SWIFT: SHIELD: A Software-Hardware Approach for Spectrum Coexistence with Rapid Interferer Learning, Detection, and Mitigation

Tingjun Chen (PI), Arun Natarajan, Leandros Tassiulas



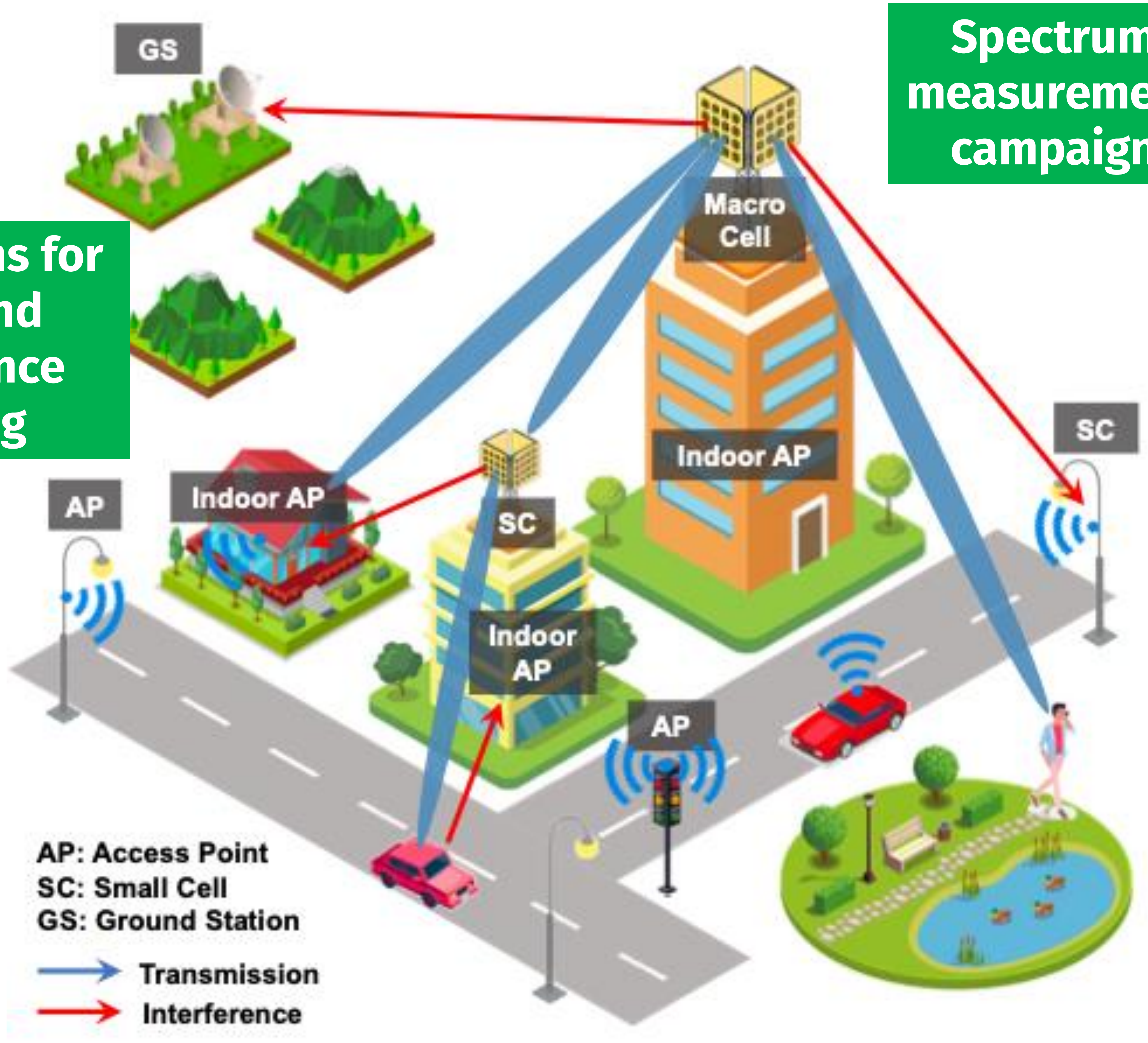
Duke University
Oregon State University
Yale

NSF SWIFT & NewSpectrum PI Meeting

Sept. 11, 2025

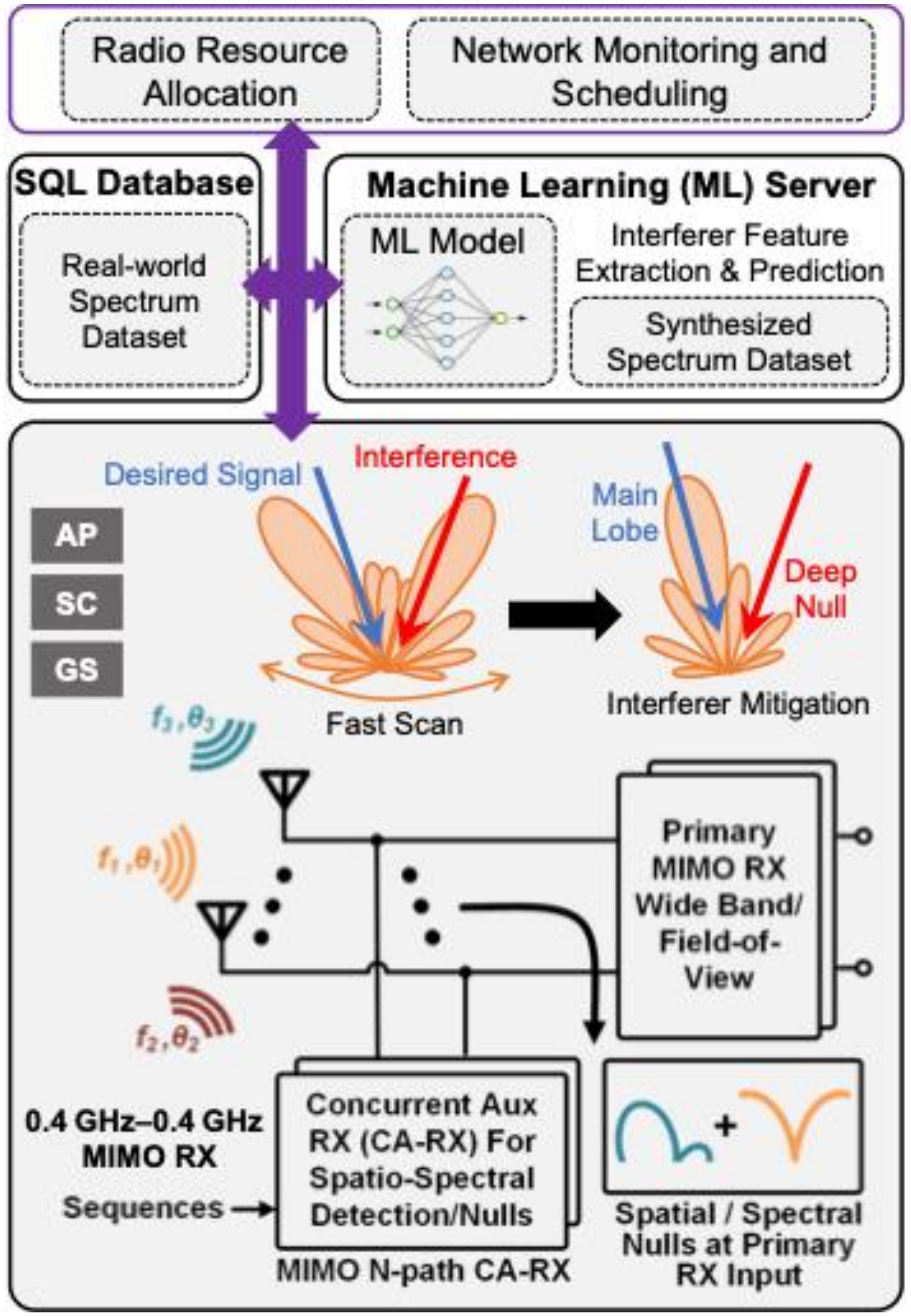
Project Vision and Goals

Digital twins for signal and interference mapping



Spectrum measurement campaign

Local LTE/5G testbeds



Novel receiver front-end circuits

Scheduling and resource allocation

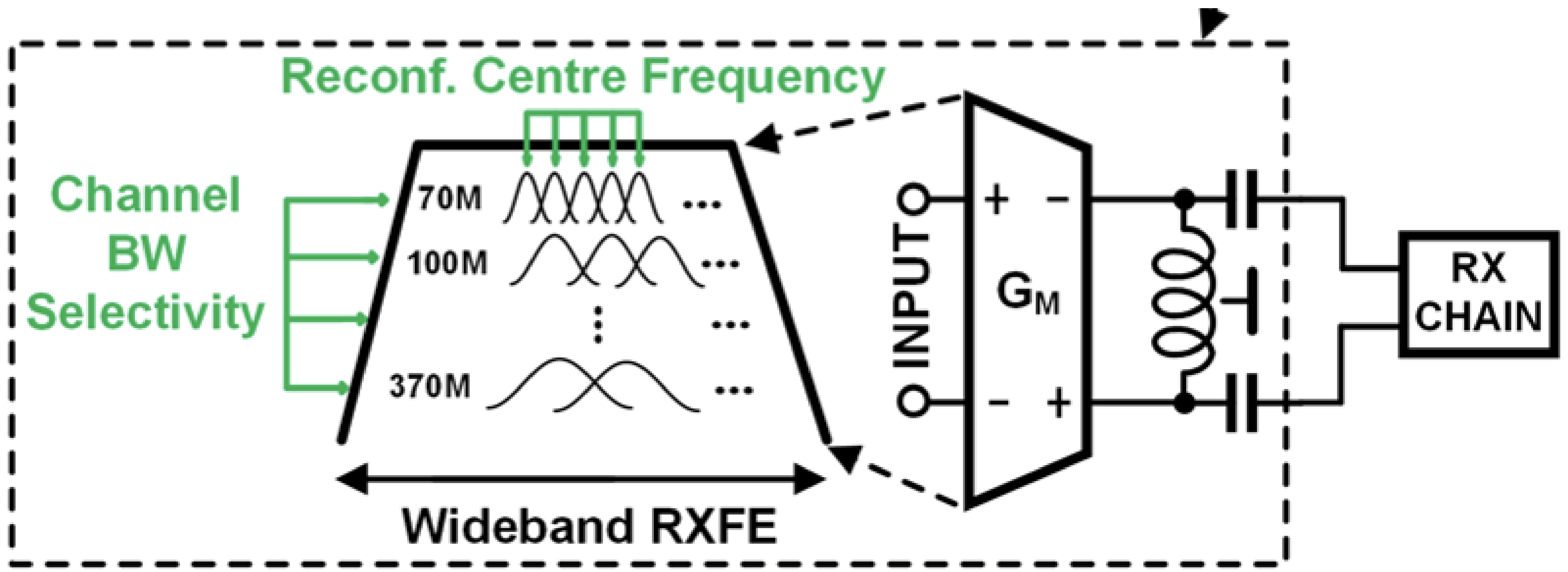
Learned interferer patterns and properties

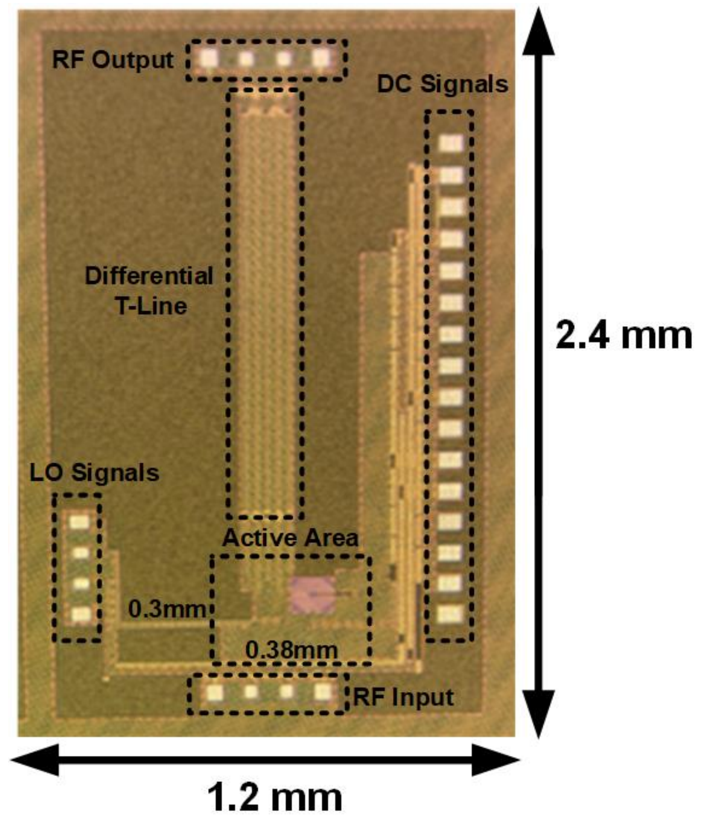
Optimized analog/digital beamforming and nulling

Duke ENGINEERING · Oregon State University · Yale

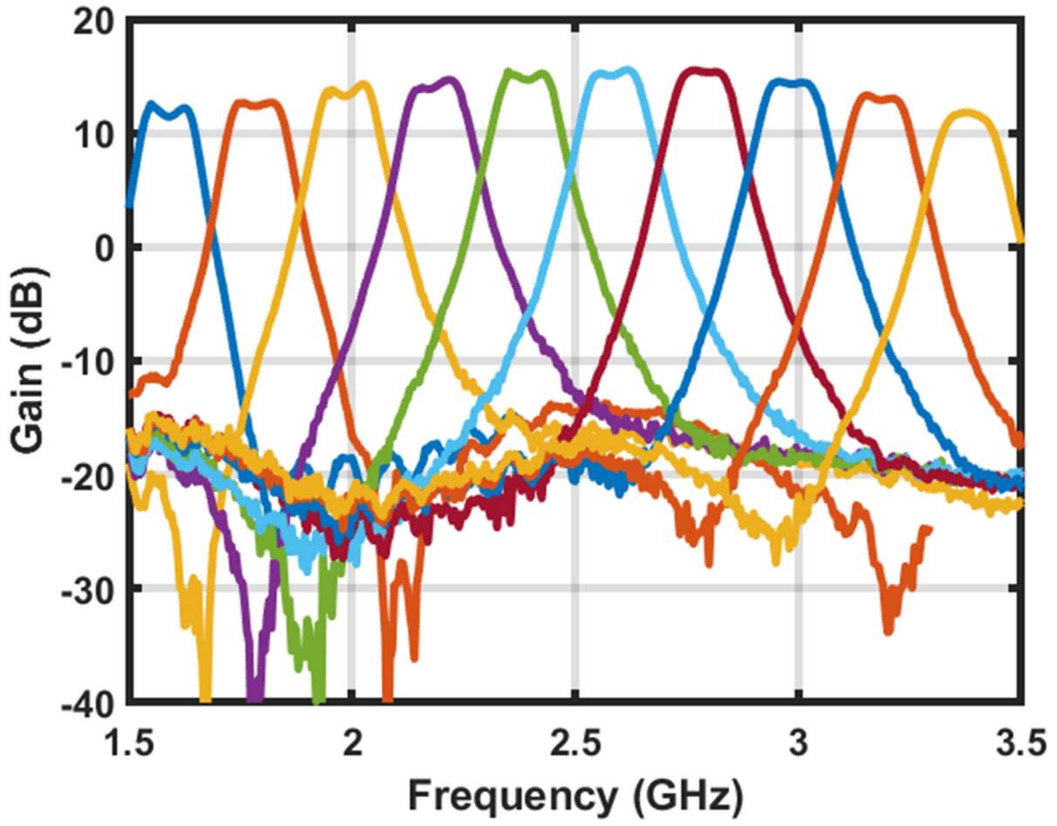
Receivers with **Reconfigurable** Center Freq. and Bandwidth

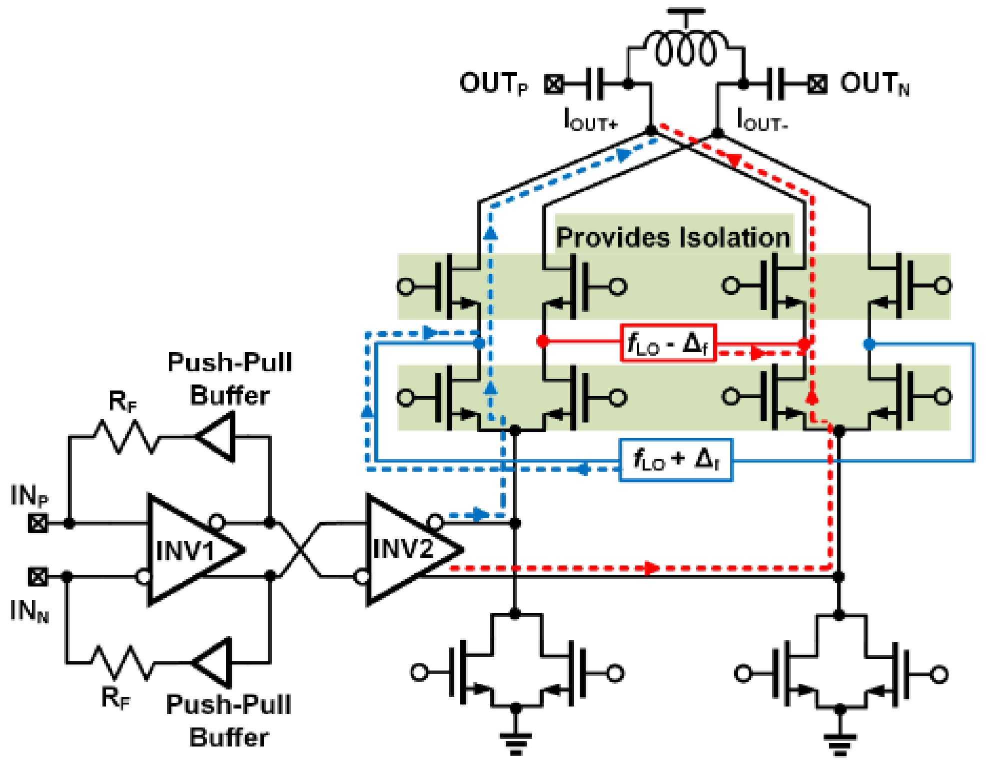
- Propose a receiver architecture capable of scanning across frequencies with reconfigurable bandwidth and deeper interferer filtering (higher-order filters) based on N-path filters
- Key performance metrics: **Reconfigurable** center frequency of **up to 3.5 GHz**, bandwidth from **70–370MHz**, with enhanced **out-of-band rejection of up to 35dB**

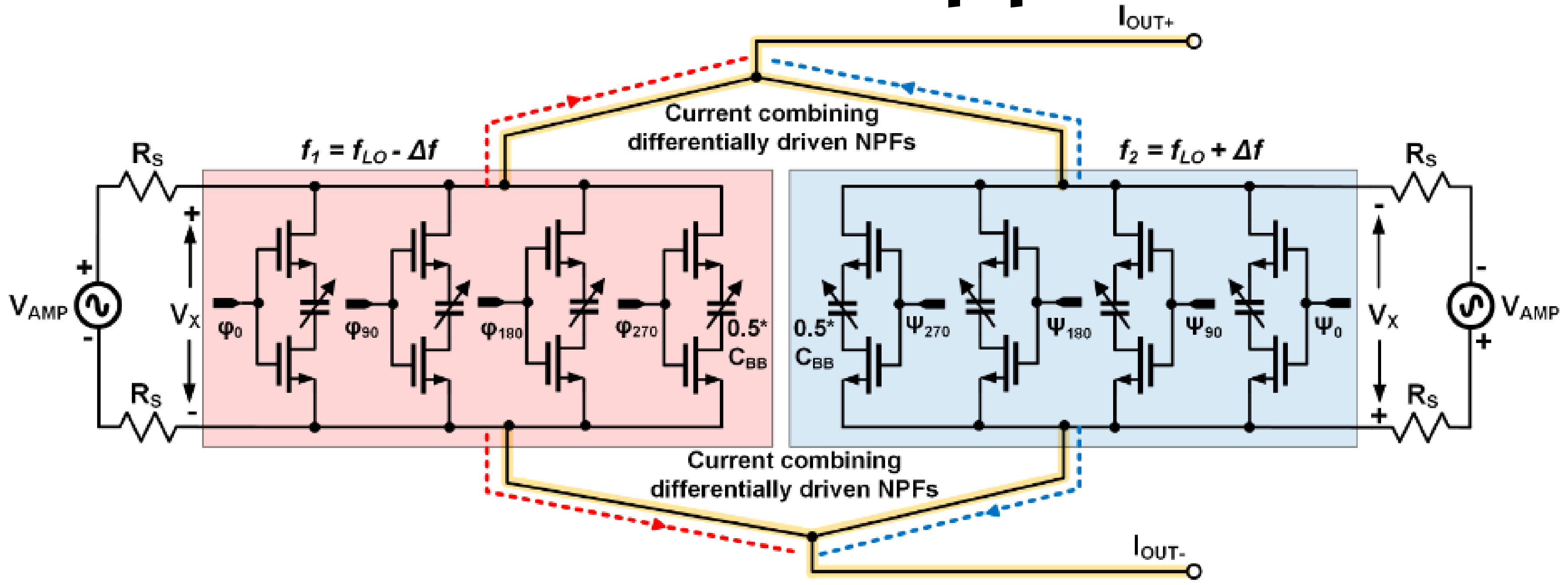


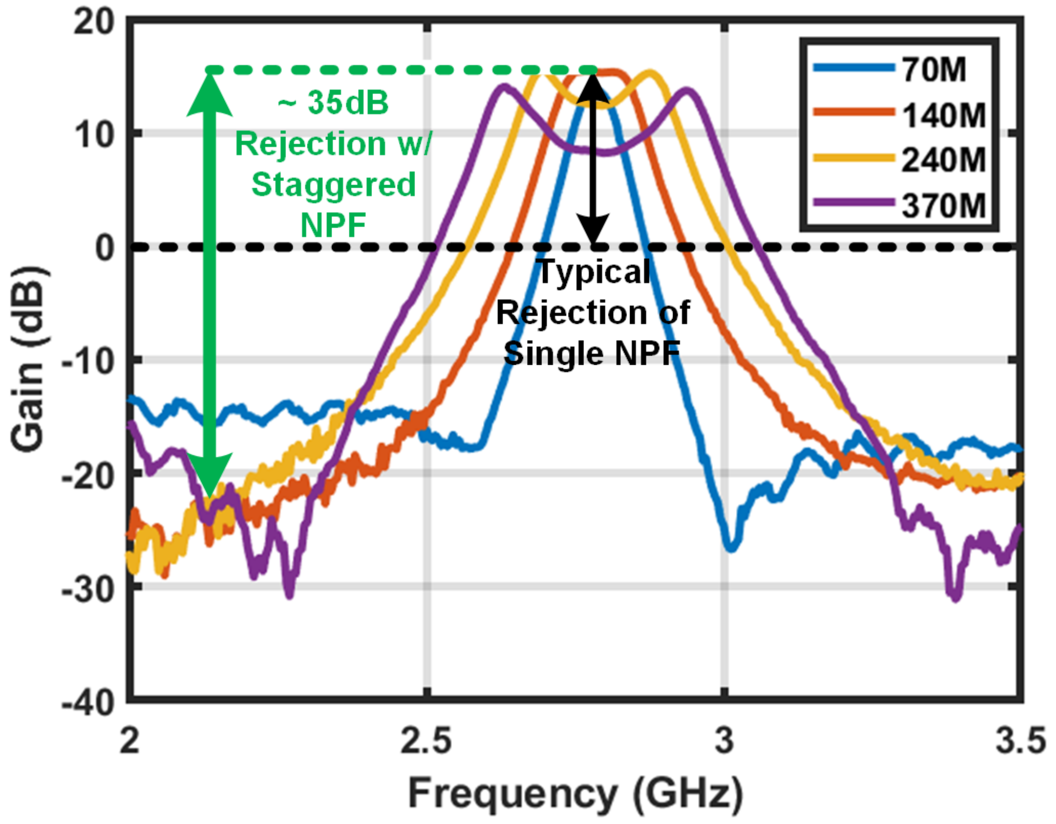


Chip photo









Measurements

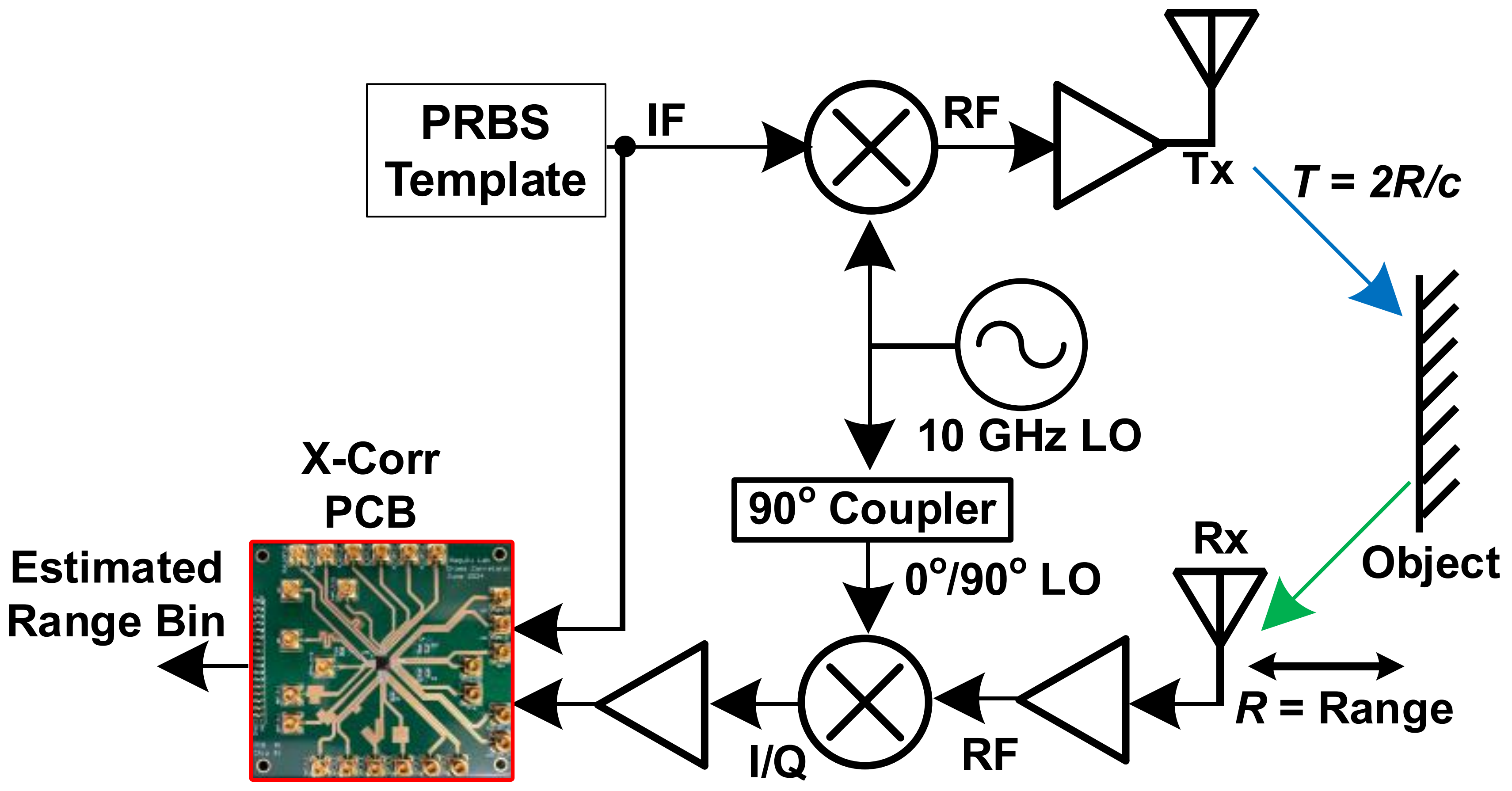
➢ S. Gupta, S. Krishnamurthy, A. Ravi, O. Degani, and A. Natarajan, “A Channel-Selective, Bandwidth-Reconfigurable Wideband Low Noise Amplifier with Dual-Frequency N-Path Filters,” in *Proc. IEEE Radio & Wireless Week (RWW’26)*, 2026.

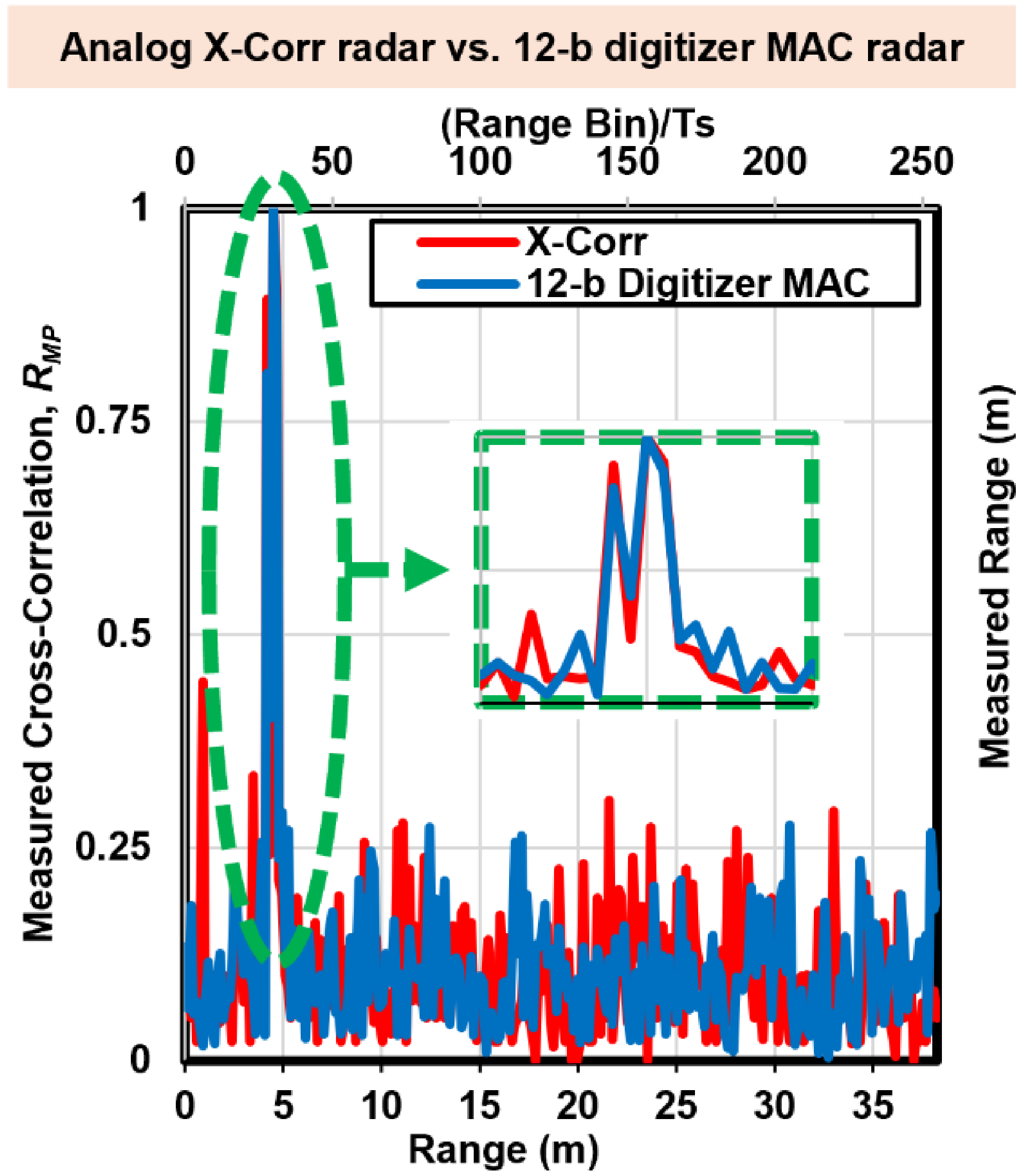
Duke ENGINEERING Oregon State University Yale

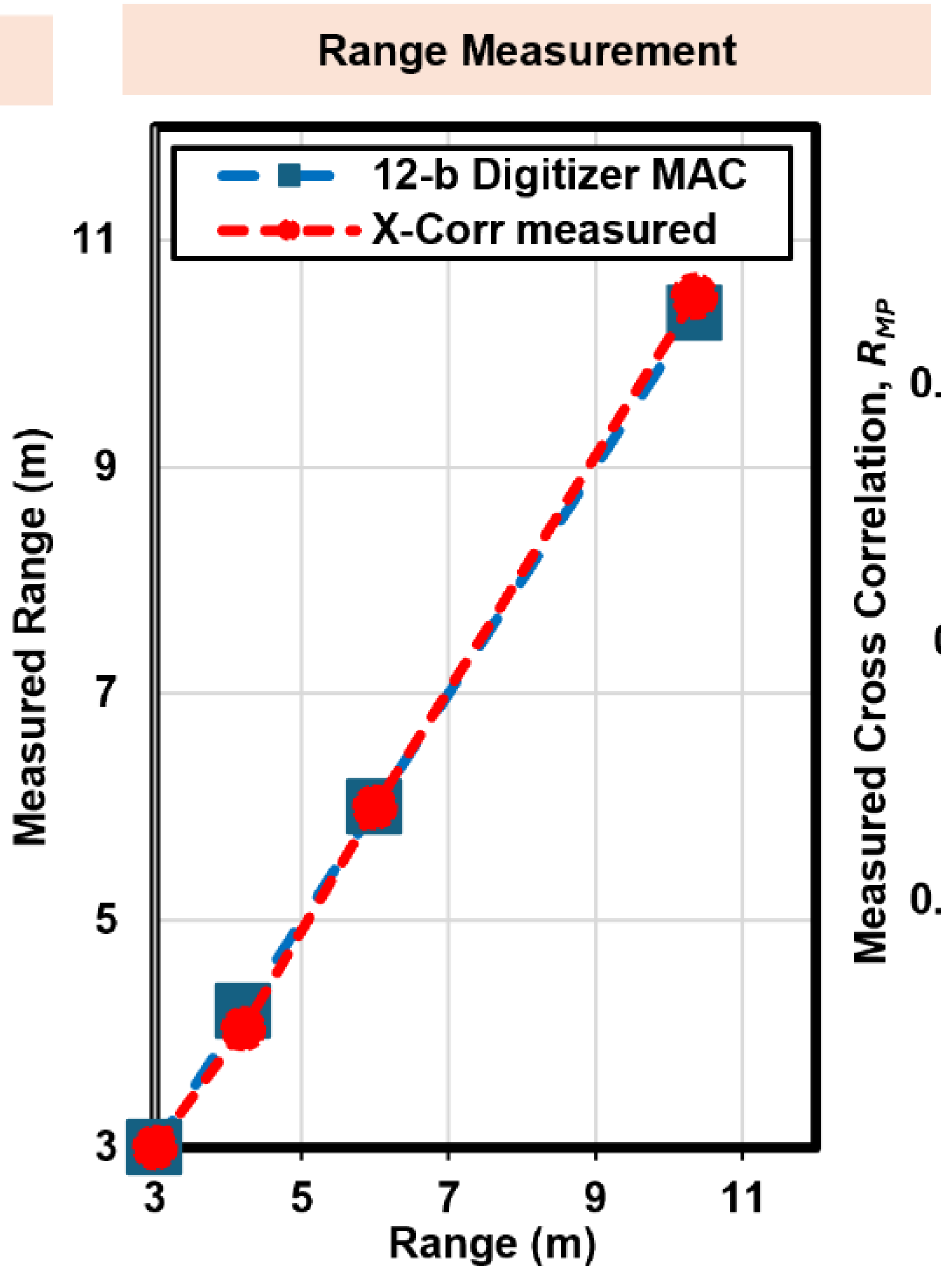
X-band Radar Detection Using an **Analog Correlator**

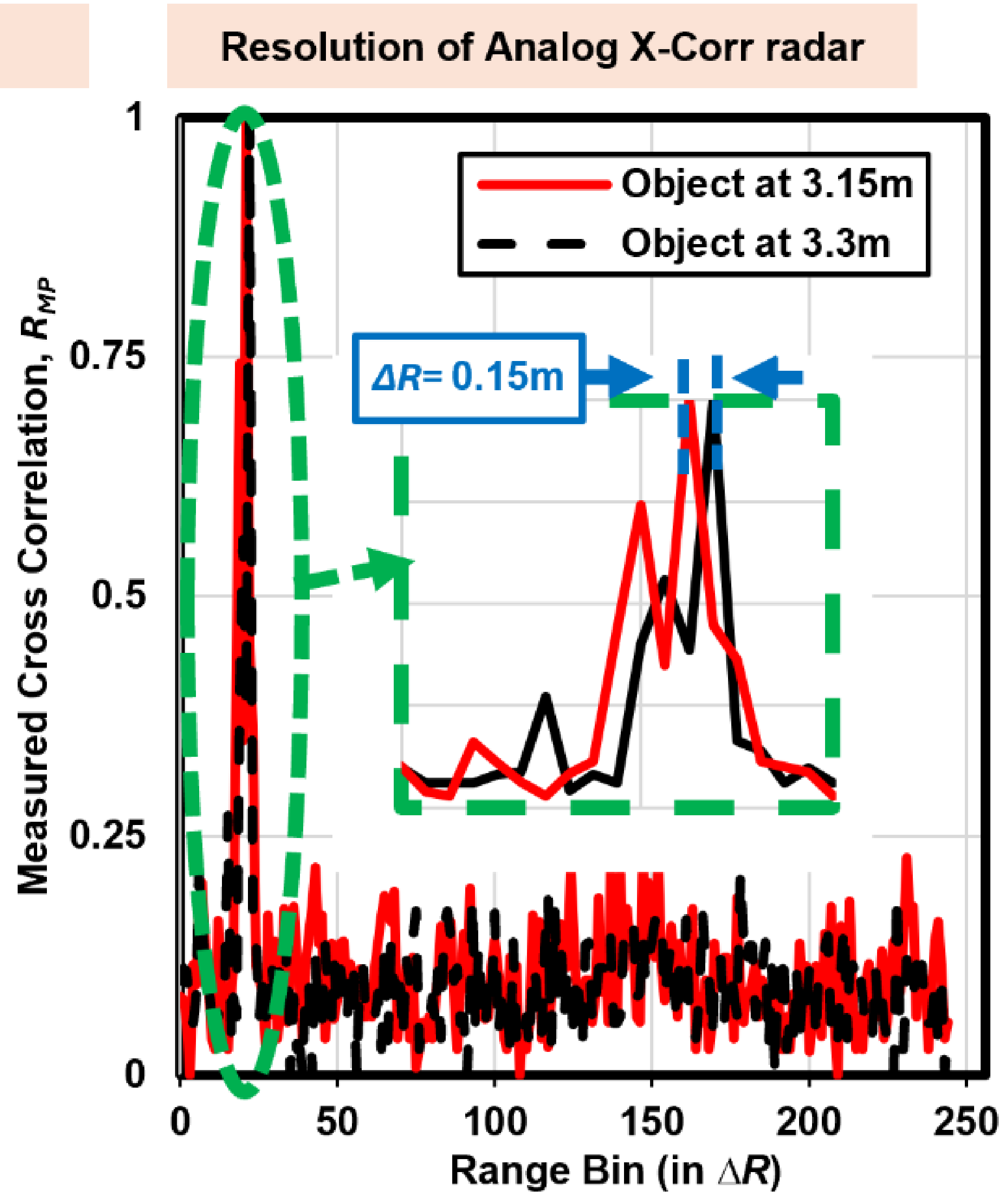
... to continue in NewSpectrum

- The analog cross-correlator IC is **integrated into a 10 GHz code-domain radar system**, where the cross-correlator acts as the core processing unit of the radar system









- The cross-correlator based radar system successfully detects the objects
- The detected range closely matches with a conventional digitizer (12-bit) + MAC based system
- The radar ranging resolution matches with its theoretical value

Duke ENGINEERING · Oregon State University · Yale

➤ A. Undavalli, K. Rashed, G. Cauwenberghs, S. Chakrabartty, A. Natarajan, and A. Nagulu, "A 4GS/s Fully Analog 256×256 MP-Based Cross-Correlator with 1000 TOPS/W Compute Efficiency and 1.3 TOPS/mm^2 Compute Density in 22nm SOI CMOS," in *Proc. IEEE ISSCC'25*, 2025.

Geo2SigMap: Tools, Datasets, and Tutorials

- **First fully automated, open-sourced, scalable pipeline for building wireless DTs**
  - CLI tool + Python API for high-fidelity 3D scene generation or *arbitrary areas of interest* (>10 km^2)
  - *Seamless integration* of the generated 3D scenes with NVIDIA's Sionna RT and AODT
  - Deep learning models and large-scale measurement datasets
  - A suite of Jupyter Lab based *examples and tutorials*

- examples
- src/scene_generation
- .gitignore
- LICENSE
- README.md
- pyproject.toml
- requirements.txt

Name	Last commit message
..	
antenna_Pattern	Adding the Sionna MSI Importer related file.
1_sionna_coverage_map.ipynb	reorg t1-t5
2_sionna_rays_analysis.ipynb	reorg t1-t5
3_visualize_measurements.ipynb	reorg t1-t5
4_ml_coverage_map.ipynb	Adding Sionna RT generated sparse measurements.
5_scene_nist_28ghz_boulder.ipynb	reorg t1-t5

Duke ENGINEERING Oregon State University Yale

➢ Y. Li, Z. Li, Z. Gao, and T. Chen, "Geo2SigMap: High-Fidelity RF Signal Mapping Using Geographic Databases," in *Proc. IEEE DySPAN'24*, 2024.

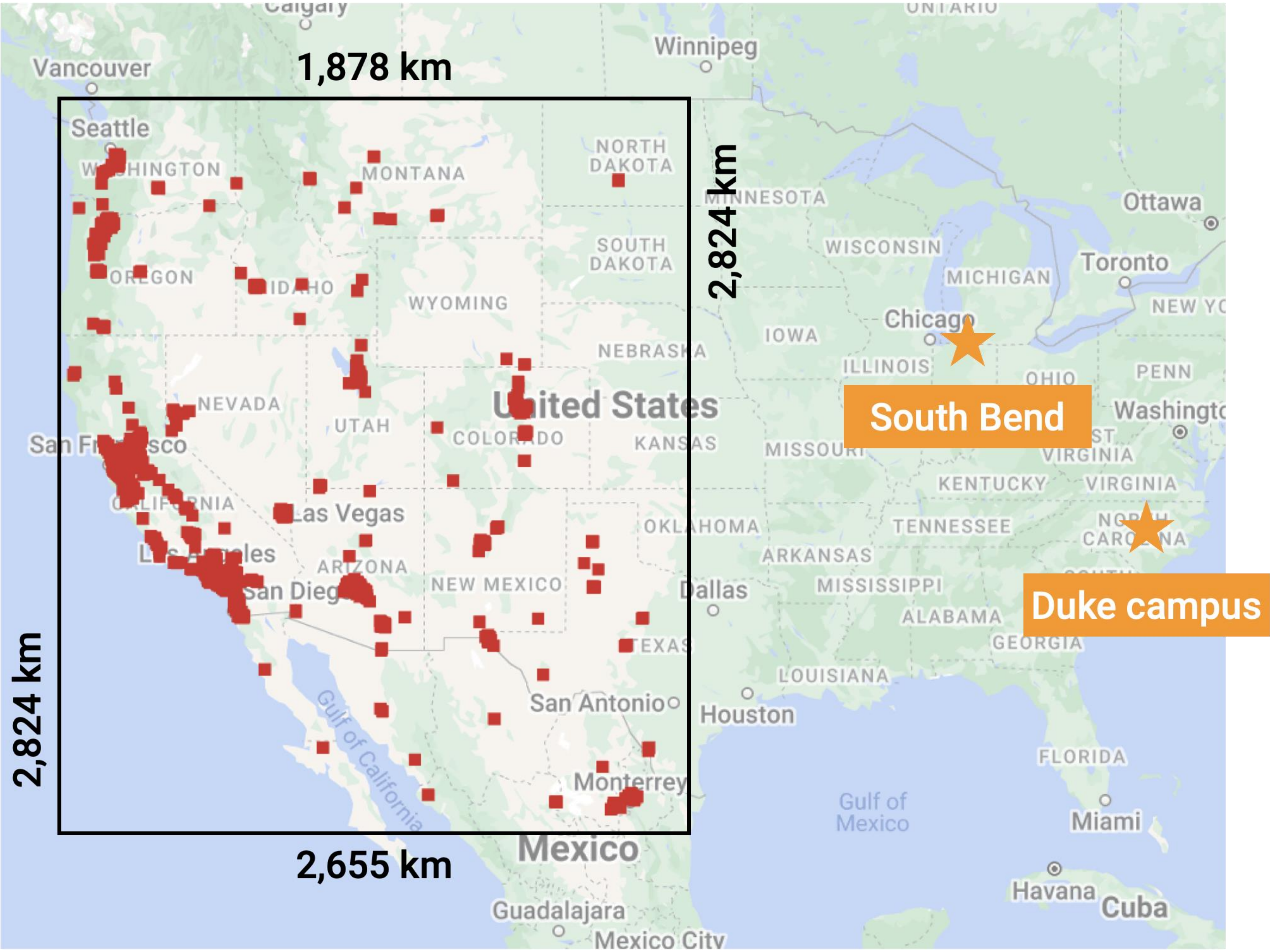
➢ Project website: https://functions-lab.github.io/projects/geo2sigmap/

Geo2SigMap: ML-based Signal Mapping

- No overlapped area between the **training set** (Sionna RT) and (RT simulation) and **testing set** (CBRS measurements)!

- **Model training**
  - Dataset: ~27K areas, ~140K path gain (PG) maps
  - Loss function: MSE between the ground truth and the predicted PG maps
  - Training/validation split ratio of 0.8/0.2
  - Model size: ~31M params

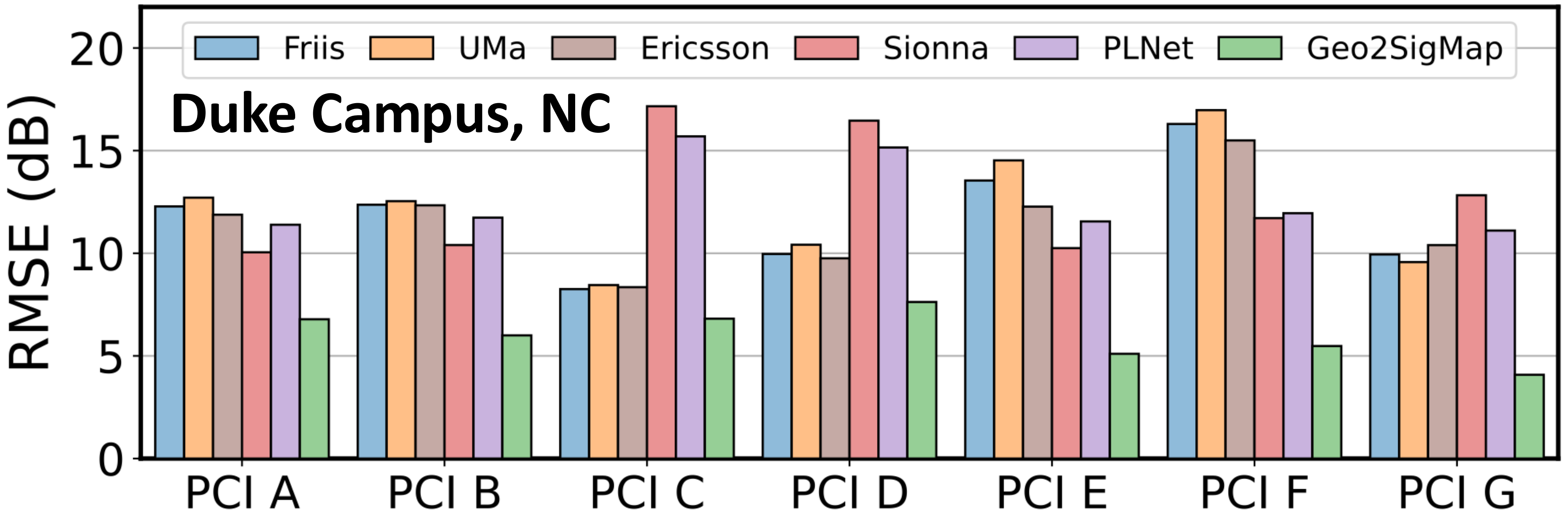
- **Model evaluation**
  - ~57K CBRS measurements collected on the Duke campus, NC, across 7 PCIs
  - ~21K CBRS measurements collected in the South Bend school district, IN, across 10 PCIs



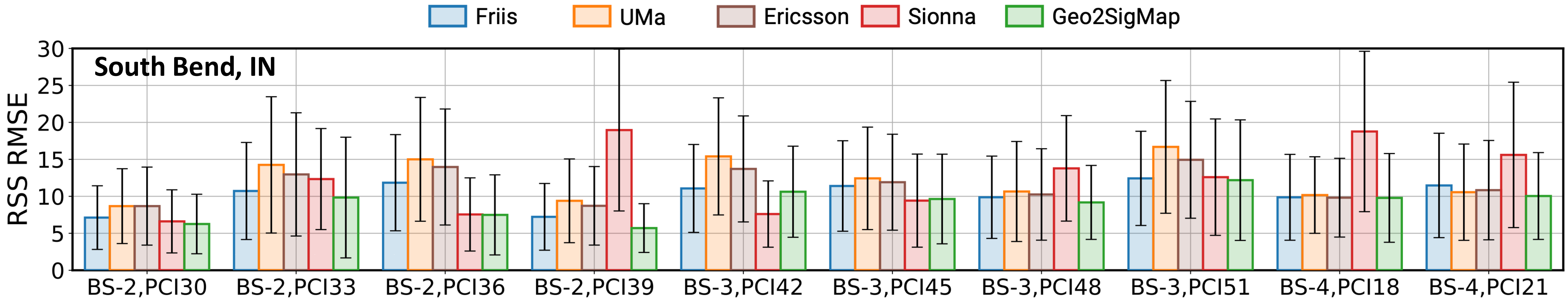
➢ Y. Li, Z. Li, Z. Gao, and T. Chen, "Geo2SigMap: High-Fidelity RF Signal Mapping Using Geographic Databases," in *Proc. IEEE DySPAN'24*, 2024.
➢ Y. Li, Z. Gao, J. Palathinkal, M. Ghosh, and T. Chen, "A Generalized Deep Learning Model for Signal Coverage Prediction in the CBRS Band," in *Proc. IEEE DySPAN'25*, 2025.

Geo2SigMap: ML-based Signal Mapping

- Baselines (w/ calibration applied)
  - **Friis** free space PG model
  - 3GPP urban macro (**UMa**) channel model
  - **Ericsson** channel model
  - "Vanilla" **Sionna RT**
  - **PLNet** with Volcano 5G & model re-training [*KDD'20*]
- Metric: Root mean square error (RMSE) for RSRP



Geo2SigMap achieves an RMSE of 7.1 dB for predicting RF signal coverage, outperforming existing methods by 4.0 dB



Geo2SigMap always achieves top-3 performance on both the median error and the 90th percentile for RSRP prediction

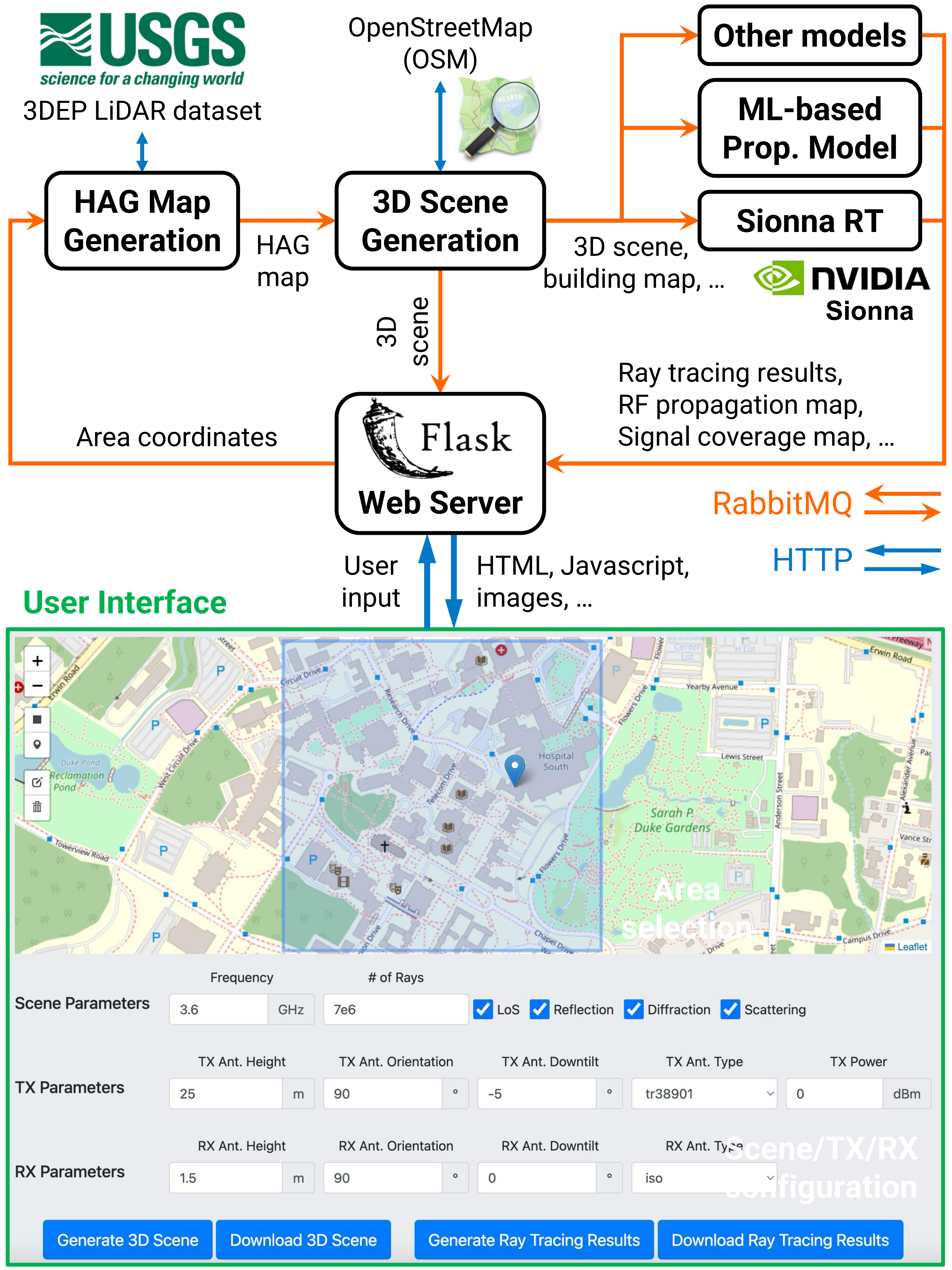
Duke ENGINEERING Oregon State University Yale

➢ Y. Li, Z. Li, Z. Gao, and T. Chen, "Geo2SigMap: High-Fidelity RF Signal Mapping Using Geographic Databases," in *Proc. IEEE DySPAN'24*, 2024.
➢ Y. Li, Z. Gao, J. Palathinkal, M. Ghosh, and T. Chen, "A Generalized Deep Learning Model for Signal Coverage Prediction in the CBRS Band," in *Proc. IEEE DySPAN'25*, 2025.

ClickDT: Building Wireless DTs with a Few Clicks

- Five key modules communicated via **HTTP** and **RabbitMQ**
  - Web-based UI with an embedded map
  - Flask web server
  - Height-above-ground (HAG) map generation
  - 3D scene generation and rendering
  - RF propagation modeling (e.g., Sionna RT, Geo2SigMap)
- Integration of a **nation-wide USGS LiDAR dataset**
  - Cross-validation of building info with OSM
- Direct **export of 3D scenes and detailed RT results**
  - Detailed scene objects and rays information
- Easy **integration of other RF propagation models**

- … to be released in Geo2SigMap v2.0 (Fall 2025)



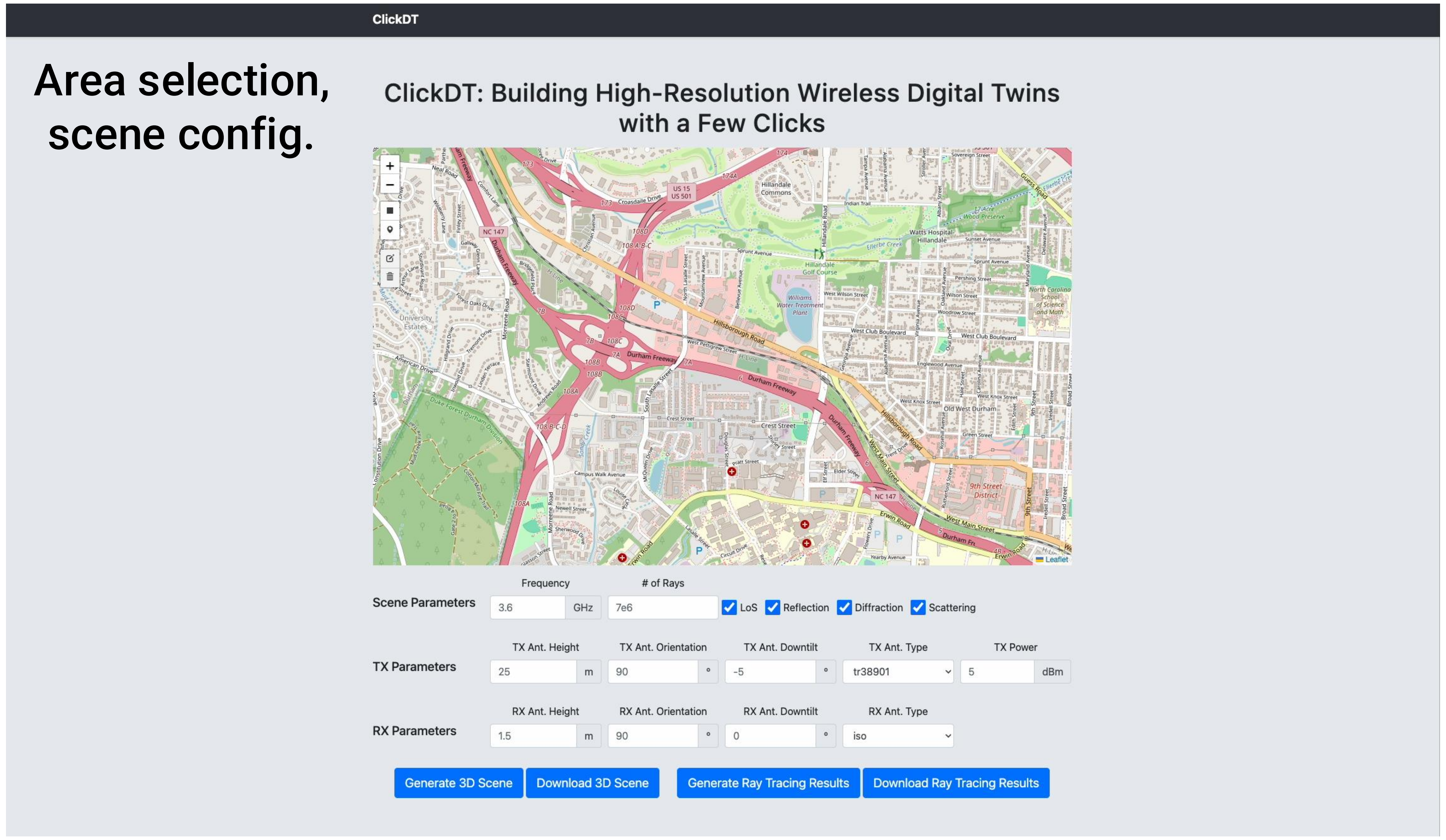
Duke ENGINEERING | Oregon State University | Yale

- Y. Li, S. Francini, Z. Gao, and T. Chen, "Demo: ClickDT: Building Scalable and High-Resolution Wireless Digital Twins with a Few Clicks," in *Proc. IEEE MILCOM'25*, 2025.
- Project website: https://functions-lab.github.io/projects/geo2sigmap/

ClickDT: Building Wireless DTs with a Few Clicks

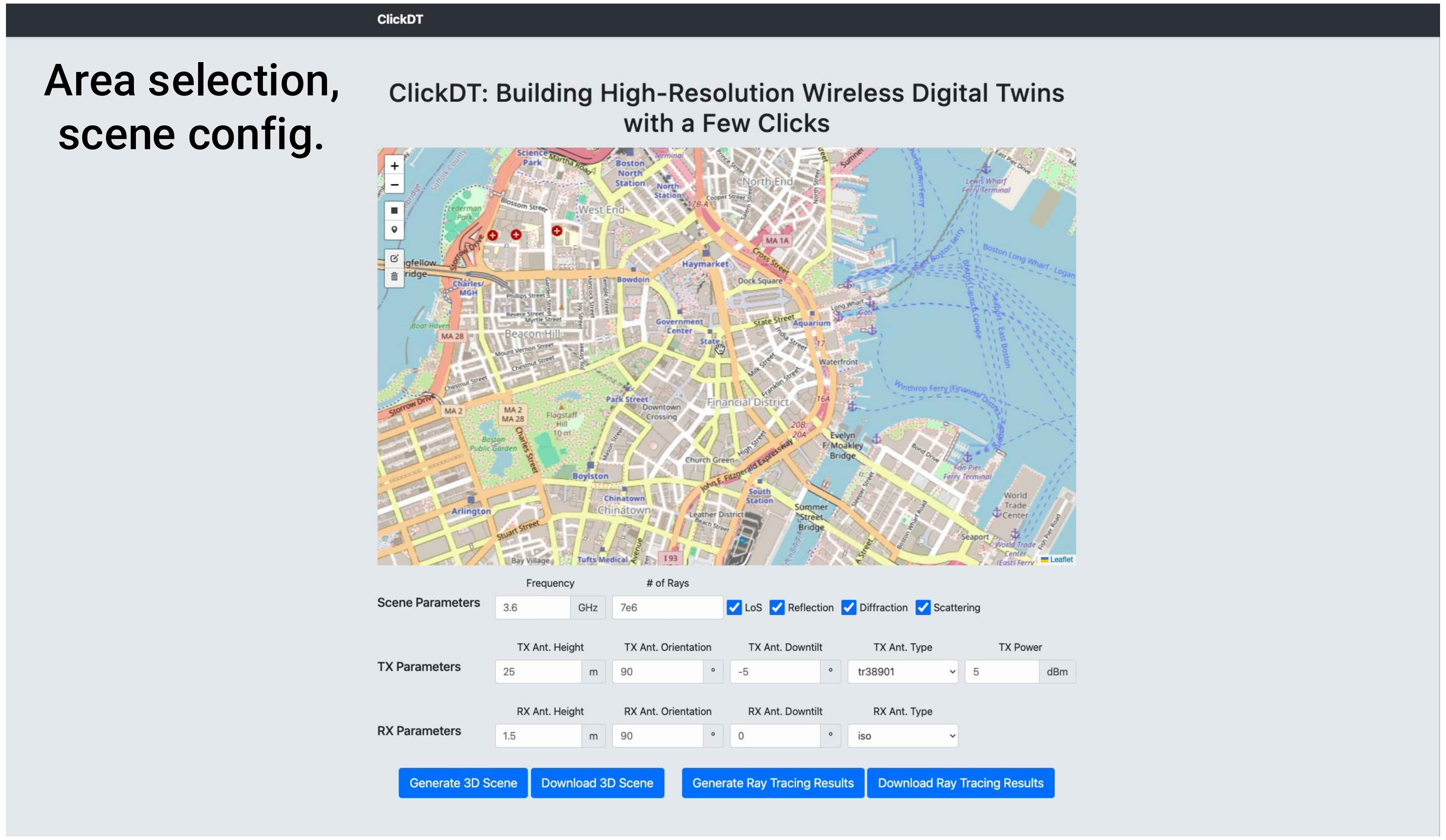
... to continue in NewSpectrum

Duke West campus



3D scene | Sionna RT output | Geo2SigMap output

Downtown Boston



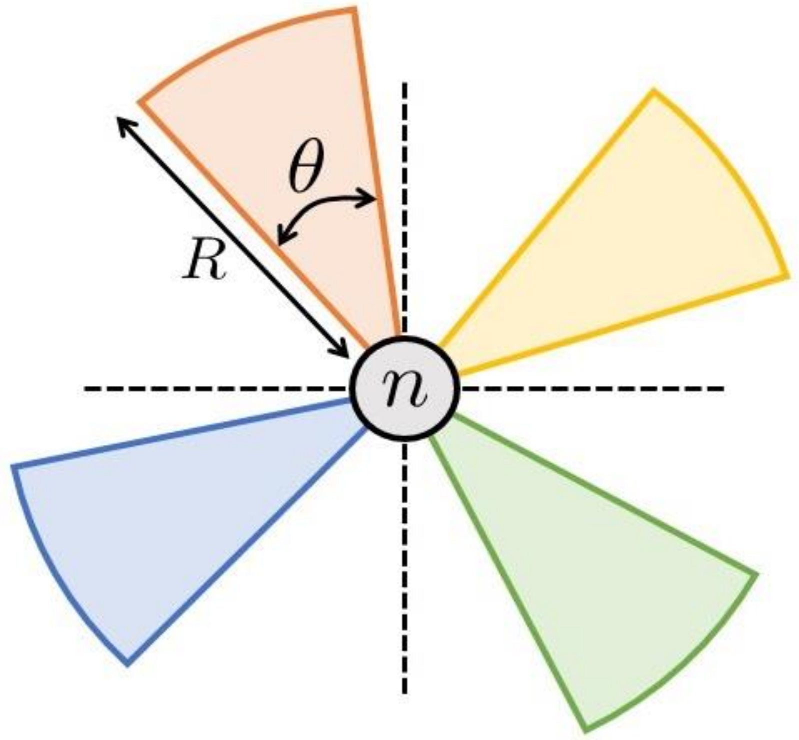
3D scene | Sionna RT output | Geo2SigMap output

Duke ENGINEERING | Oregon State University | Yale

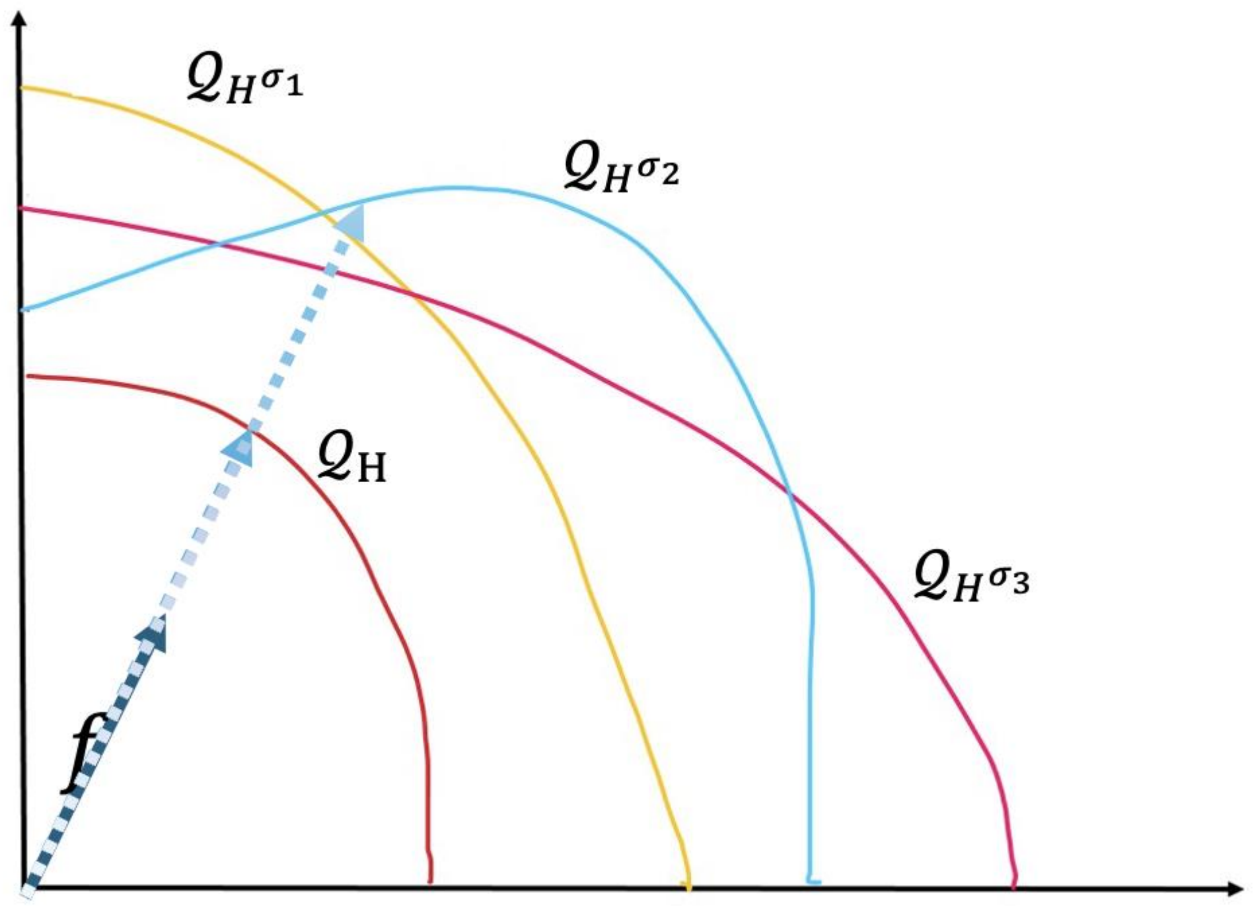
- Y. Li, S. Francini, Z. Gao, and T. Chen, "Demo: ClickDT: Building Scalable and High-Resolution Wireless Digital Twins with a Few Clicks," in *Proc. IEEE MILCOM'25*, 2025.
- Project website: https://functions-lab.github.io/projects/geo2sigmap/

Scheduling & Resource Allocation in **Sectorized** Wireless Networks

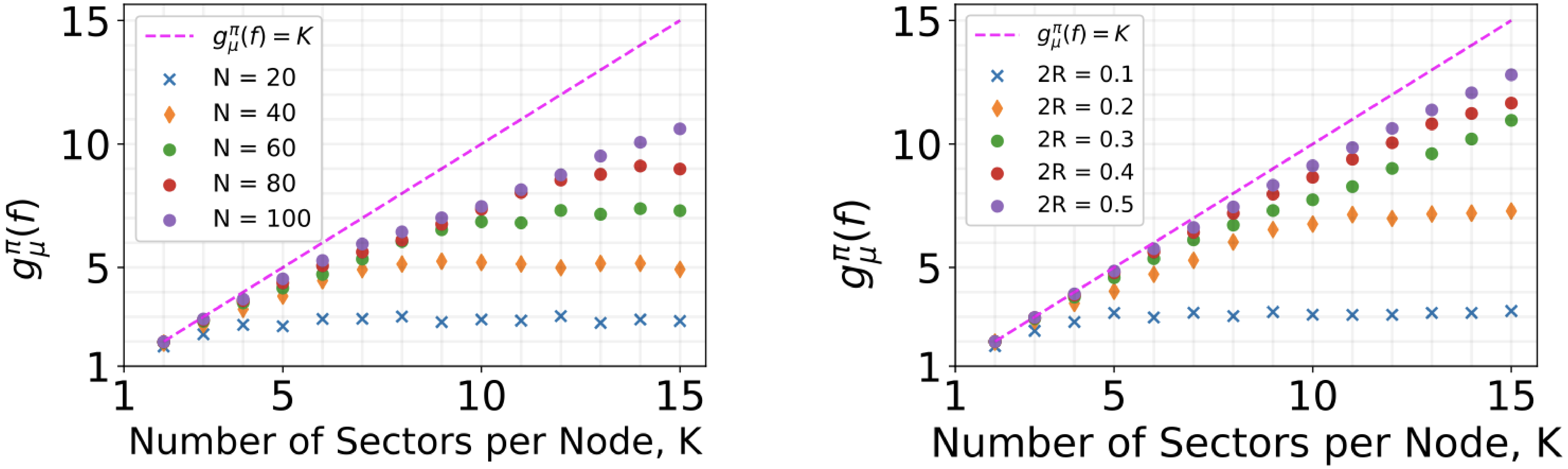
- **Capacity region characterization** of sectorized wireless networks
- **A distributed approximation algorithm** that optimizes the sectorization of each node under a network flow with performance guarantees
- In case one can (periodically) change the sectorization depending on the network condition, we proposed a **throughput-optimal joint routing, scheduling, and sectorization policy**



Dynamic sectorization of an infrastructure node



Different sectorization results in different throughput regions



Network capacity increases sub-linearly with increased number of sectors

Duke ENGINEERING Oregon State University Yale

- P. Promponas, T. Chen, and L. Tassiulas, "Optimizing sectorized wireless networks: Model, analysis, and algorithm." in *Proc. ACM MobiHoc'23*. 2023.
- P. Promponas, T. Chen, and L. Tassiulas, "On the Optimization and Stability of Sectorized Wireless Networks," *IEEE/ACM Transactions on Networking*, July 2025.

Publications and References (a partial list)

Novel receiver front ends and analog computing circuits

- A. Undavalli, K. Rashed, G. Cauwenberghs, S. Chakrabartty, A. Natarajan, and A. Nagulu, “A 4GS/s Fully Analog 256×256 MP-Based Cross-Correlator with 1000 TOPS/W Compute Efficiency and 1.3 TOPS/mm^2 Compute Density in 22nm SOI CMOS,” in *Proc. IEEE ISSCC’25*, 2025.
- K. Rashed, A. Undavalli, S. Chakrabartty, A. Nagulu, and A. Natarajan, “A Scalable and Instantaneously Wideband RF Correlator Based on Margin Computing,” *IEEE Journal of Solid-State Circuits*, 2024.
- S. Gupta, S. Krishnamurthy, A. Ravi, O. Degani, and A. Natarajan, “A Channel-Selective, Bandwidth-Reconfigurable Wideband Low Noise Amplifier with Dual-Frequency N-Path Filters,” in *Proc. IEEE Radio & Wireless Week (RWW’26)*, 2026.

Spectrum monitoring techniques and systems

- Z. Gao, Y. Chen, and T. Chen, “Swirls: Sniffing Wi-Fi Using Radios with Low Sampling Rates,” in *Proc. ACM MobiHoc’23*, 2023.
- Z. Gao, Y. Zhang, and T. Chen, “DeepMon: Wi-Fi Monitoring Using Sub-Nyquist Sampling Rate Receivers with Deep Learning,” in *Proc. ACM ML4NextG’24*, 2024.
- W. Cheng, Z. Gao, and T. Chen, “SPEAR: Software-defined Python-Enhanced RFSoC for Wideband Radio Applications,” in *Proc. ACM WiNTECH’24*, 2024.
- W. Cheng, Z. Gao, J. Guajardo, H. Beshary, A. Niknejad, and T. Chen, “SPEAR+: Streaming-Based Multi-Channel SDR Implementation Using the RFSoC Platform,” in *Proc. MILCOM’25*, 2025.

Wireless digital twins and ML for signal (and interference) mapping

- Y. Li, Z. Li, Z. Gao, and T. Chen, “Geo2SigMap: High-Fidelity RF Signal Mapping Using Geographic Databases,” in *Proc. IEEE DySPAN’24*, 2024.
- Y. Li, Z. Gao, J. Palathinkal, M. Ghosh, and T. Chen, “A Generalized Deep Learning Model for Signal Coverage Prediction in the CBRS Band,” in *Proc. IEEE DySPAN’25*, 2025.
- Y. Li, S. Francini, Z. Gao, and T. Chen, “Demo: ClickDT: Building Scalable and High-Resolution Wireless Digital Twins with a Few Clicks,” in *Proc. IEEE MILCOM’25*, 2025.
- Code and measurements: https://functions-lab.github.io/projects/geo2sigmap/

Resource allocation, scheduling, and SDN

- A. Mudvari, K. Poularakis, and L. Tassiulas, “Robust SDN Synchronization in Mobile Networks Using Deep Reinforcement and Transfer Learning,” in *Proc. IEEE ICC’23*, 2023.
- P. Promponas, T. Chen, and L. Tassiulas, “Optimizing Sectorized Wireless Networks: Model, Analysis, and Algorithm.” in *Proc. ACM MobiHoc’23*, 2023.
- P. Promponas, T. Chen, and L. Tassiulas, “On the Optimization and Stability of Sectorized Wireless Networks,” *IEEE/ACM Transactions on Networking*, July 2025.

Duke ENGINEERING Oregon State University Yale

Thank You!

tingjun.chen@duke.edu

Tingjun Chen (PI), Arun Natarajan, Leandros Tassiulas

NSF SWIFT & NewSpectrum PI Meeting

Sept. 11, 2025

Duke ENGINEERING Oregon State University LUX ET VERITAS Yale NSF