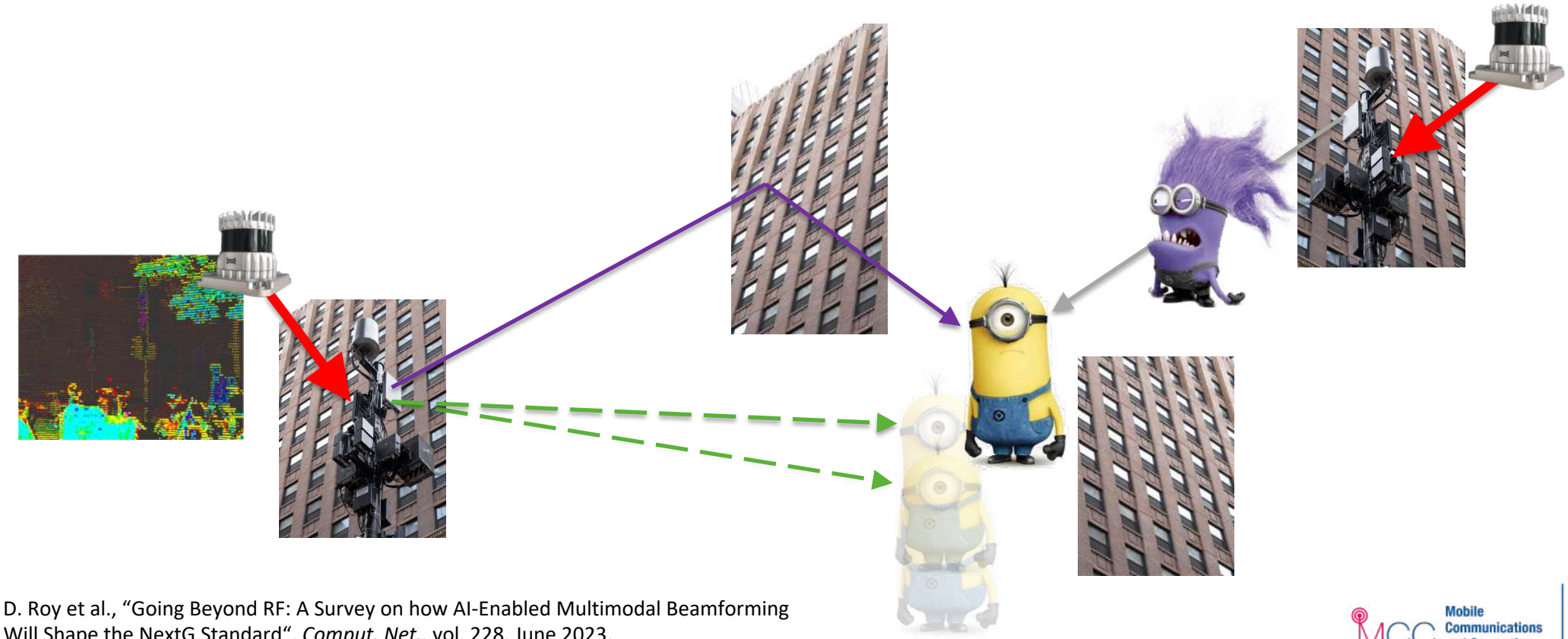


Environment-Aware RRM for 6G Beamforming

➔ leveraging **non-RF sensors** (LiDAR, camera, radar, GPS, etc.)

➔ **real-time environment awareness**, e.g. via **AI/ML**





[1] D. Roy et al., "Going Beyond RF: A Survey on how AI-Enabled Multimodal Beamforming Will Shape the NextG Standard", *Comput. Net.,* vol. 228, June 2023.

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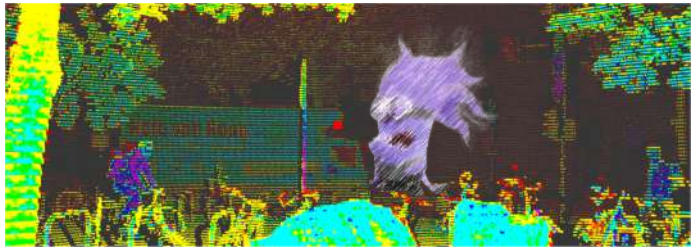

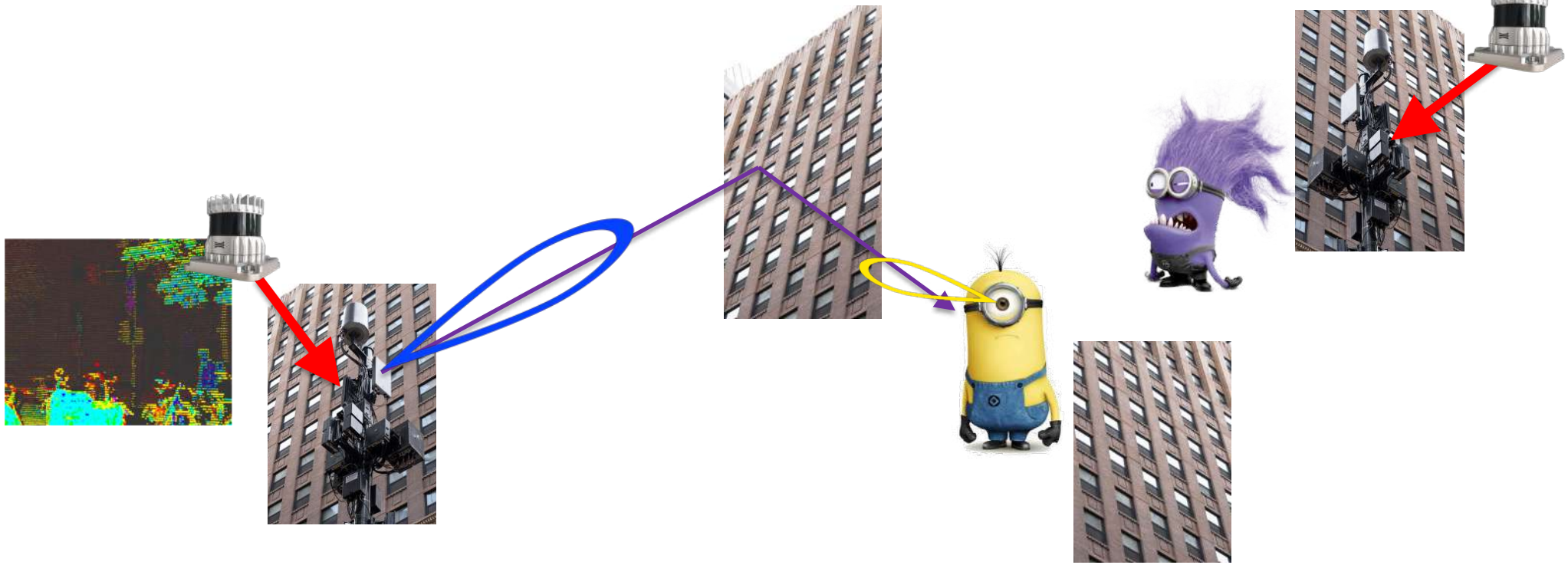

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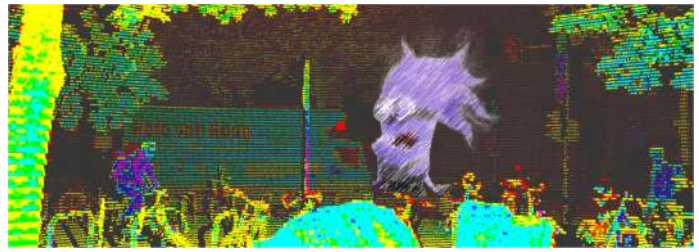
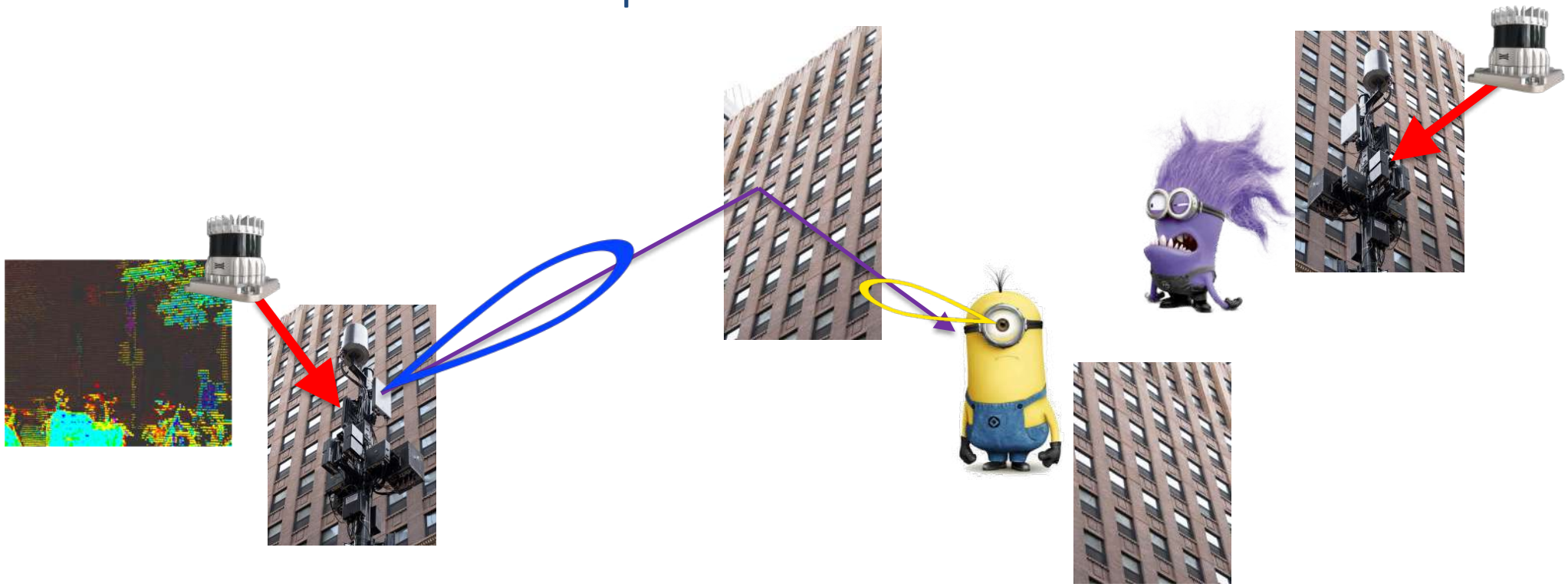
Environment-Aware RRM for 6G Beamforming

➔ inherently site-specific: **large & diverse multi-modal sensor/RF datasets needed** for AI/ML training & validation of environment-aware RRM protocols





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Environment-Aware RRM for 6G Beamforming: The Devil's in the Data

① diverse real-world sensing/RF datasets → **measure!**

② high-quality synthetic data/Digital Twins → **validate!**

③ real-time, real-world 6G RRM protocol evaluation → **experiment!**

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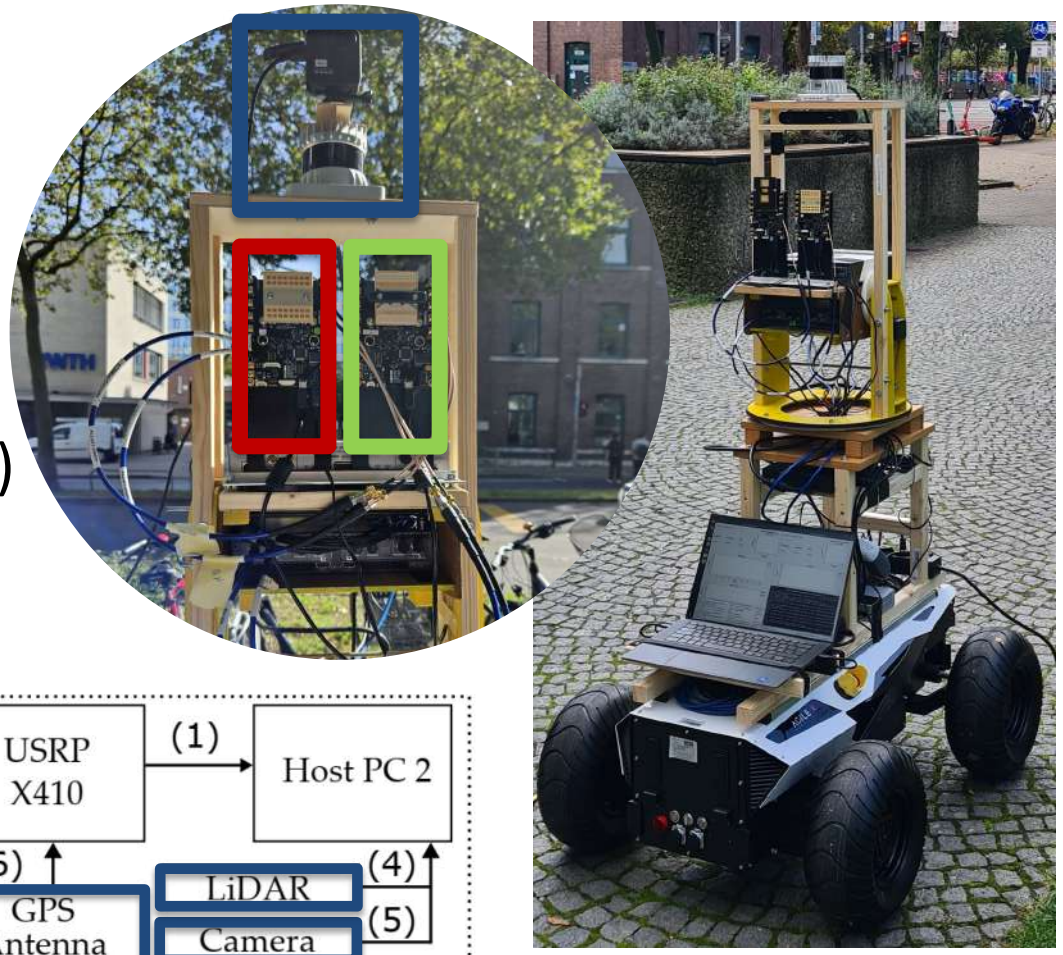
① Measurement Platform [2] for Multi-Modal Sensing/RF Datasets

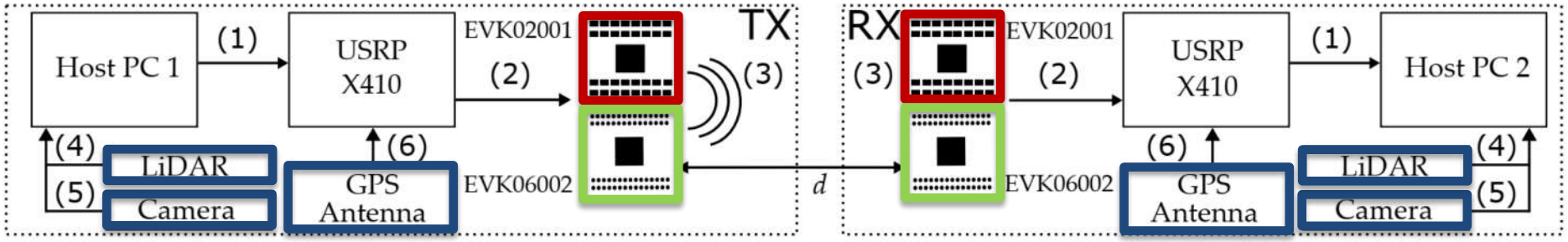
- SDR-based **multi-band mm-wave** platform integrating **multi-modal sensors**

[2] A. Schott, A. Ichkov, B. Acikgöz, N. Beckmann, L. Reiher, and **L. Simić**, "A Multi-Band mm-Wave Experimental Platform Towards Environment-Aware Beam Management in the Beyond-5G Era", in *Proc. WiNTECH in ACM MobiCom,* 2024.

① Measurement Platform [2] for Multi-Modal Sensing/RF Datasets

- **28 GHz** + **60 GHz** SIVERS phased-antenna arrays
- **fine-grained directional-directional RF measurements** (electronic sweeping of 22-beam codebooks + mechanical sector/elevation rotation)
- **time-synched sensor data** (**LiDAR, camera, GPS**)





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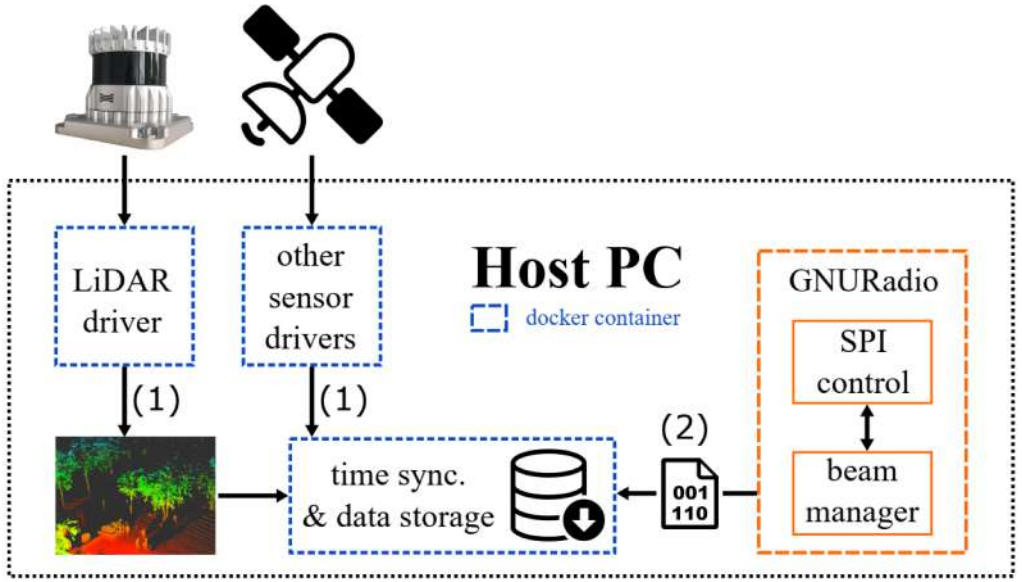
① Measurement Platform [2] for Multi-Modal Sensing/RF Datasets

- SW framework for automatic dataset creation:
  - **RF data (RSS, f-/ϕ- offset, TX/RX beam IDs)**
  - **time-synched sensor data**



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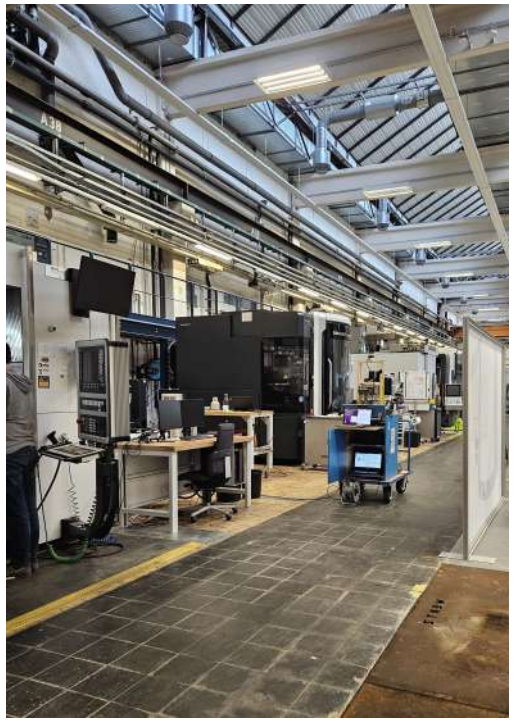
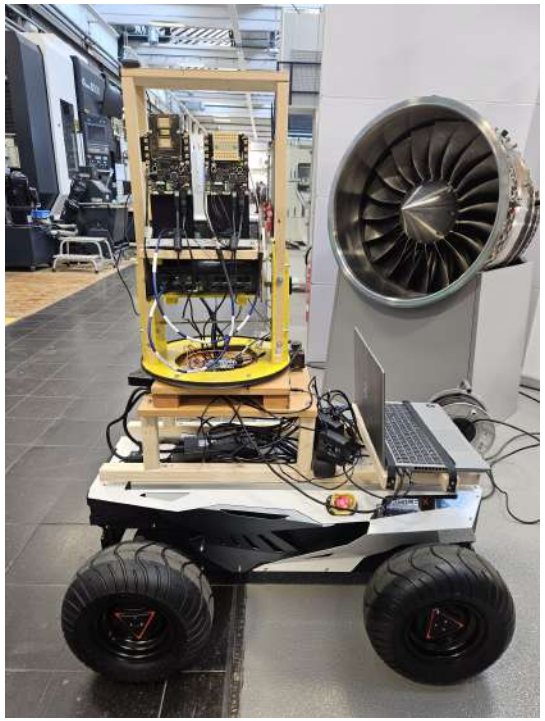
① Measurement Platform [2] for Multi-Modal Sensing/RF Datasets

- large-scale measurements in Aachen: multi-band RF + multi-modal sensor datasets
  - **urban outdoor**
  - **indoor industrial [3]**





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[3] A. Schott, A. Ichkov, N. Beckmann, N. König and **L. Simić**, "Mm-Wave Connectivity in Industrial Environments: A Measurement Study at 28 and 60 GHz", in Proc. *IEEE GLOBECOM,* 2024.

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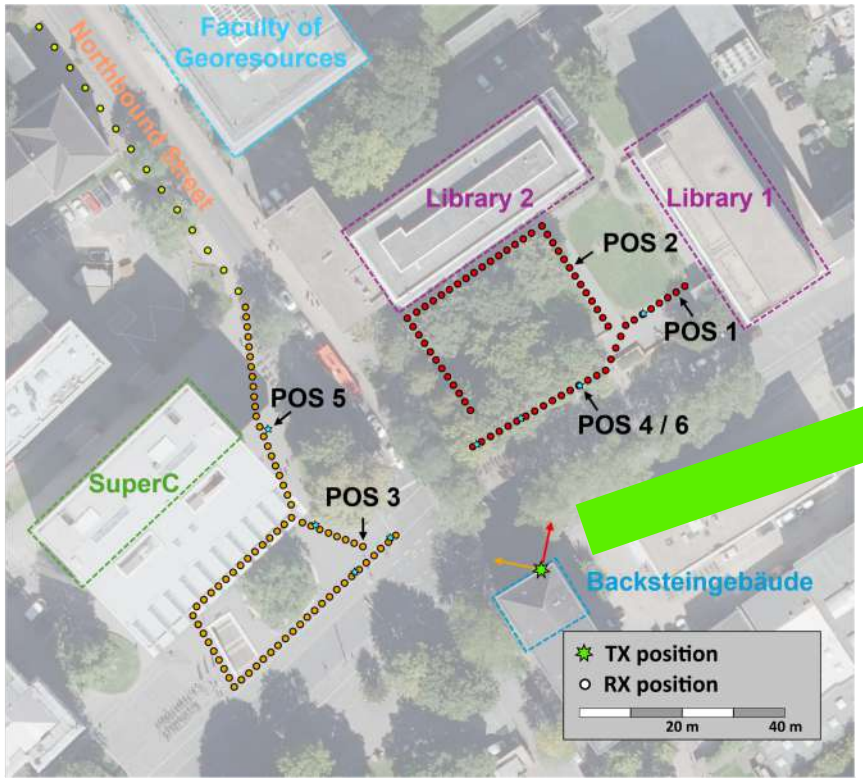

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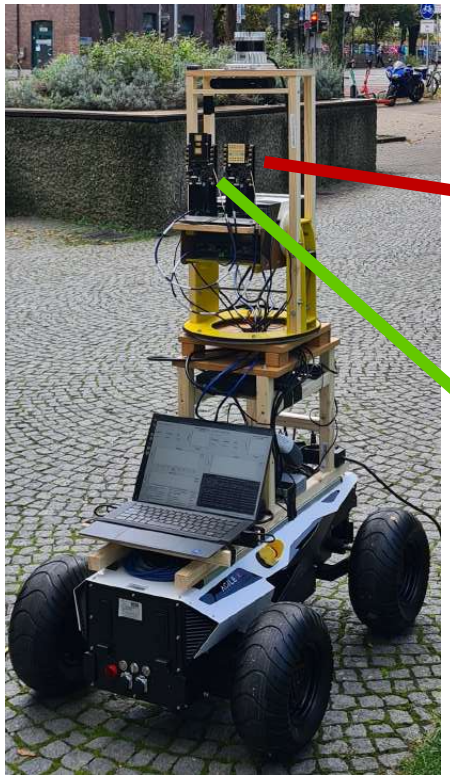

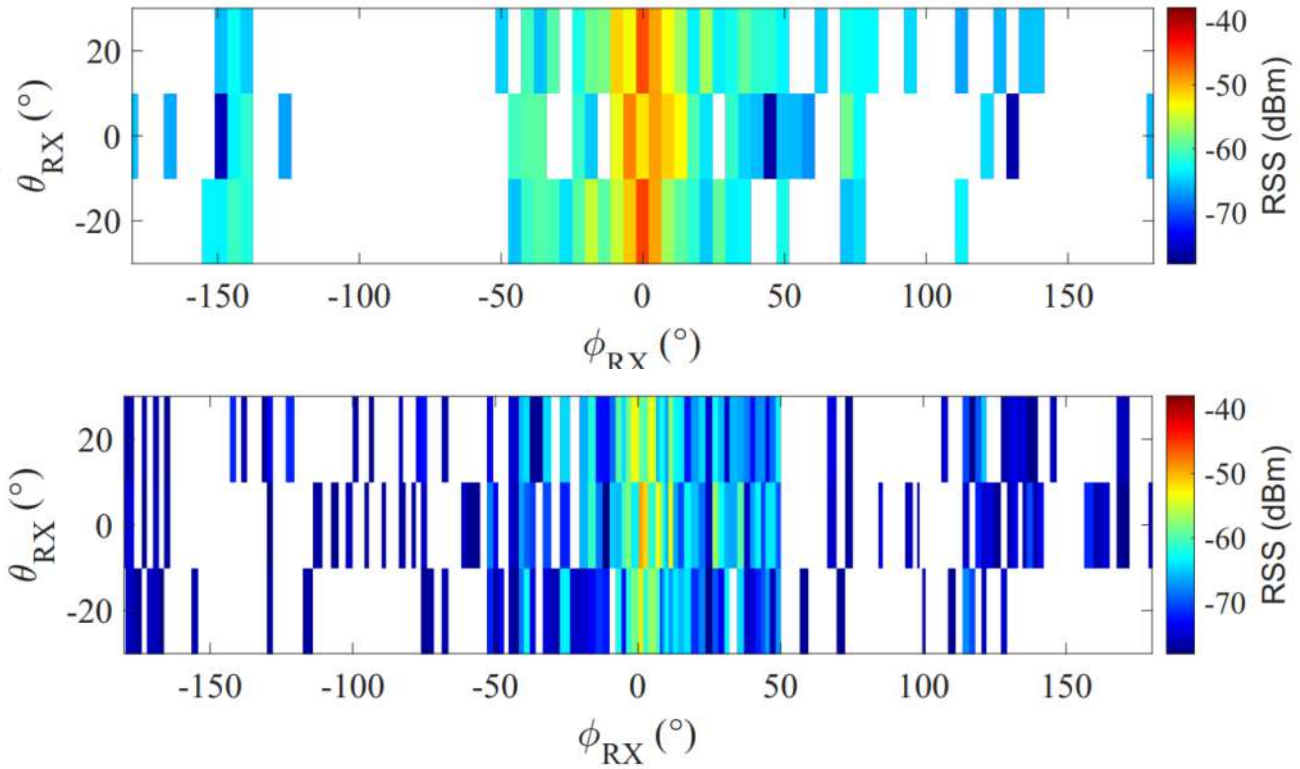

RSS heatmap @ 28 GHz

RSS heatmap @ 60 GHz

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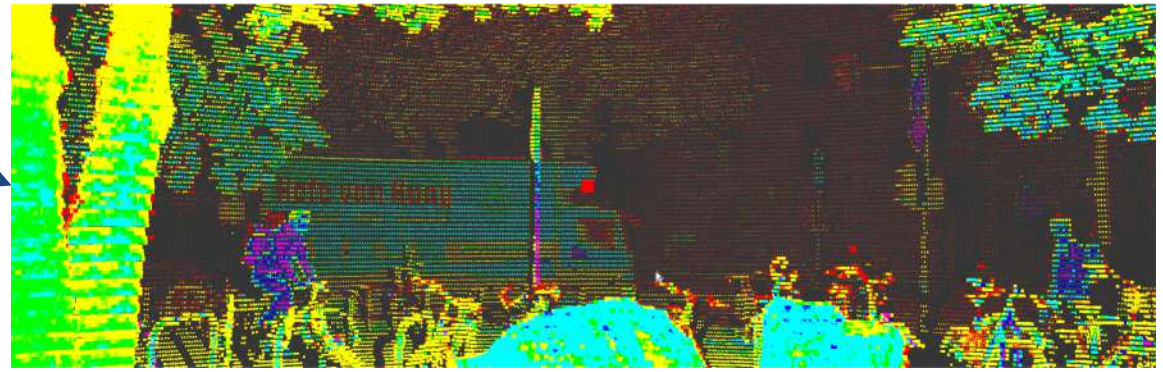

LiDAR

camera

[2] A. Schott, A. Ichkov, B. Acikgöz, N. Beckmann, L. Reiher, and **L. Simić**, "A Multi-Band mm-Wave Experimental Platform Towards Environment-Aware Beam Management in the Beyond-5G Era", in *Proc. WiNTECH in ACM MobiCom,* 2024.

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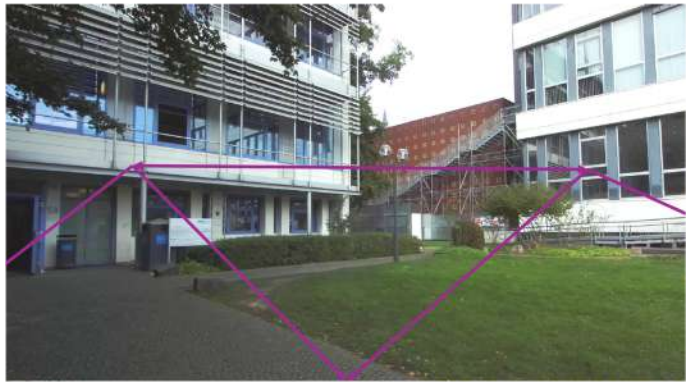

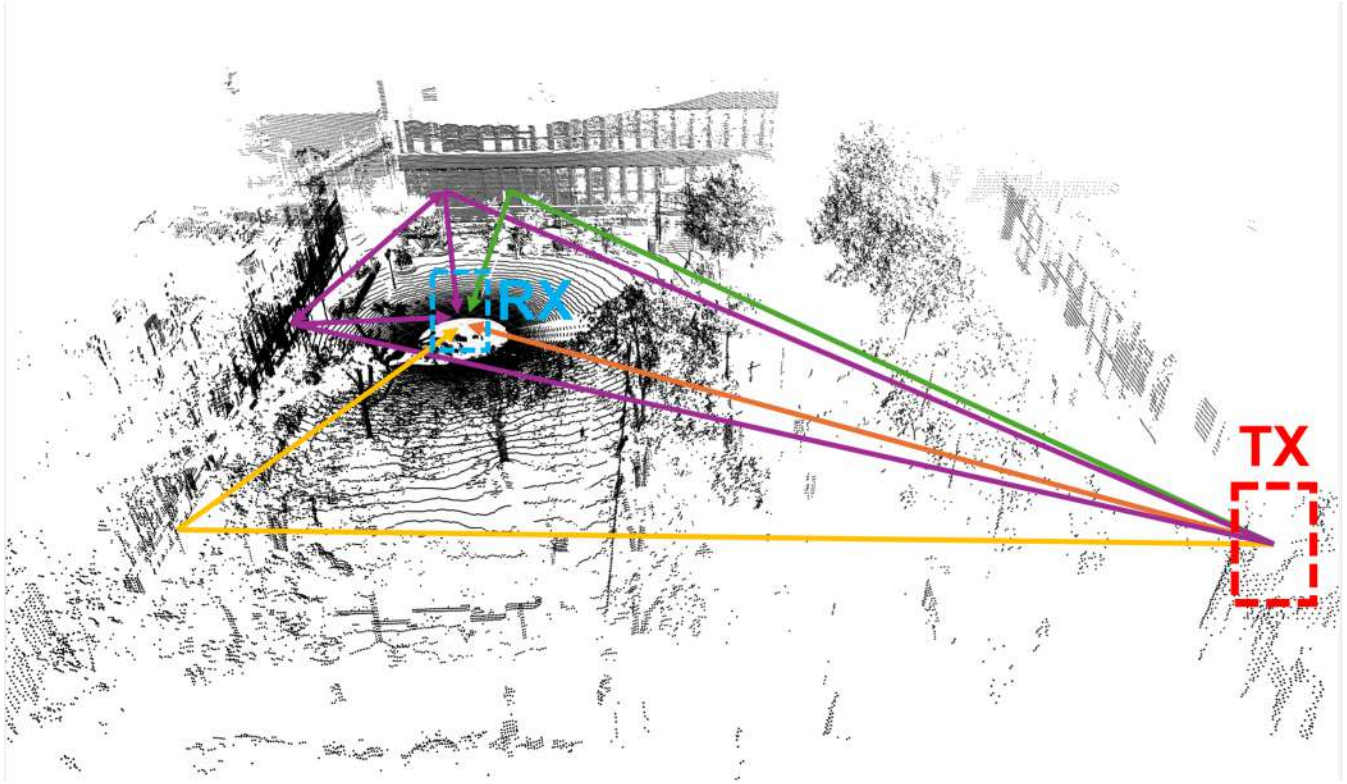

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[4] P. Dominguez, "Emprical Characterization of Outdoor Multi-Band Millimeter-Wave Link Opportunities", *BSc. Thesis*, RWTH Aachen University, 2025.

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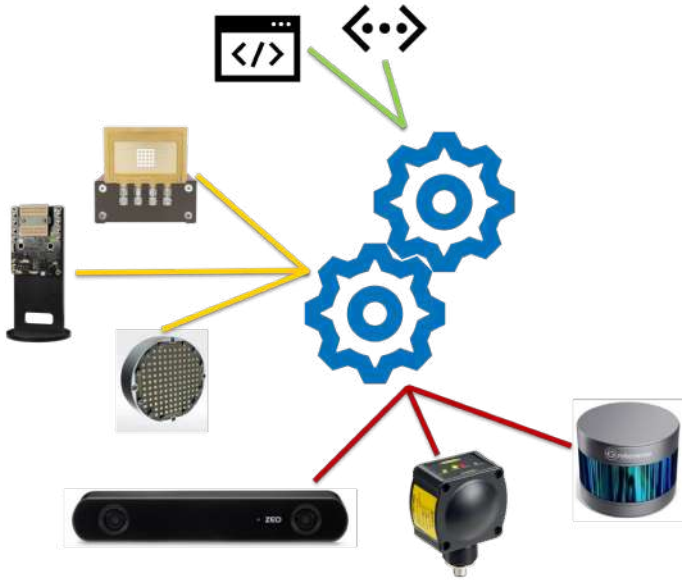
① Measurement Platform [2] for Multi-Modal Sensing/RF Datasets

- **build your own!**



Code available:

GitHub

https://github.com/inets-rwth/GNURadio-mmWave

[2] A. Schott, A. Ichkov, B. Acikgöz, N. Beckmann, L. Reiher, and **L. Simić**, "A Multi-Band mm-Wave Experimental Platform Towards Environment-Aware Beam Management in the Beyond-5G Era", in *Proc. WiNTECH in ACM MobiCom,* 2024.

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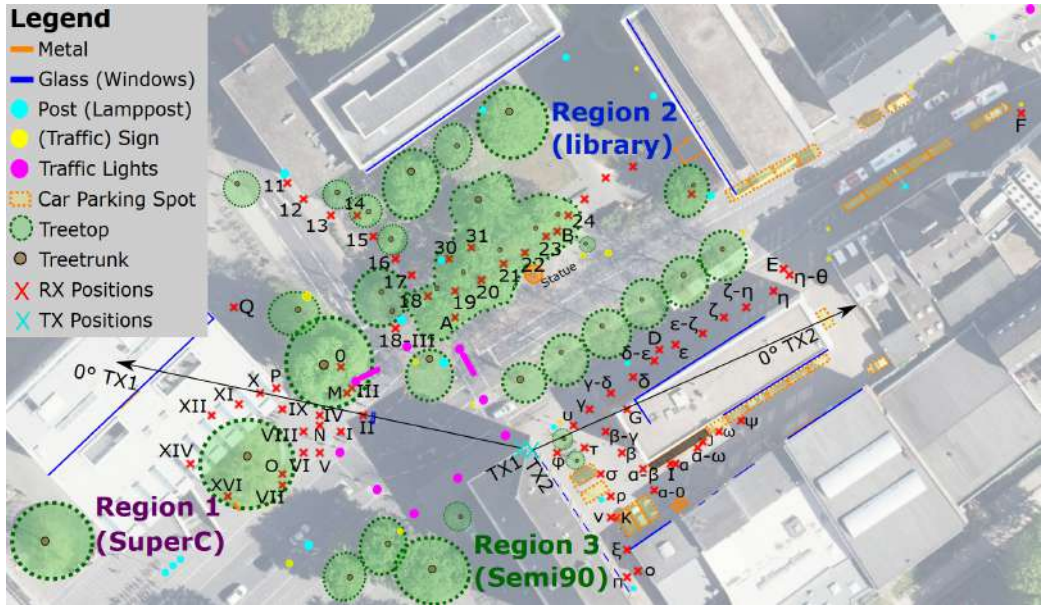
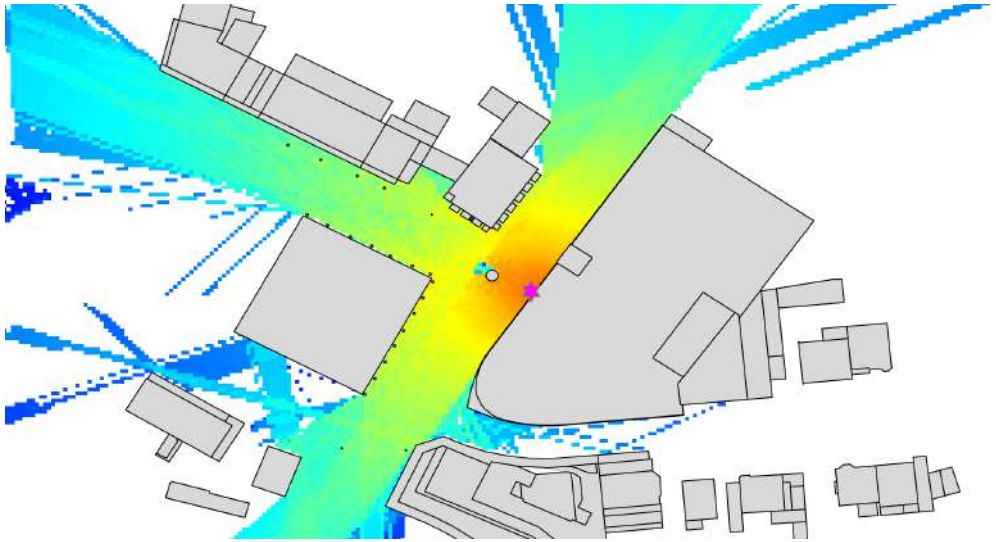
② Validation of Wireless Digital Twin Synthetic Data: How Detailed is Detailed Enough?

- measurement vs. ray-tracing propagation modelling for mm-wave networks





[5] A. Schott, A. Ichkov, P. Mähönen, and **L. Simić**, "Measurement Validation of Ray-Tracing Propagation Modeling for mm-Wave Networking Studies: How Detailed is Detailed Enough?", in *Proc. EuCAP*, 2023.

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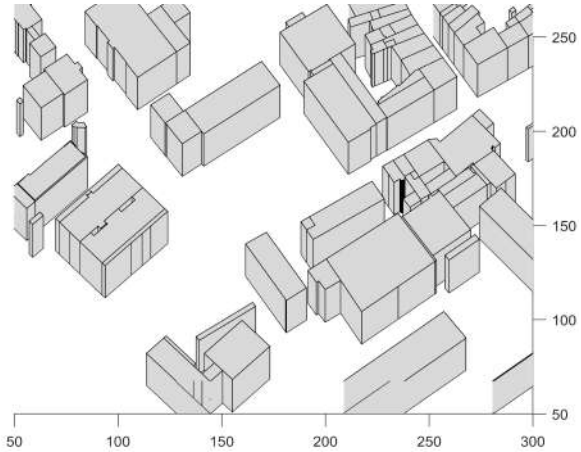
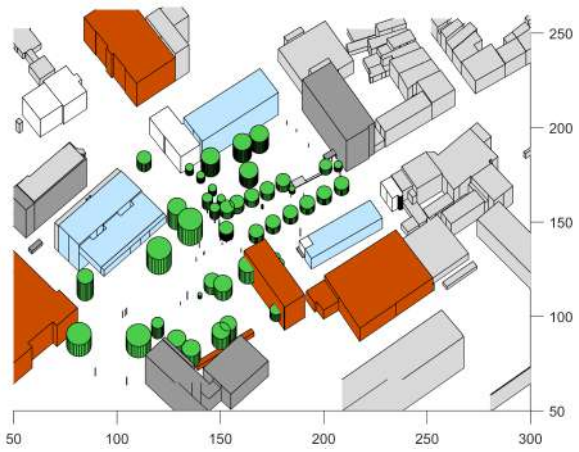
② Validation of Wireless Digital Twin Synthetic Data: How Detailed is Detailed Enough?

basic environment model

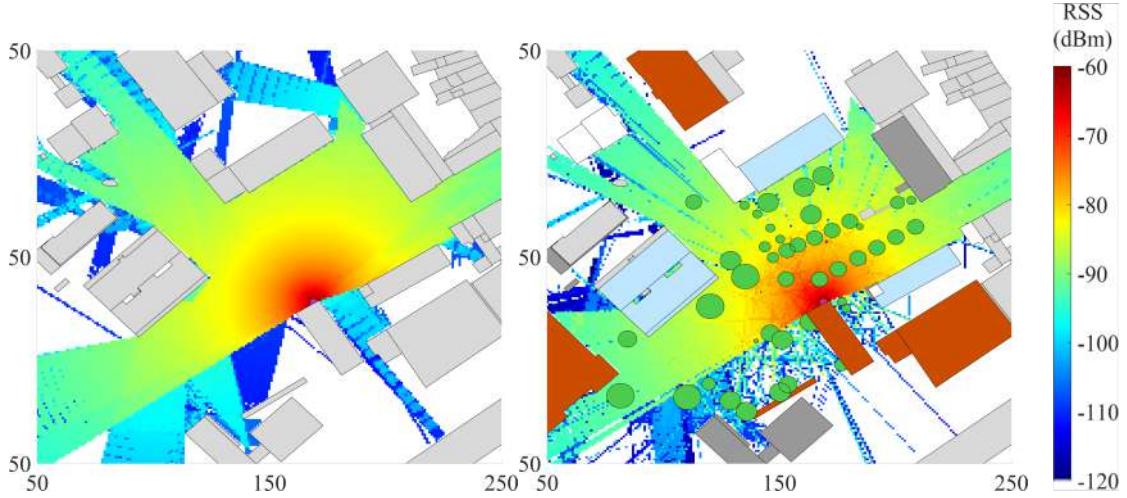


Material type	Reflection loss (dB)	Color code
Brick	12.3	
Concrete	9.6	
Plasterwork	23.1	
Glass	8.4	

detailed environment model



Material type	Reflection loss (dB)	Color code
Tree trunk	8	
Metal	1	
Default	6	
Foliage	5.5 dB/m (Pathloss)	



60 GHz ray-tracing omnidirectional output

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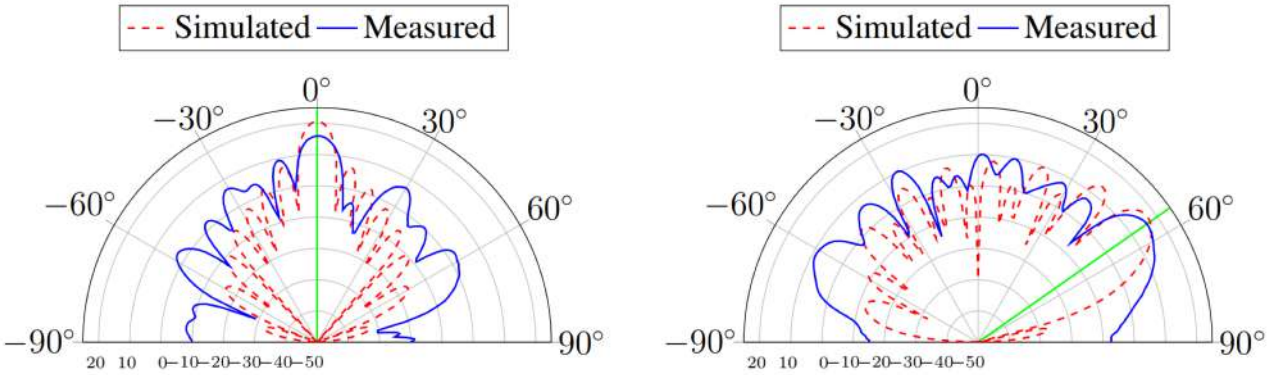
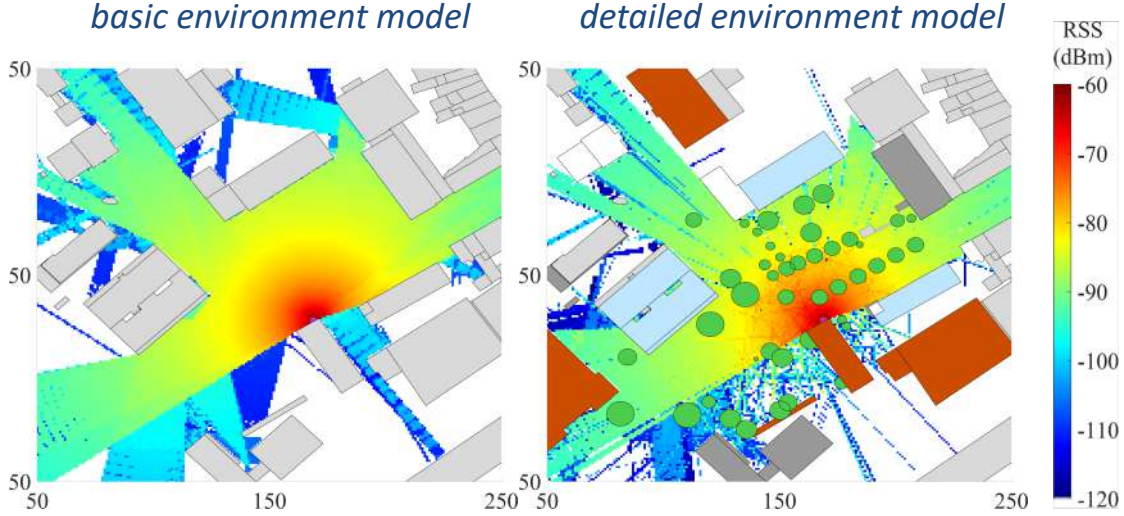
simulated vs. measured antenna models



(a) Beam index 24 (0° azimuth steering angle)

(b) Beam index 44 (55° azimuth steering angle)

basic environment model *detailed environment model*



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② Validation of Wireless Digital Twin Synthetic Data: How Detailed is Detailed Enough?

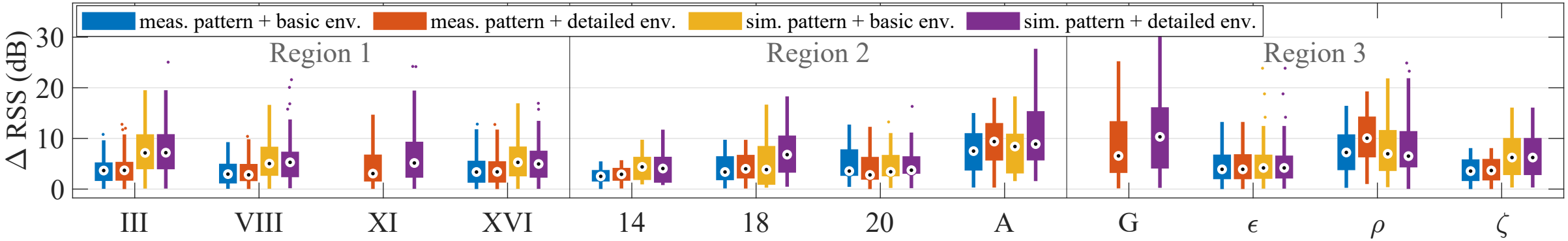

Fig. 4: RSS prediction error of the ray-tracing output versus the measurements (as absolute value), for the basic/detailed environment and simulated/measured antenna models for 12 selected RX positions.

- median directional RSS error under 4 dB for most RX position
- similar performance for both environment models
- simulated antenna model overestimates dominant MPCs due to main lobe modeling inaccuracies

[5] A. Schott, A. Ichkov, P. Mähönen, and **L. Simić**, "Measurement Validation of Ray-Tracing Propagation Modeling for mm-Wave Networking Studies: How Detailed is Detailed Enough?", in *Proc. EuCAP*, 2023.

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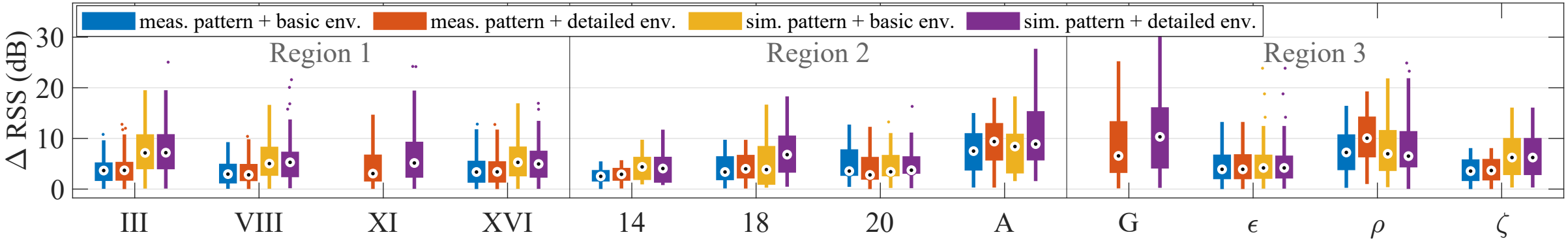

Fig. 4: RSS prediction error of the ray-tracing output versus the measurements (as absolute value), for the basic/detailed environment and simulated/measured antenna models for 12 selected RX positions.

- **simple environmental models**, with all major building features modeled, **sufficient**
- **measured antenna model of** irregular codebook-based phased antenna array **crucial**

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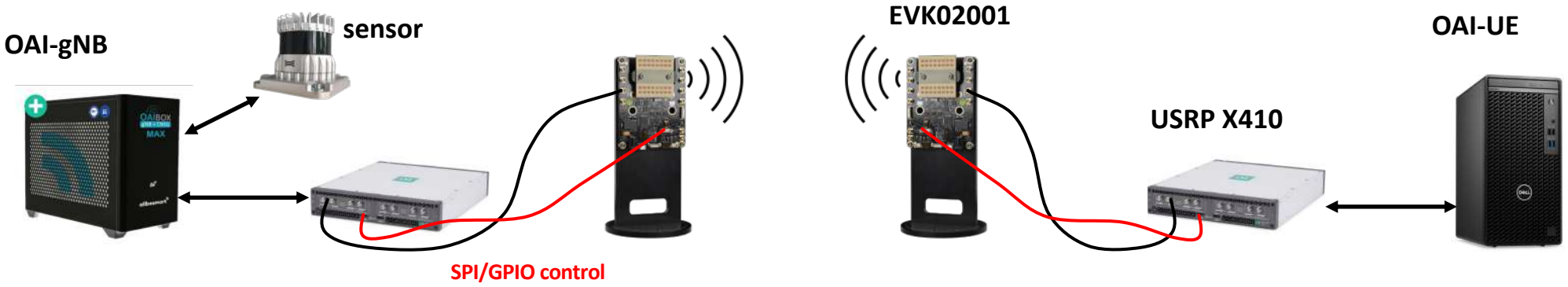
③ Real-time 6G Experimentation Platform:
OpenAirInterface Meets Sensor-Aided Environment Awareness

6G Berlin Conference 2025 demo – we are the first to integrate:

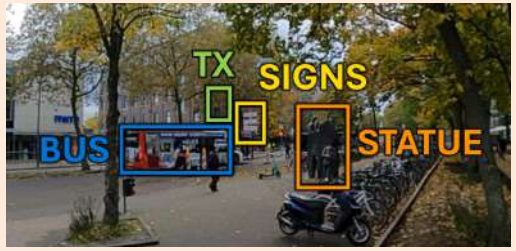
① non-RF multi-modal sensors,
② low-cost FR2 transceiver frontends, and
③ standard-compliant beam management in OpenAirInterface

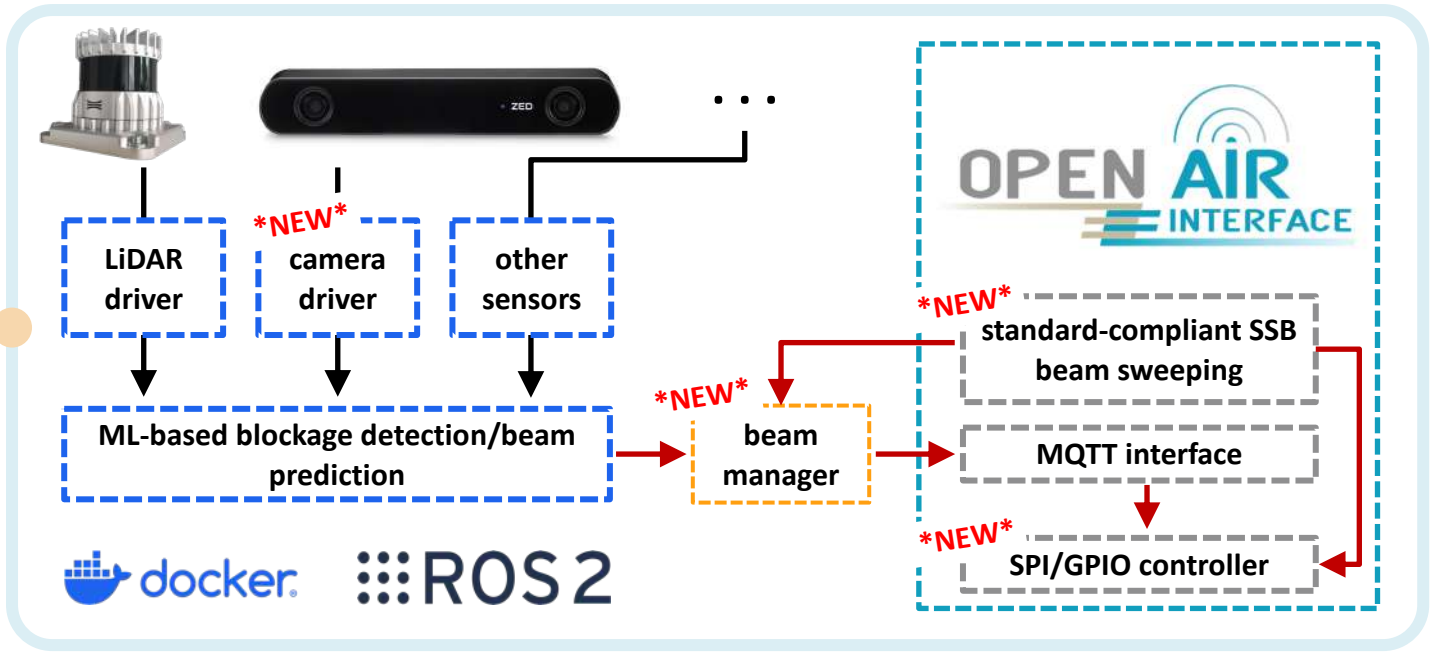


③ Real-time 6G Experimentation Platform:
OpenAirInterface Meets Sensor-Aided Environment Awareness

1

First-ever sensor input integration in OpenAirInterface for environment aware RRM

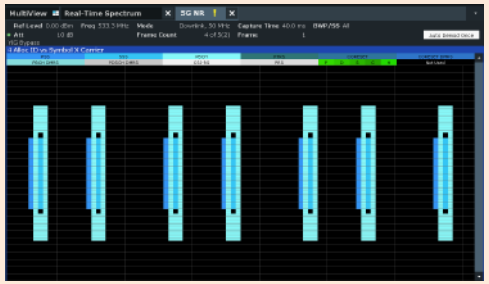


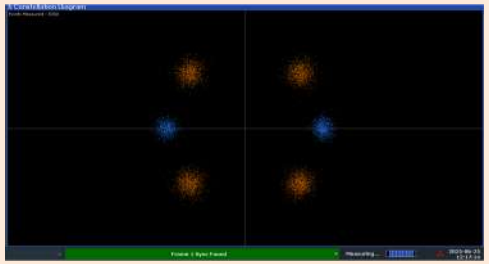


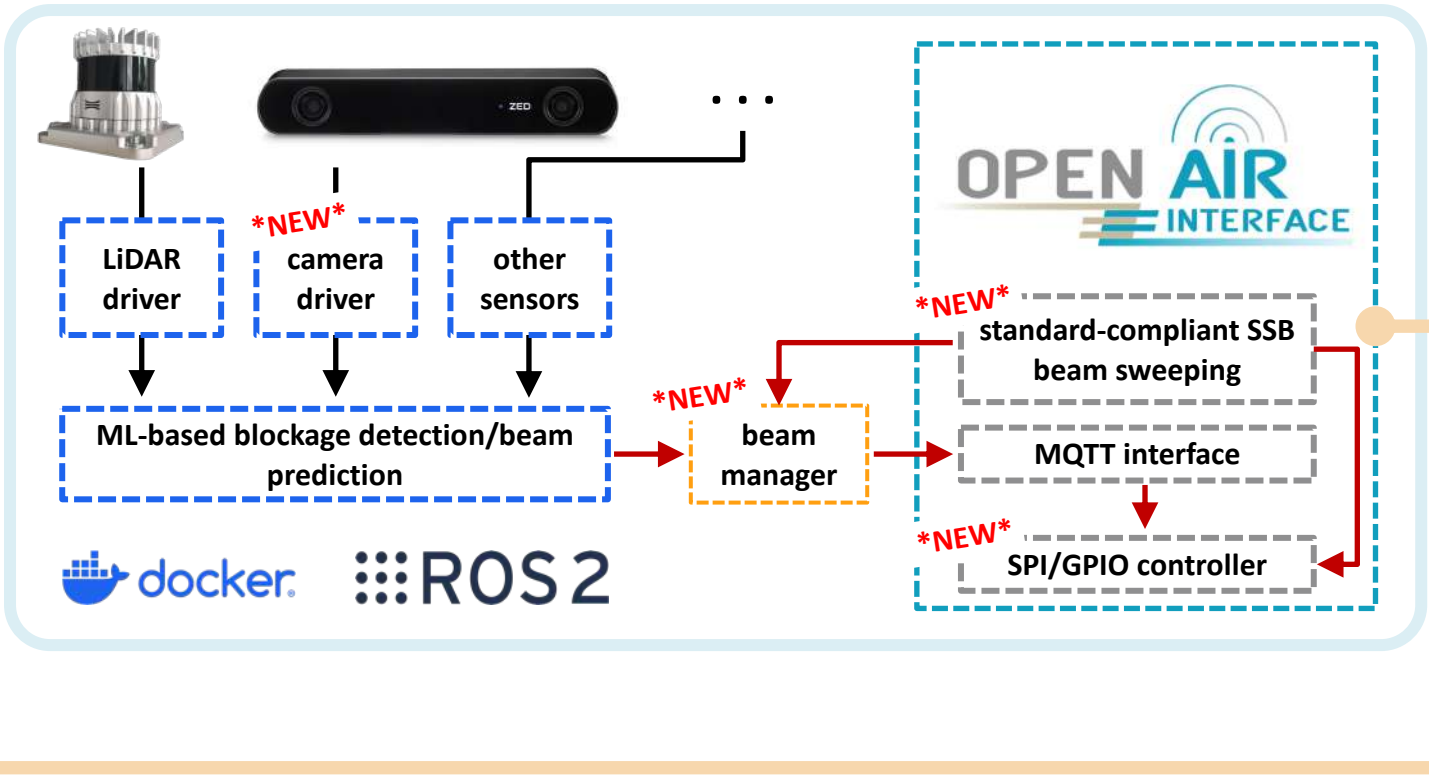
③ Real-time 6G Experimentation Platform:
OpenAirInterface Meets Sensor-Aided Environment Awareness

2

First-ever lab-verification of beam sweeping based on generated SSBs



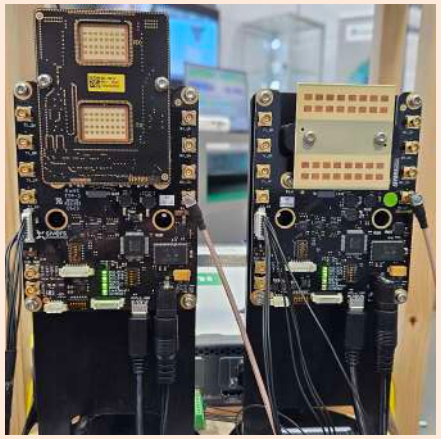




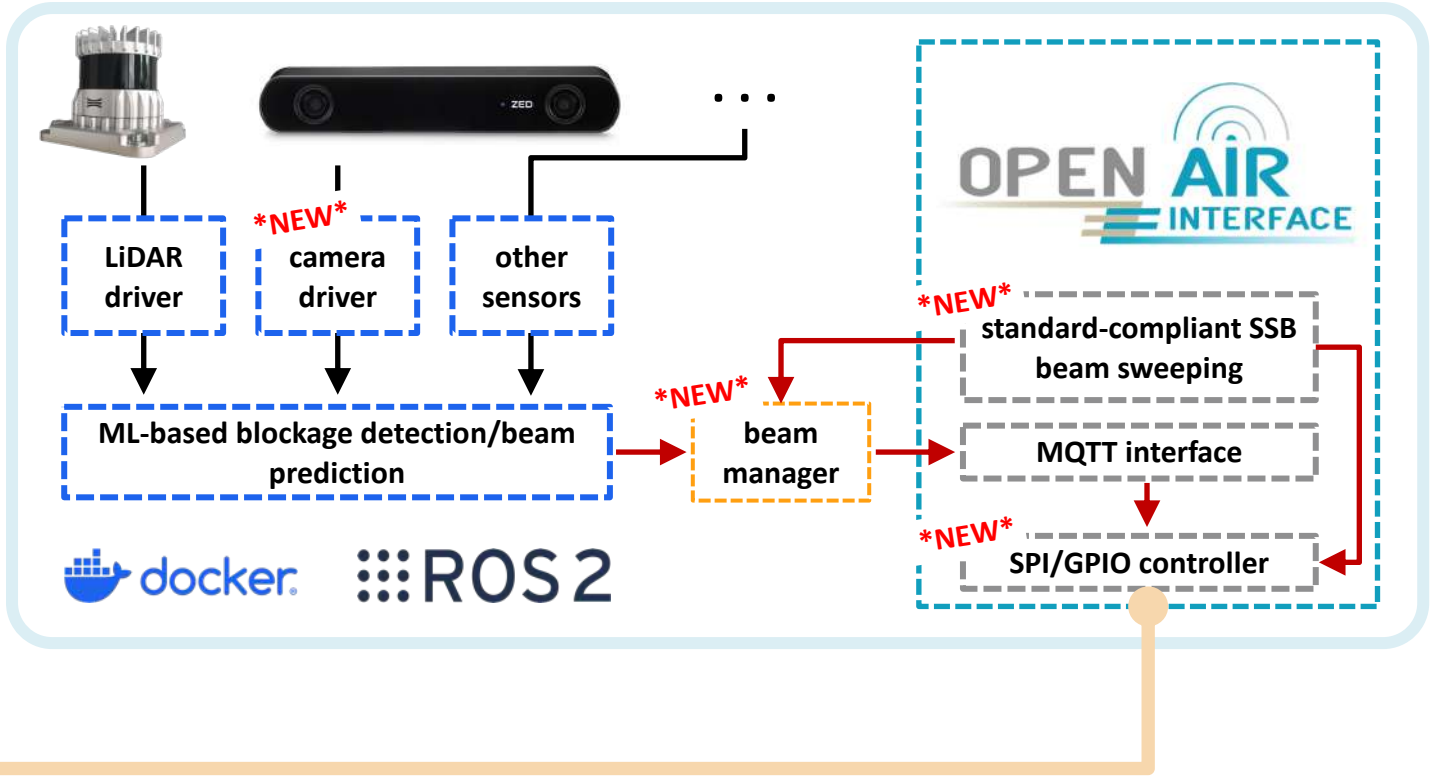
③ Real-time 6G Experimentation Platform:
OpenAirInterface Meets Sensor-Aided Environment Awareness

3

First-ever integration of popular low-cost SIVERS 28/60 GHz transceivers



Fast beam switching via SPI/GPIO control.



③ Real-time 6G Experimentation Platform:
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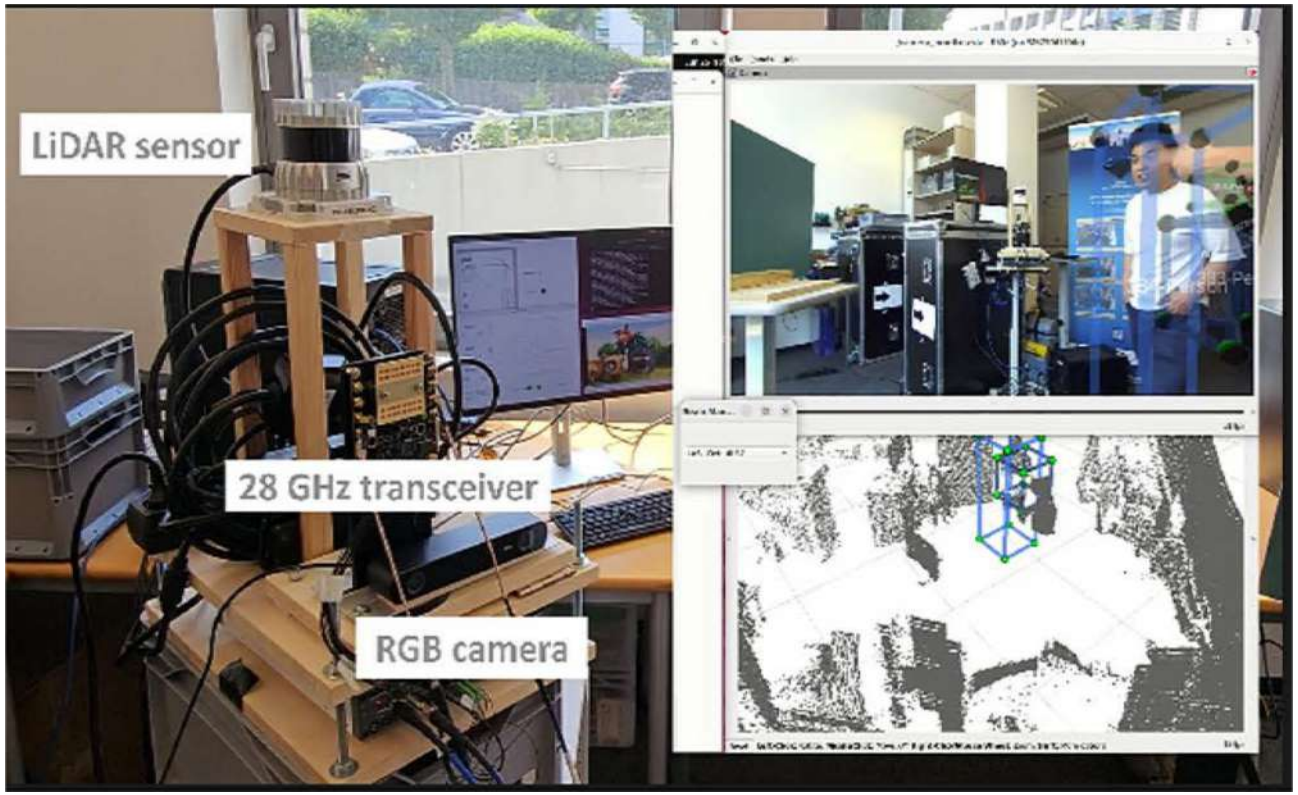
- **6G Berlin Conference 2025 demo:** LiDAR/camera-aided beam management



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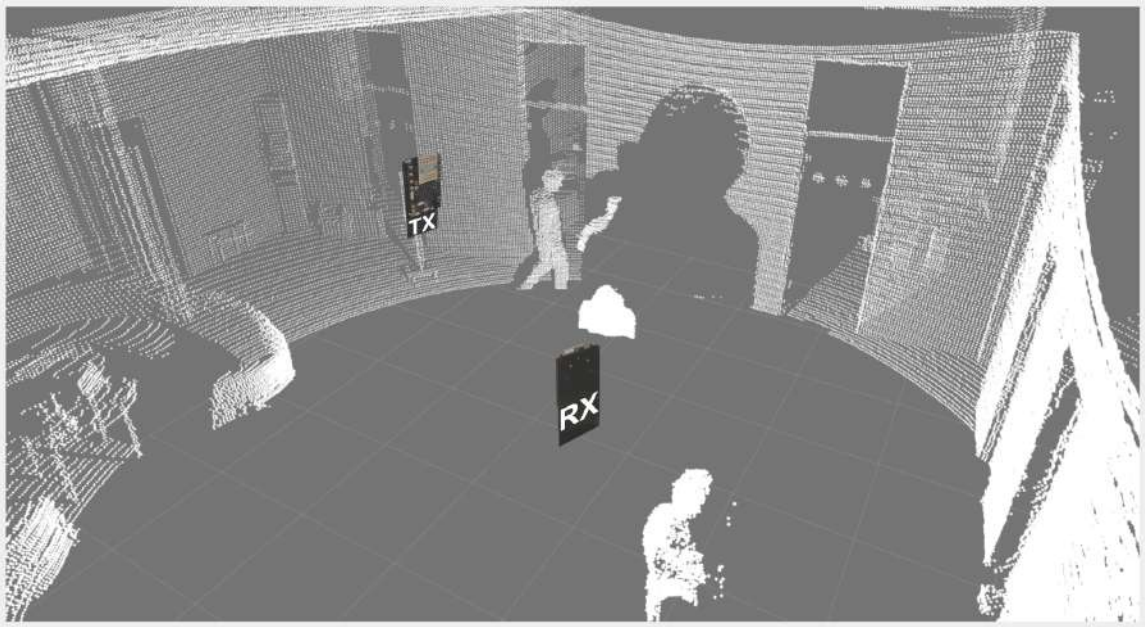

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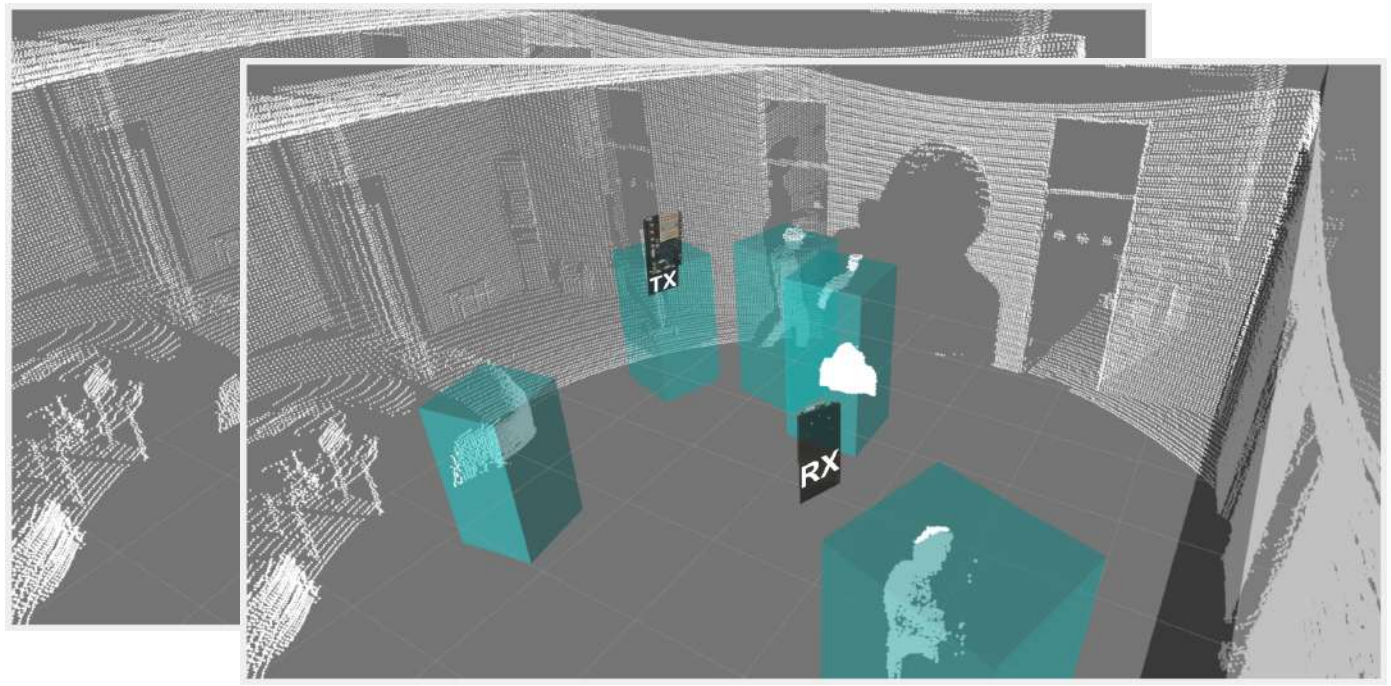

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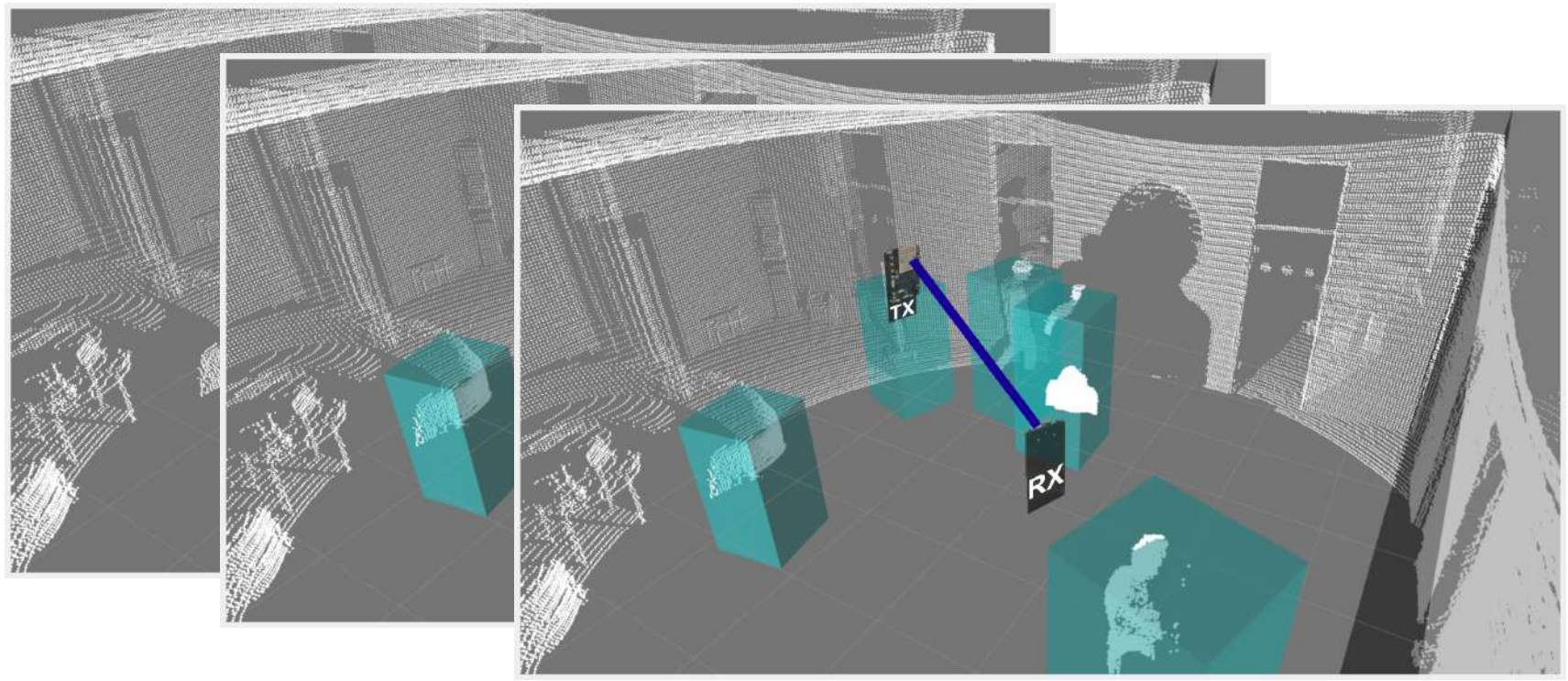

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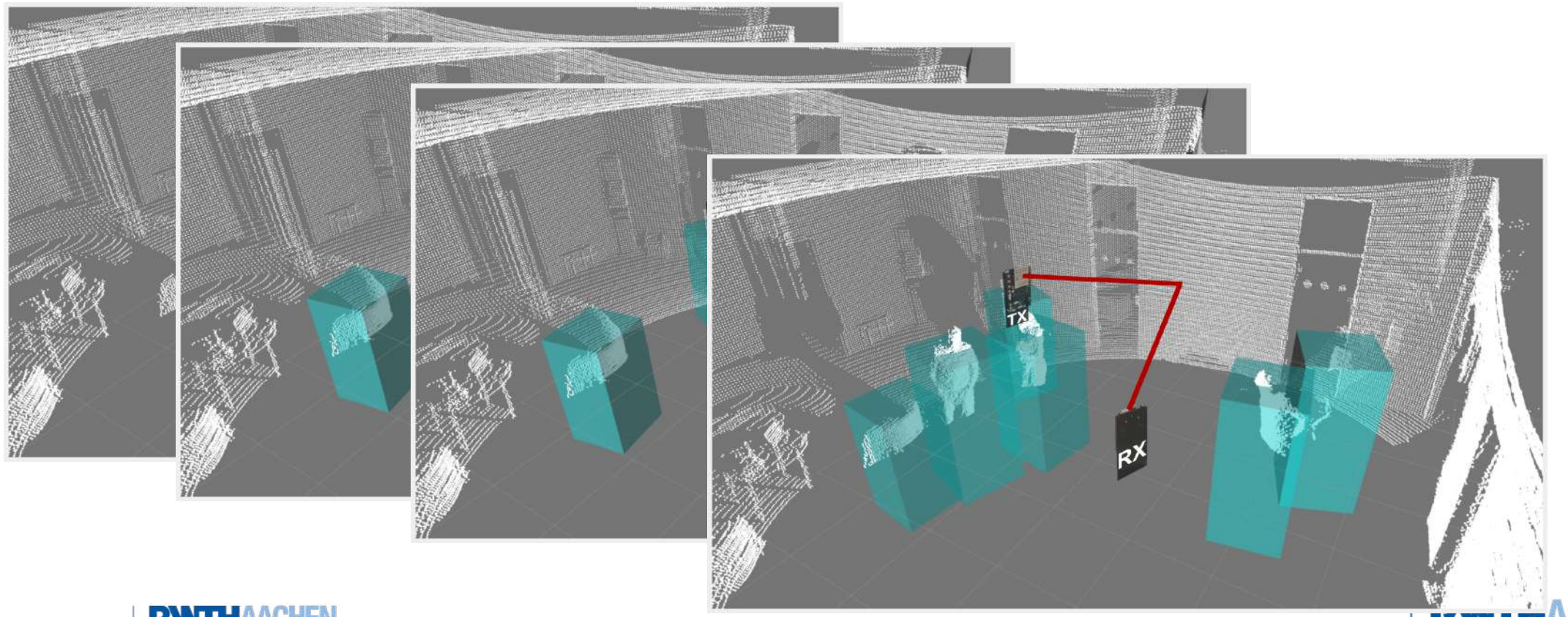

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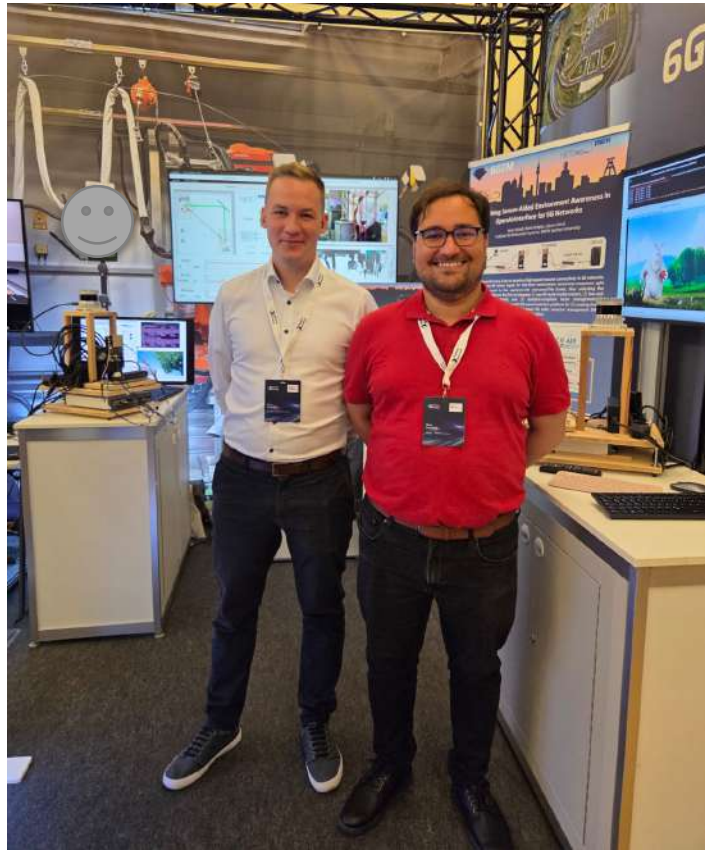
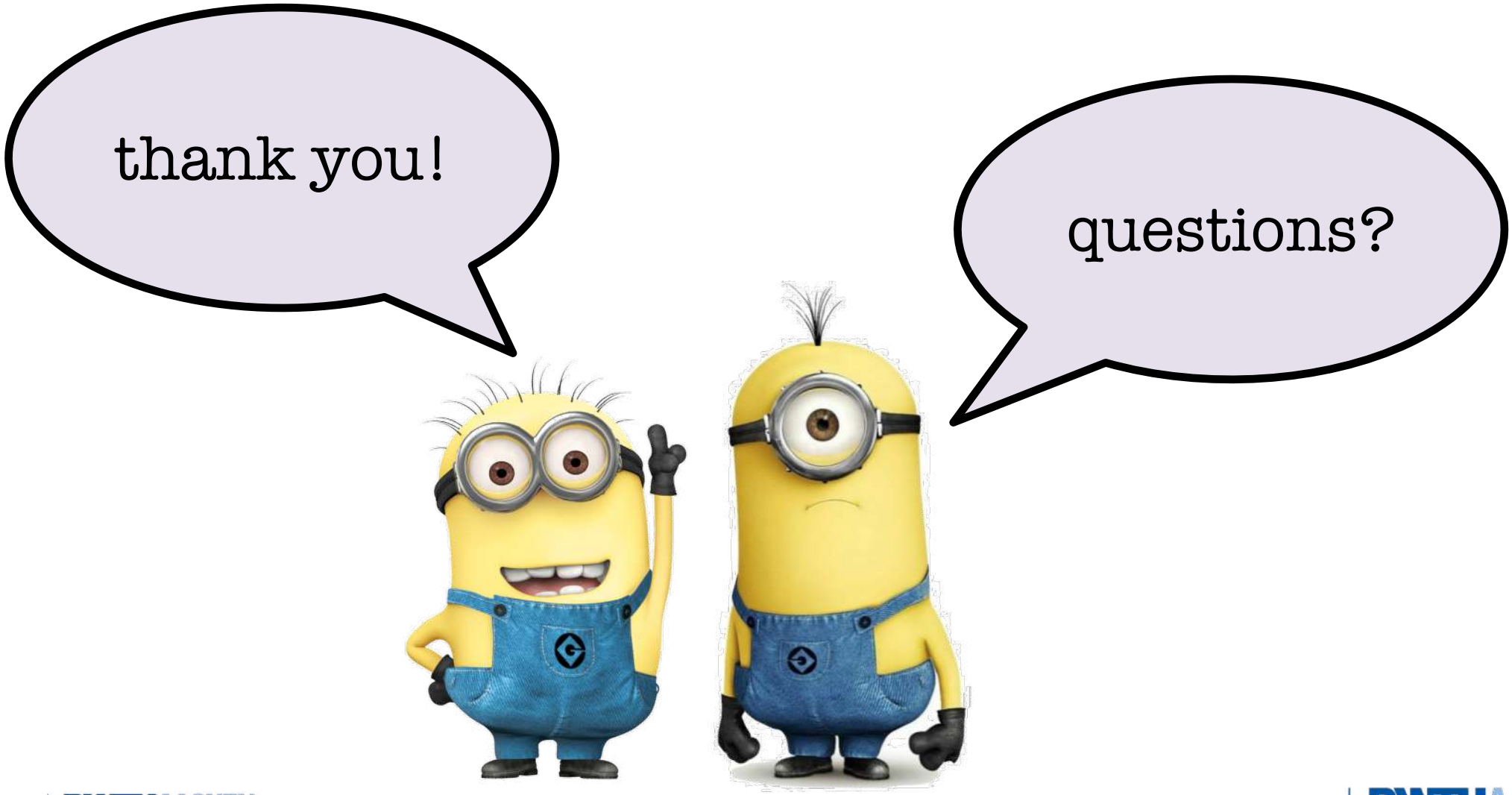


Conclusions

- leveraging sensor-aided **real-time environment awareness**, e.g. via AI/ML, for agile beam management is key to **unlocking the potential of spectrum-rich bands for 6G**

- for environment-aware RRM for 6G beamforming: **“the devil’s in the data”**
  1. diverse real-world sensing/RF datasets → **measure!**
  2. high-quality synthetic data/Digital Twins → **validate!**
  3. real-time, real-world 6G RRM protocol evaluation → **experiment!**


thank you!
questions?