

The COSMOS Testbed – a Platform for Advanced Wireless, Edge Cloud, Optical, and Smart Streetscapes Experimentation

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Electrical Engineering, Columbia University

The COSMOS testbed design and deployment is joint work with the COSMOS team (www.cosmos-lab.org).



COSMOS: Project Vision

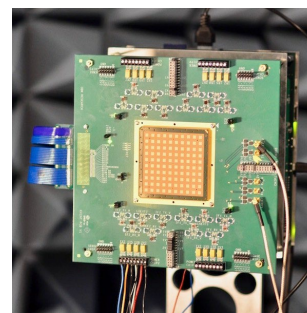
Cloud enhanced Open Software-defined MObile wireless testbed for city-Scale deployment

- **Latency** and **compute power** are two important dimensions and metrics
- **Edge computing** can enable real-time applications
- **Objective:** Real-world investigation of urban environments with
 - Ultra-high bandwidth (~Gbps)
 - Low latency (<5 ms)
 - Powerful edge computing
- **Enablers:**
 - 10s of 64-element millimeter-wave arrays
 - 10s of miles of Manhattan dark fiber
 - B5G edge cloud base stations
 - Remote-access
 - Programmability

Local Computing
(Device-Level Apps)

Edge Computing
(Streetscape Apps)

Cloud Computing
(Global Apps)



Ultra-high bandwidth, low latency, and powerful edge computing will enable new classes of real-time applications. Domains including AR/VR, connected cars, and smart streetscapes (with high-bandwidth sensing)

- D. Raychaudhuri, I. Seskar, G. Zussman, T. Korakis, D. Kilper, T. Chen, J. Kolodziejewski, M. Sherman, Z. Kostic, X. Gu, H. Krishnaswamy, S. Maheshwari, P. Skrimponis, and C. Gutterman, "Challenge: COSMOS: A city-scale programmable testbed for experimentation with advanced wireless," in *Proc. ACM MobiCom'20*, 2020.

COSMOS: Deployment Area

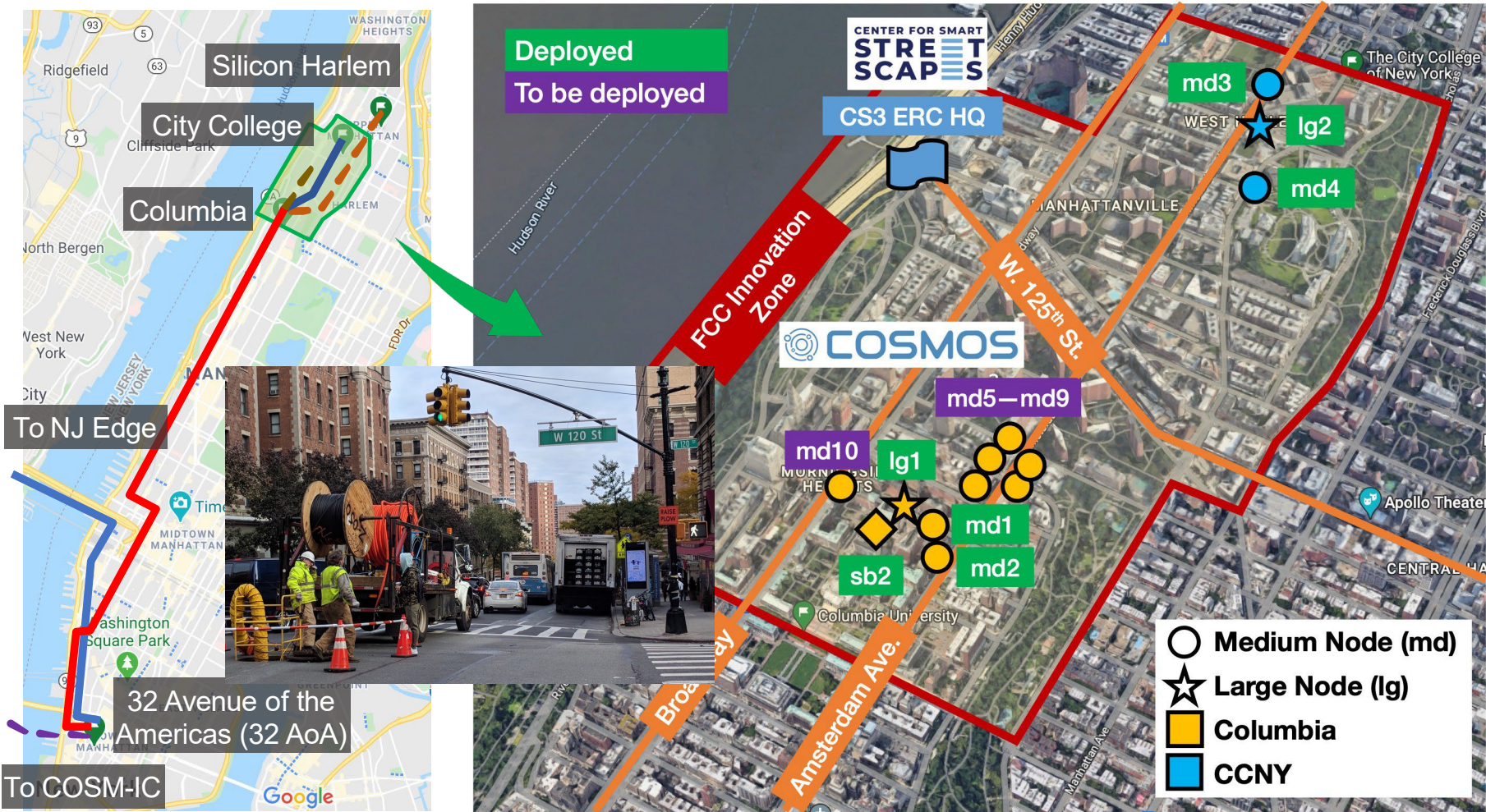


COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

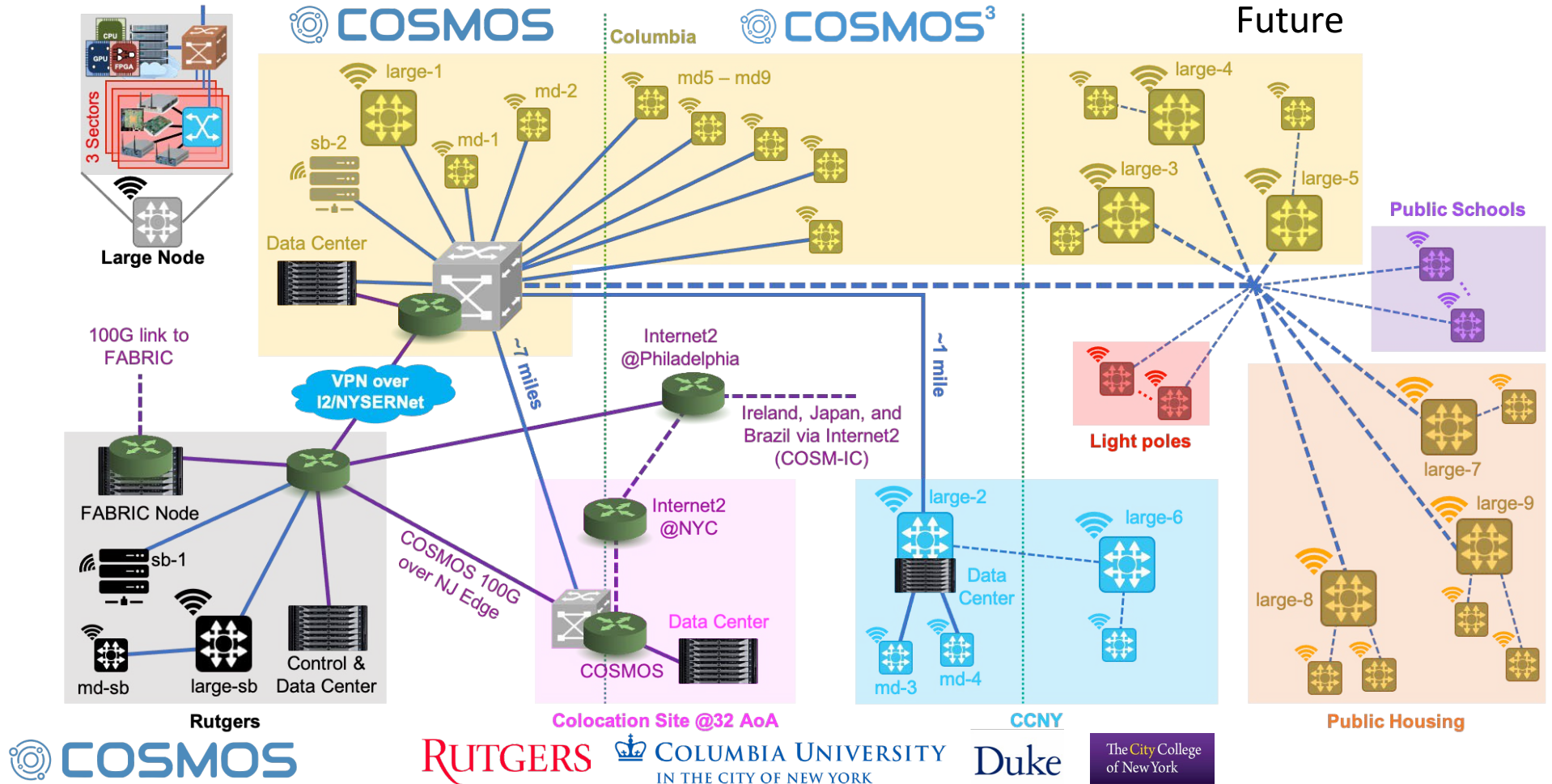
Duke

The City College
of New York

COSMOS: Deployment

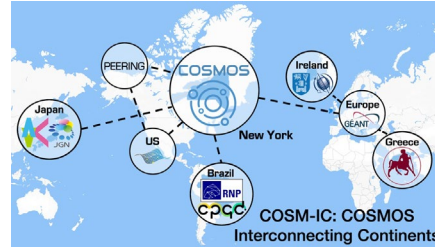


COSMOS: Envisioned Deployment

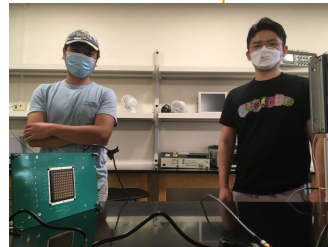
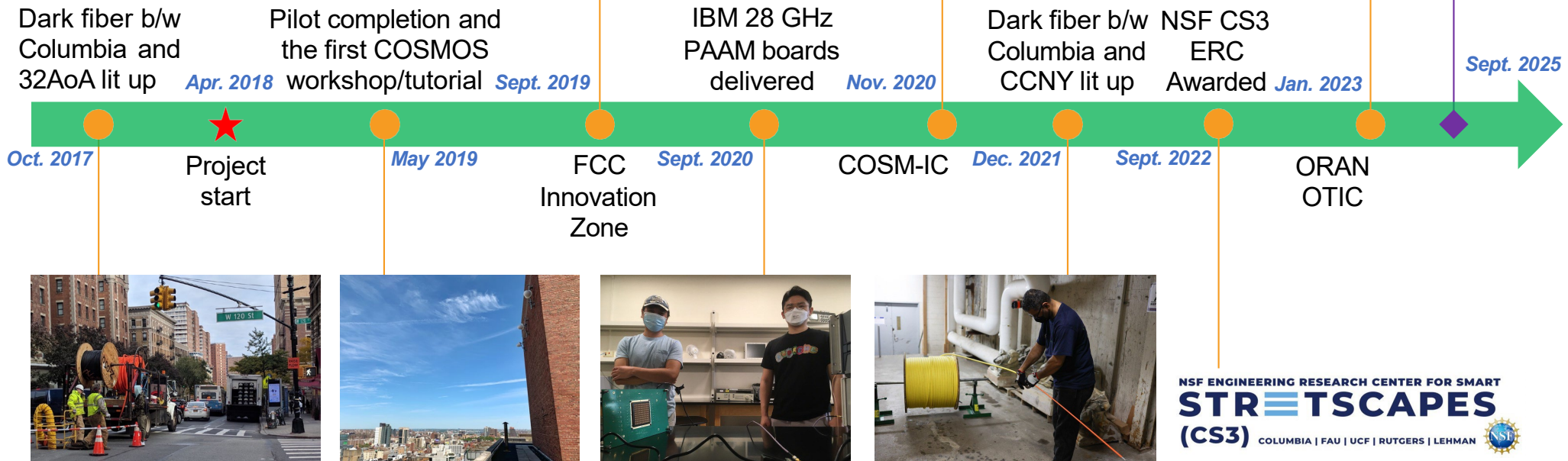


COSMOS: Project Timeline

 COSMOS³



 **ORAN**
ALLIANCE



NSF ENGINEERING RESEARCH CENTER FOR SMART
STREETSCAPES
(CS3) COLUMBIA | FAU | UCF | RUTGERS | LEHMAN 

 COSMOS

RUTGERS

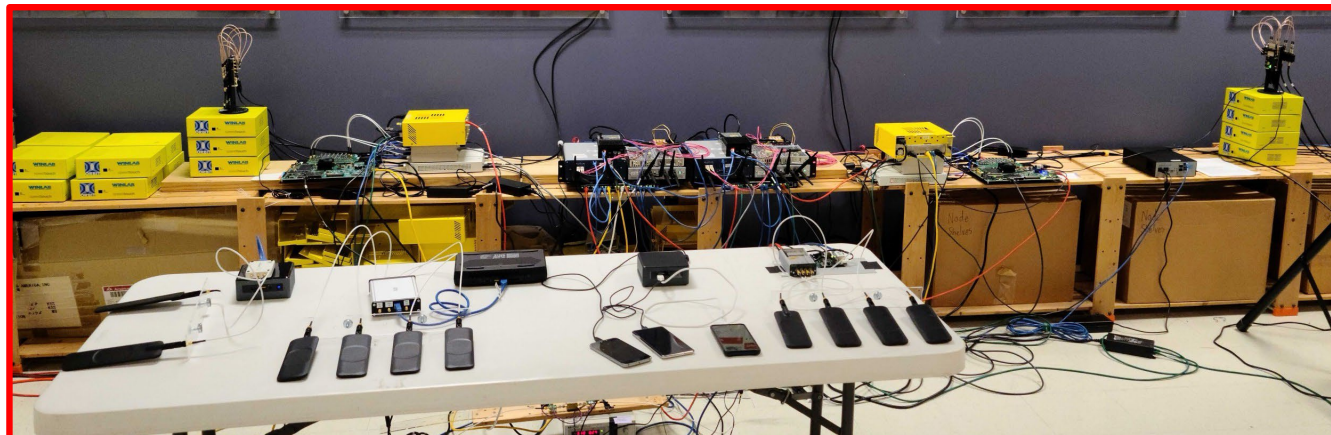
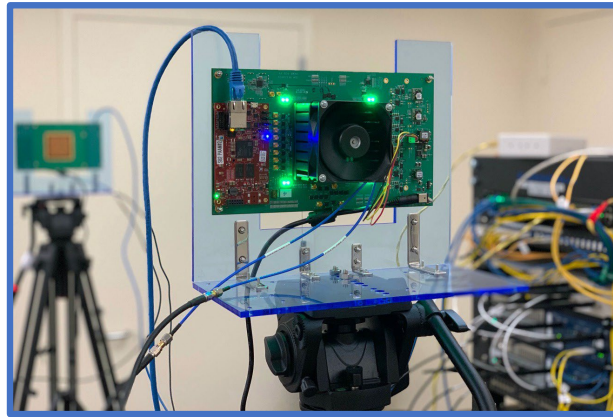
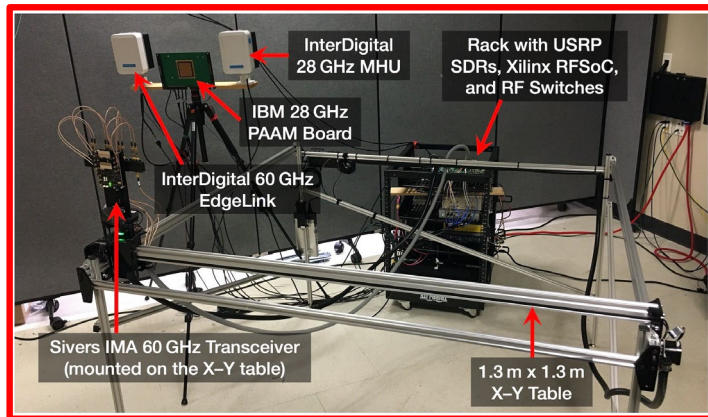
 COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Duke

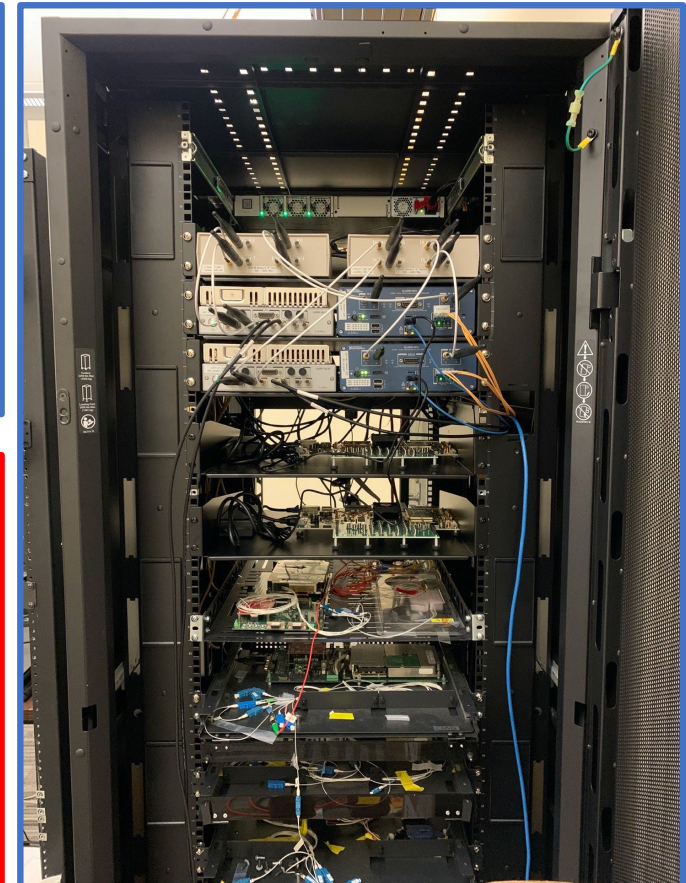
The City College
of New York



Rutgers and Columbia Sandboxes (sb1 and sb2)

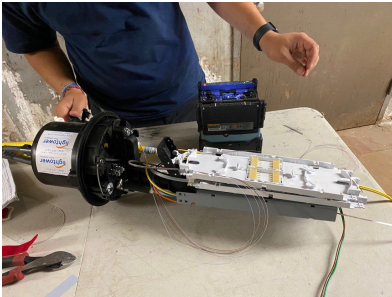
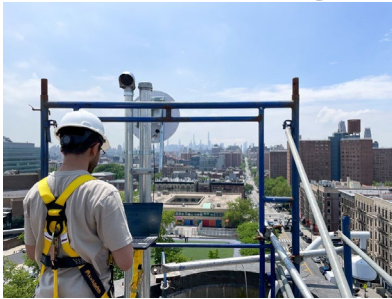


Sandbox1 (sb1) @Rutgers



Sandbox2 (sb2) @Columbia

CCNY Large and Medium Nodes (lg2 and md3)



COSMOS³ at a Glance

CIRC: GRAND/ENS: COSMOS3 — Enhancing and Sustaining the COSMOS Platform

The award

- NSF CIRC cooperative agreement 2450567
- Oct 2025 – Sep 2029; \$3.8M, fully obligated (July 2026)
- Community infrastructure for CISE: smart-city and spectrum-sharing research in a dense urban setting
- West Harlem FCC Innovation Zone

Rutgers / WINLAB

Lead; platform operations, radios, compute, portal
Ivan Seskar (PI), Dipankar Raychaudhuri

Columbia

West Harlem deployment, street cameras & analytics, quantum networking
Gil Zussman, Zoran Kostić

Duke

Digital twin, RF signal mapping, ISAC
Tingjun Chen

City College of New York, New York City

Deployment site partners

Headline targets committed to NSF

100+

active experimenter research groups

3 bands

FR1 / FR3 / FR2, 1 to 28 GHz

>10×

AI compute over the legacy A100 pod

20×

channel-sounding positions for the twin

100%

open documentation, tutorials, datasets

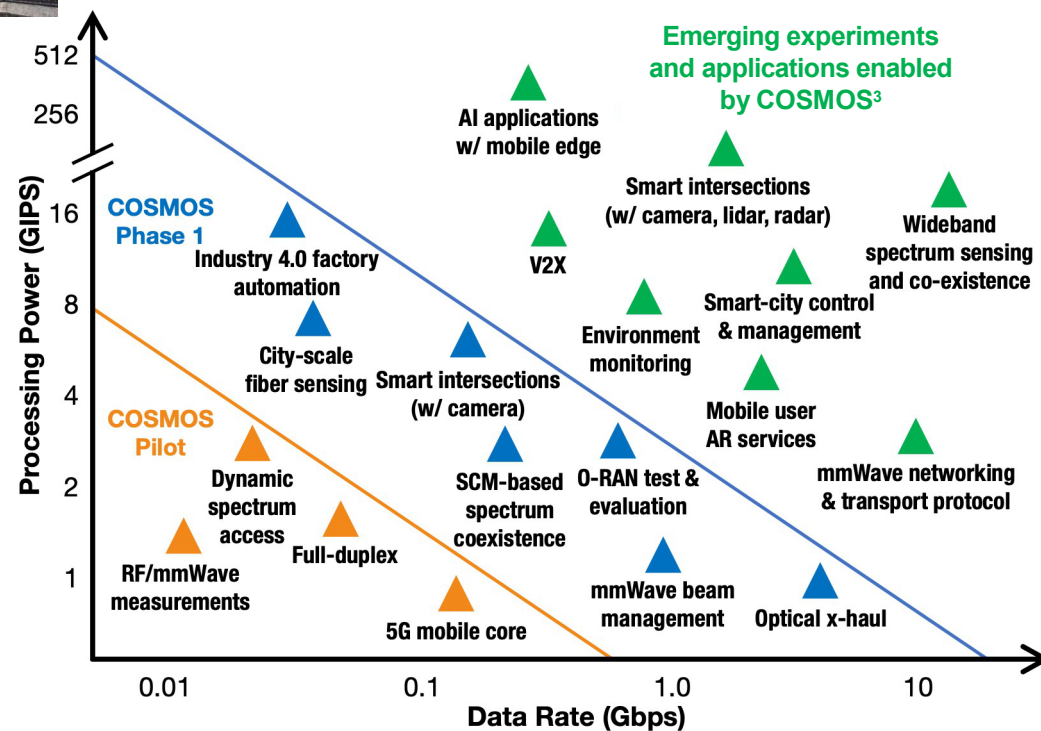


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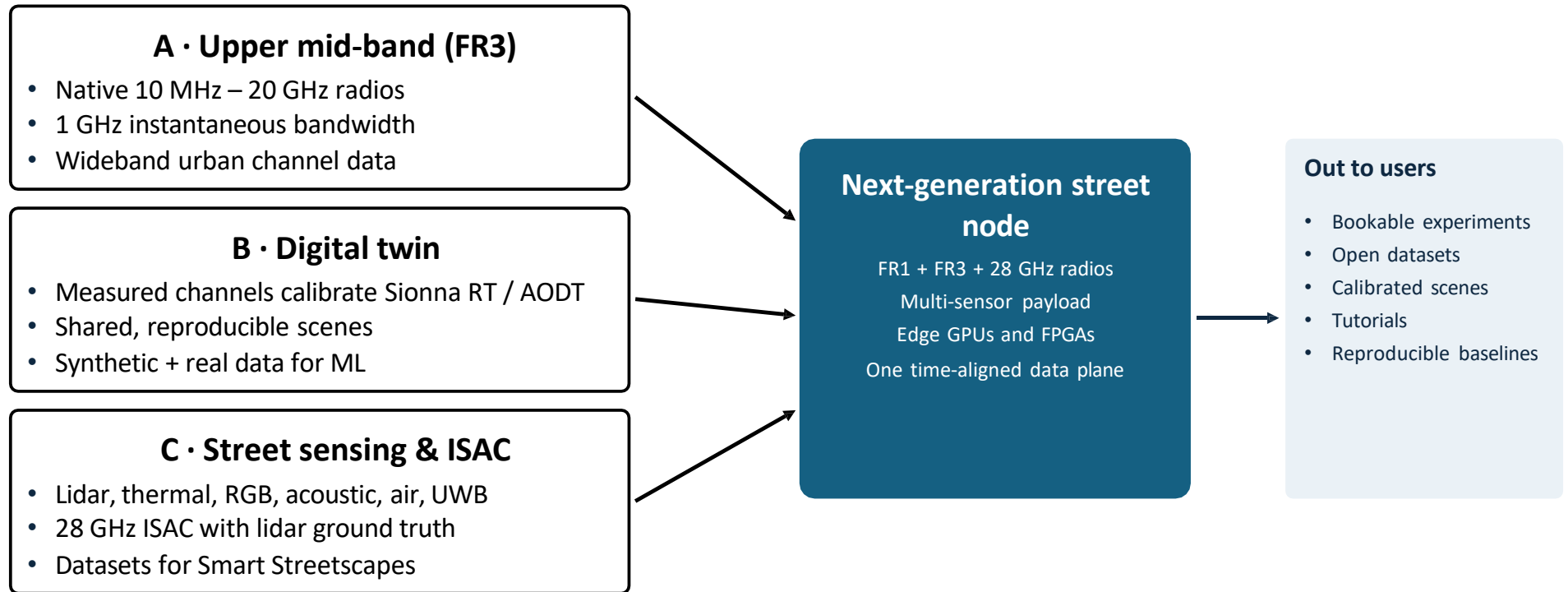
COSMOS → COSMOS³ (COSMOS Smart Streets)

CIRC: GRAND/ENS: COSMOS³: Enhancing and Sustaining the COSMOS Platform (2025–2029)



COSMOS³ - Three Threads, One Platform

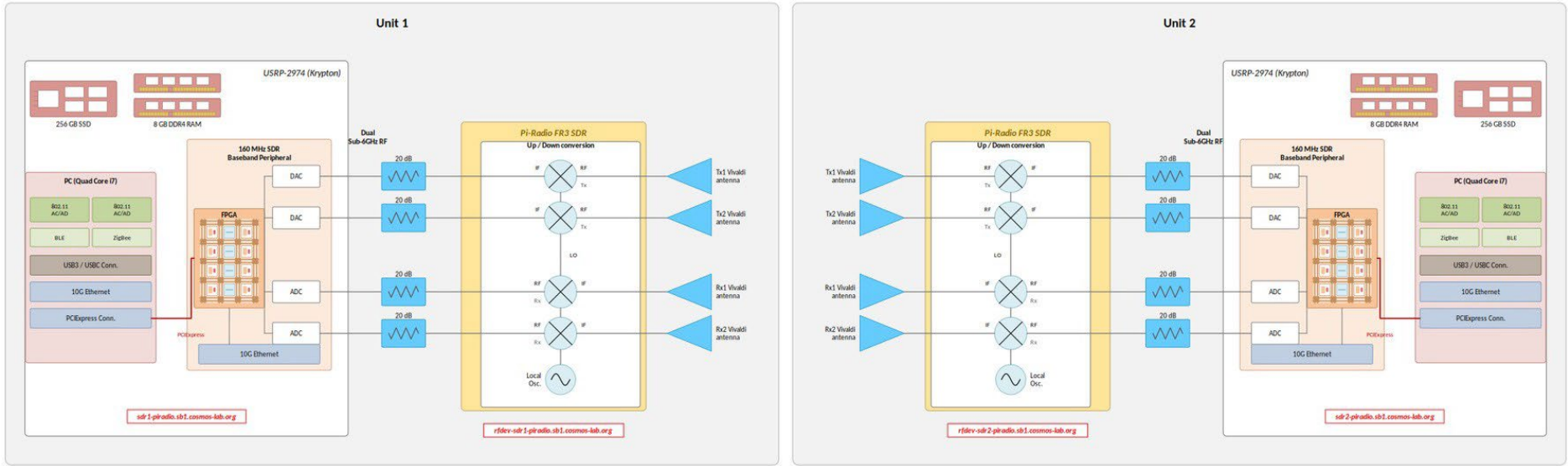
Where FR3, the digital twin and street-level sensing meet



FR3 Today: The SB1 Sandbox

Upper mid-band experimentation you can book now at sb1.cosmos-lab.org

Upper mid-band experimentation you can book now at sb1.cosmos-lab.org



TX / RX per unit, Pi-Radio
front ends on USRP-2974

wideband Vivaldi
antennas

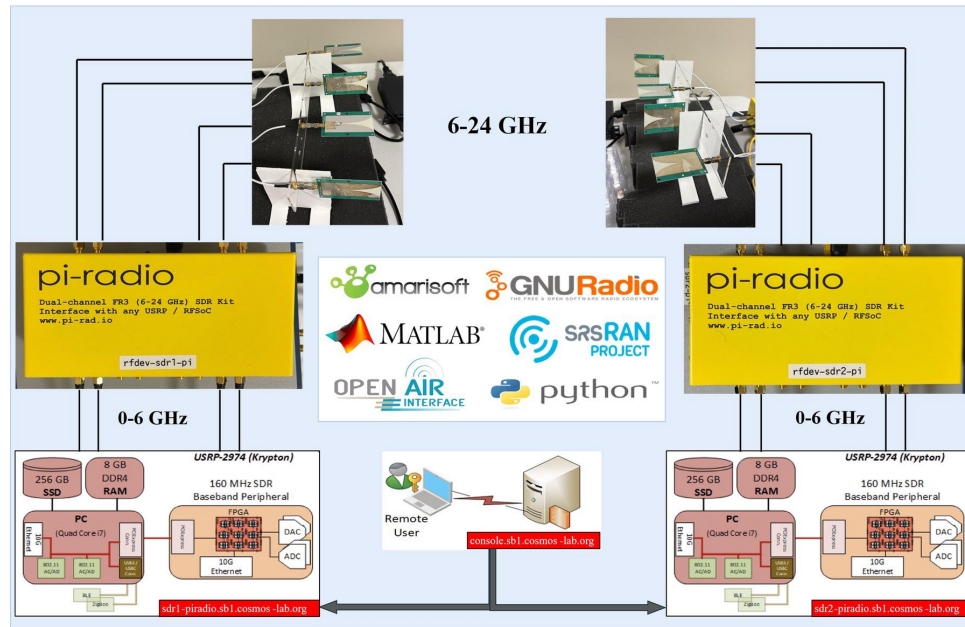
signalling bandwidth, precise gain and LO control

first links: 10–10.5 and 12.2–12.7 GHz

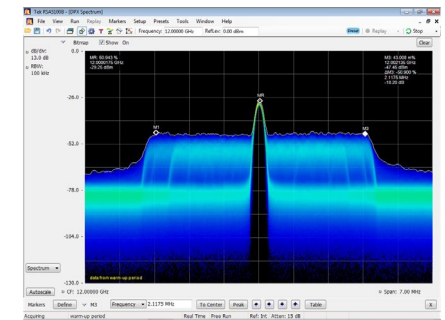
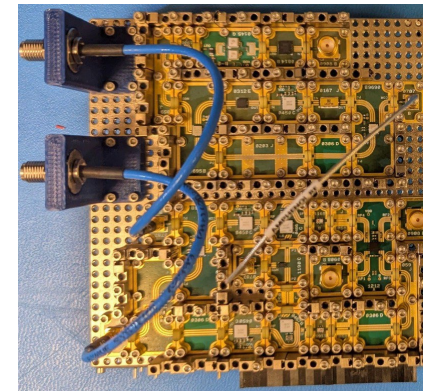
tutorials: sine, analog FM,
OFDM, full 5G (Amarisoft) over
FR3

FR3 Today: Hardware and First Signals

Pi-Radio integration in SB1 and an in-house heterodyne transceiver up to 24 GHz



Pi-Radio FR3 integration in the COSMOS SB1 domain, with the supported software stacks

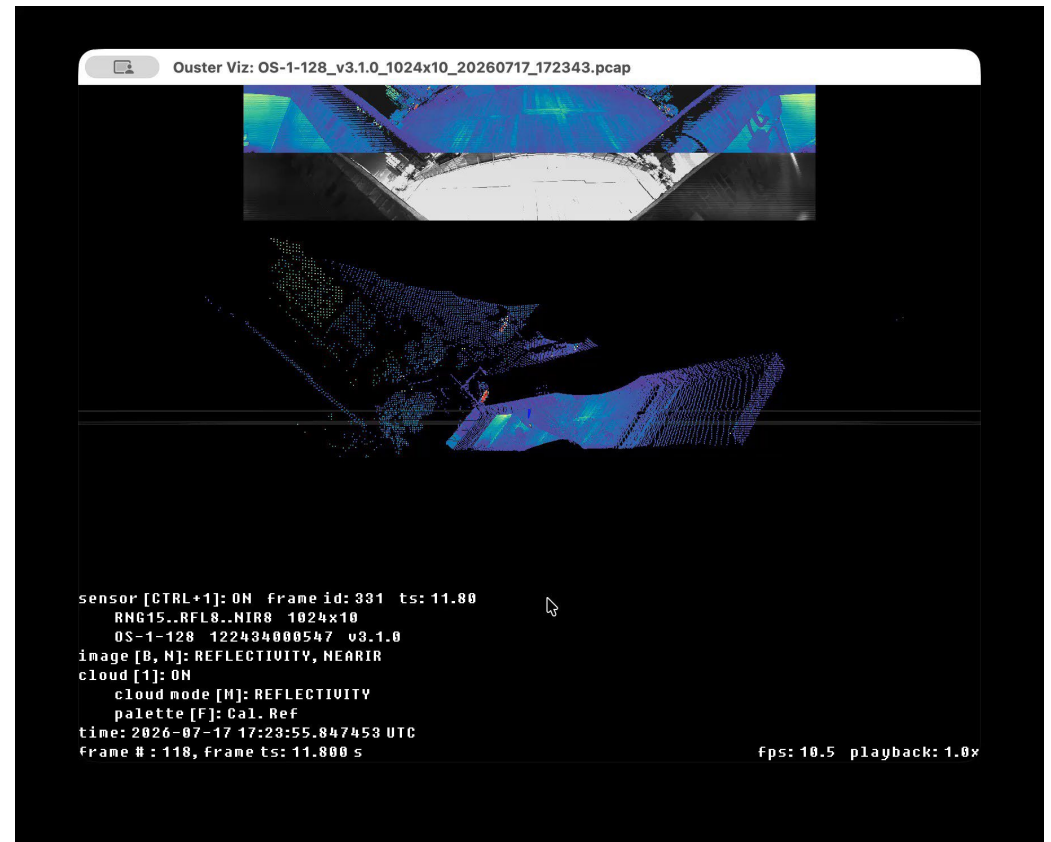


Heterodyne FR3 transceiver (left) · 5 MHz 5G signal at 12 GHz (right)

- Built and tested **up to 24 GHz**, filters optimized for 10–12 GHz
- Open to the global COSMOS user community: remote access, logging, documentation
- Supports 2x2 MIMO, OAI 5G links, O-RAN radio units and channel sounding

Lidar (deployed at md2 location)

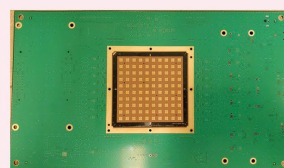
Model: Ouster-OS1-128



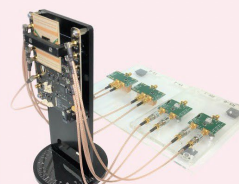
Key Technology: mmWave

- Programmable mmWave front ends with different baseband options:
 - IBM 28 GHz 64-element PAAMs
 - Integrated in Sandbox 1 and 2
 - Up to ~500 MHz bandwidth using the Xilinx UltraScale+ RFSoc platform
 - Experiment with adaptive beamforming and mmWave MIMO communications
 - Sivers IMA 60 GHz WiGig transceiver
- End-to-end mmWave systems:
 - Facebook Terragraph 60 GHz radios
 - InterDigital 28 GHz 5G NR platform
 - InterDigital 60 GHz EdgeLink nodes

Millimeter-Wave Front Ends



IBM 28 GHz Phased Array Antenna Module (PAAM)



Sivers IMA 60 GHz Phased Array

SDR and Baseband



USRP 2974



USRP B210



USRP N310



Xilinx RFSoc

End-to-End Systems



InterDigital 28 GHz 5G NR Platform



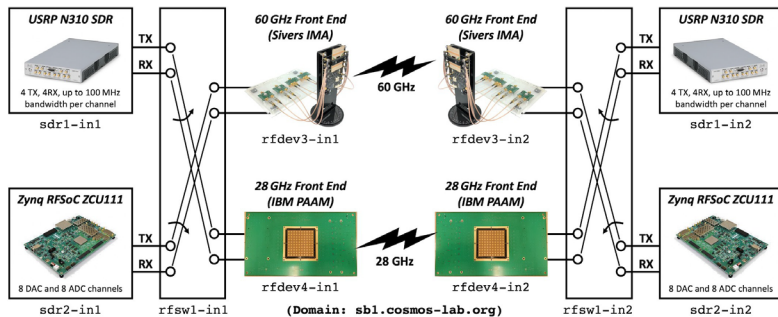
InterDigital 60 GHz EdgeLink Node



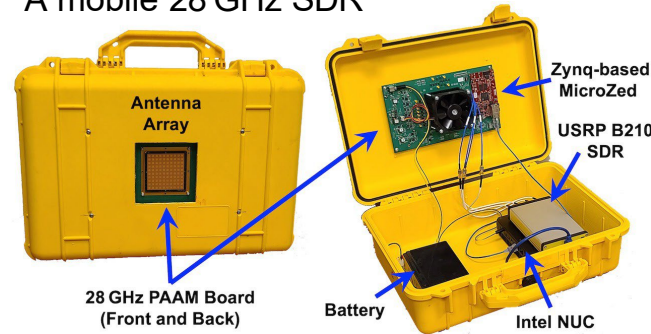
Facebook 60 GHz Terragraph Radio

- T. Chen, P. Maddala, P. Skrimponis, J. Kolodziejcki, X. Gu, A. Paidimarri, S. Rangan, G. Zussman, and I. Seskar, "Programmable and open-access millimeter-wave radios in the PAWR COSMOS testbed," in *Proc. ACM MobiCom'21 Workshop on Wireless Network Testbeds, Experimental evaluation & CHaracterization (WinTECH'21)*, 2021.
- X. Gu, A. Paidimarri, B. Sadhu, C. Baks, S. Lukashov, M. Yeck, Y. Kwark, T. Chen, G. Zussman, I. Seskar, and A. Valdes-Garcia, "Development of a compact 28-GHz software-defined phased array for a city-scale wireless research testbed," in *Proc. IEEE International Microwave Symposium (IMS'21)*, 2021. **Finalist of IMS'21 Advanced Practice Paper Competition (APPC)**

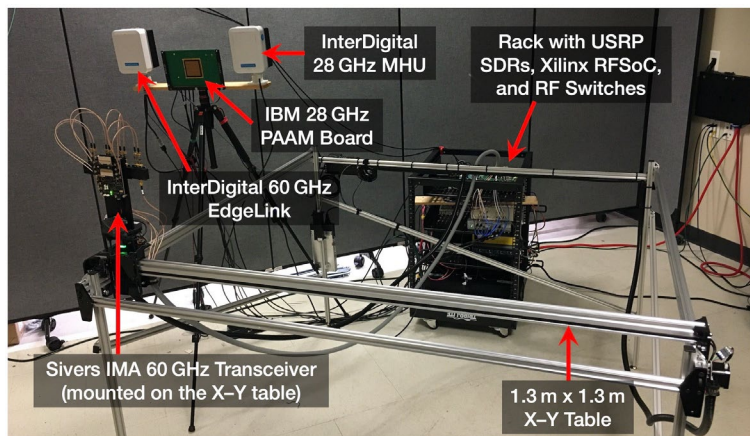
COSMOS' mmWave SDRs



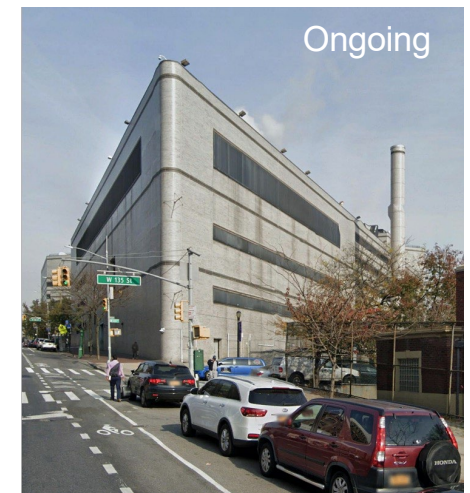
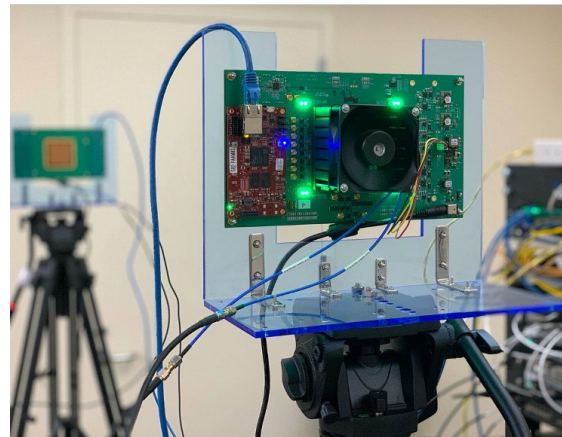
A mobile 28 GHz SDR



A medium node with two 28 GHz SDRs



Indoor deployment at Rutgers (sb1) and Columbia (sb2)



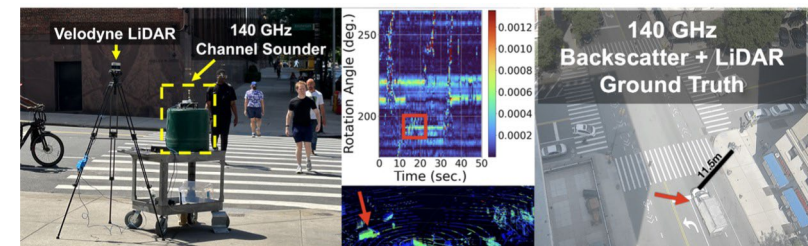
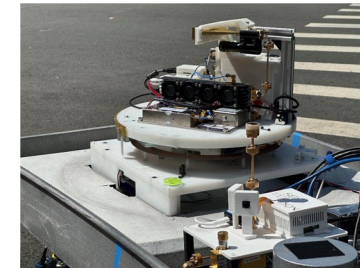
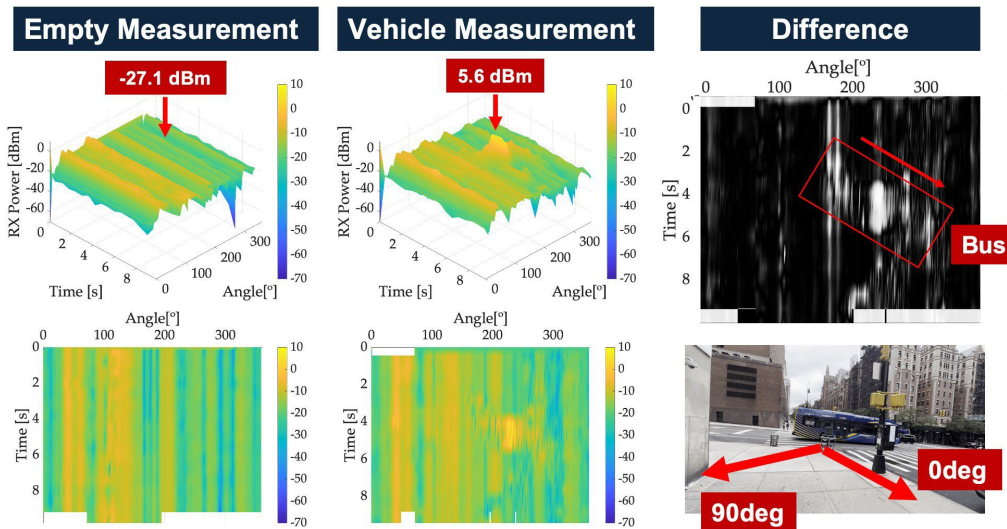
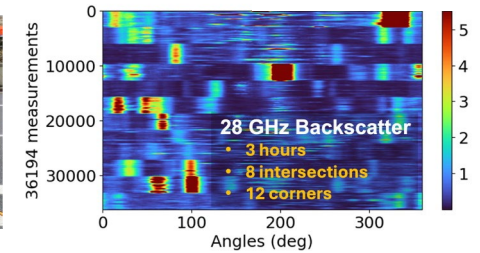
Outdoor deployment at CCNY

- T. Chen, P. Maddala, P. Skrimponis, J. Kolodziejski, A. Adhikari, H. Hu, Z. Gao, A. Paidimarri, A. Valdes- Garcia, S. Rangan, G. Zussman, and I. Seskar, "Programmable and Open-Access Millimeter-Wave Radios in the COSMOS Testbed: Design, Deployment, and Experimentation," *Computer Networks (COMNET)* (invited), vol. 234, pp. 109922, Oct. 2023.

28GHz and 140 GHz ISAC

- **Motivation:** Beyond-5G and 6G Integrated Sensing and Communication (ISAC)
- Use 28 GHz and 140 GHz channels to opportunistically sense backscatter from vehicles, pedestrians, buildings, and lightpoles.

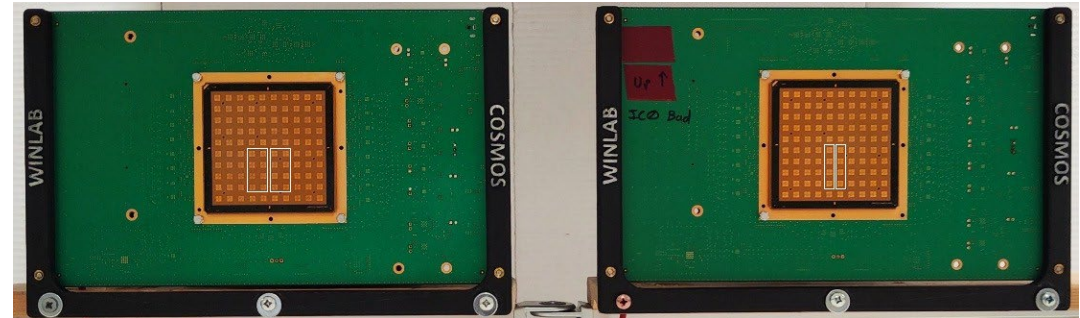
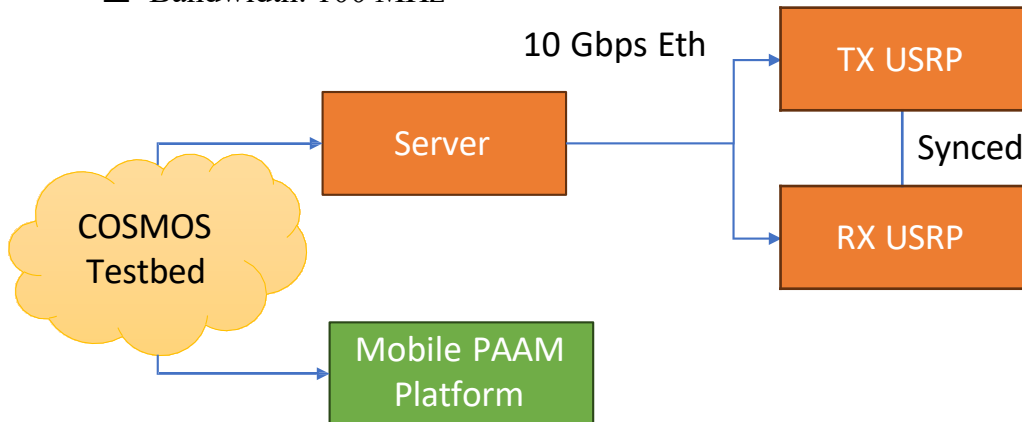
NOKIA
Bell Labs



Bell Labs 140 GHz Channel Sounder

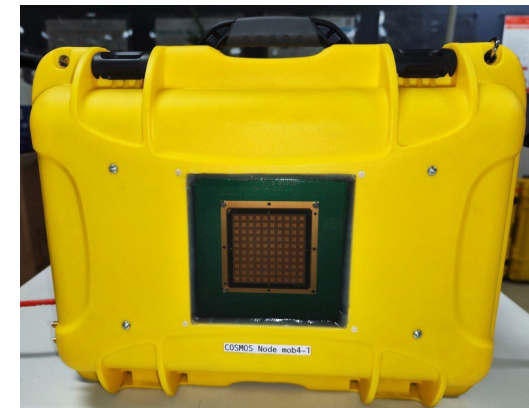
Integrated Sensing and Communication (ISAC) Experimental Setup

- ❑ Radar
 - ❑ 2× NI USRP-2974
 - ❑ 2× IBM 28 GHz 64-Element Phased Array Antenna Modules (PAAMs)
 - ❑ Common clock and LO reference
- ❑ Communication Receiver
 - ❑ NI USRP-2974
 - ❑ IBM 28 GHz Phased Array Antenna Module (PAAM)
 - ❑ Mobile platform
- ❑ Parameters
 - ❑ Carrier Frequency: 28 GHz
 - ❑ Bandwidth: 100 MHz



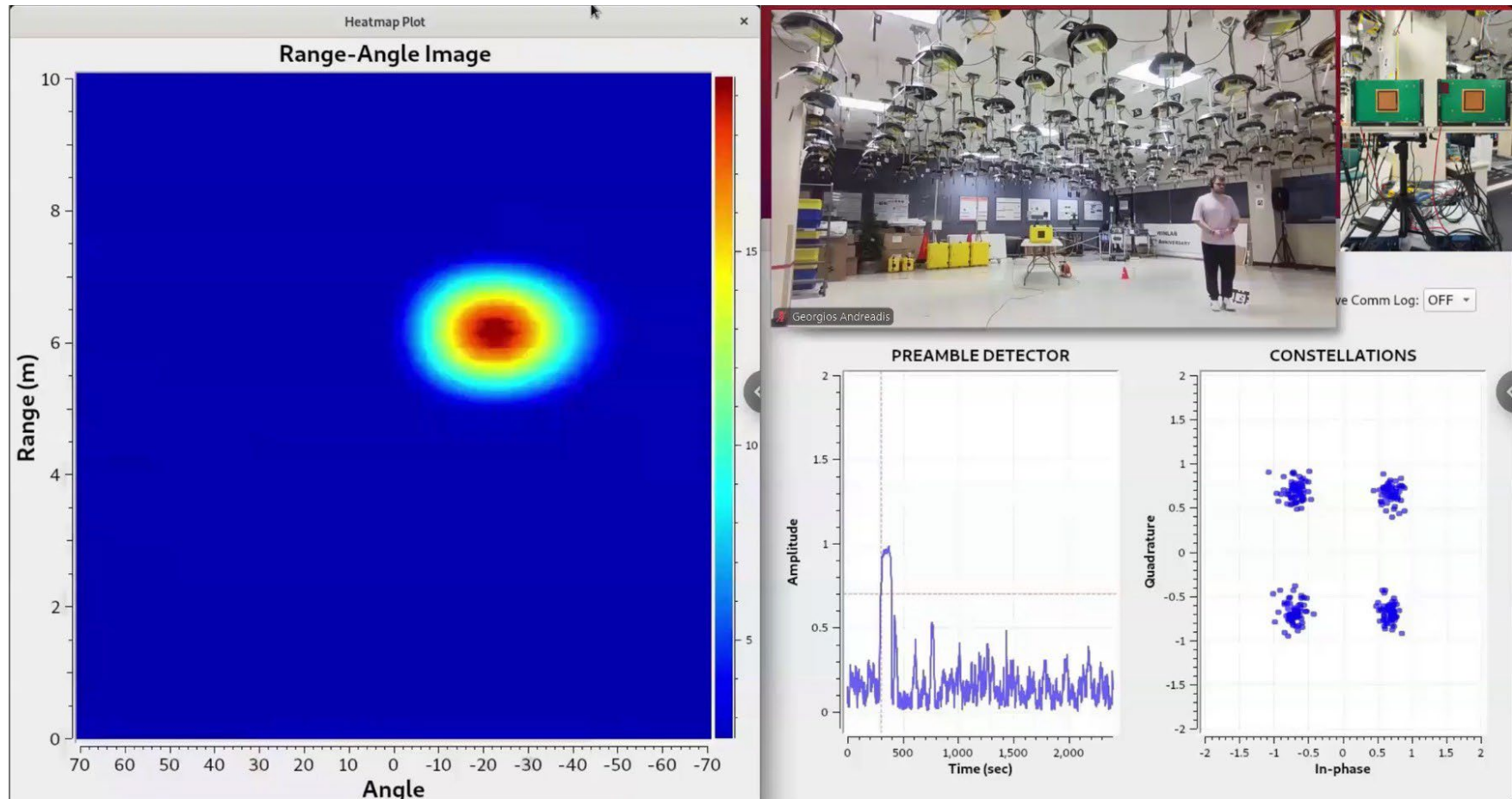
Radar RX PAAM
2 RF Chains
8 elements each

Radar TX PAAM
2 RF Chains
4 elements each



Communication RX PAAM
1 RF Chain with 64 elements

Demo Video



Geo2SigMap: Tools, Datasets, and Tutorials

- v1.0 (released 2025/02): The *first* fully open-sourced, scalable pipeline for building wireless DTs
 - CLI tool + Python API for 3D scene generation of *arbitrary areas of interest*
 - *Seamless integration* of the generated 3D scenes with NVIDIA's Sionna RT and AODT
 - Downstream tasks: comparison with real-world measurements, integration with deep learning models,

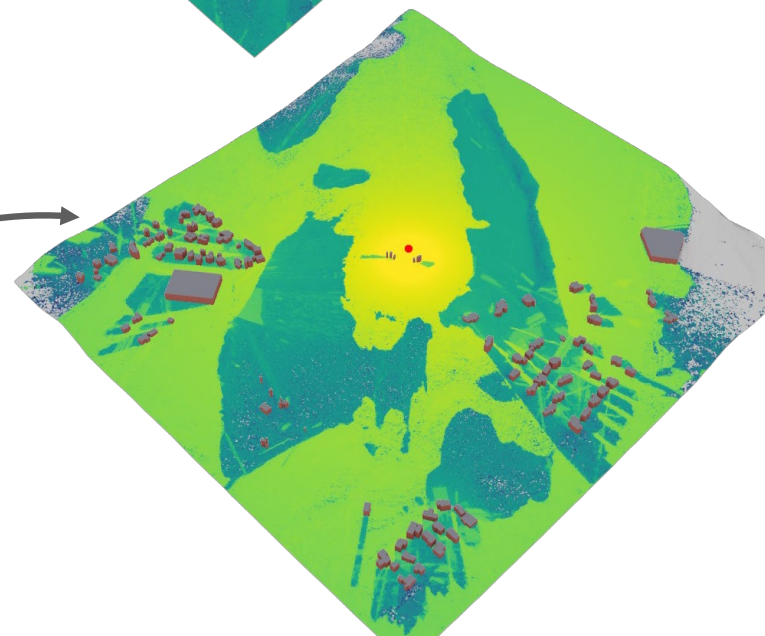
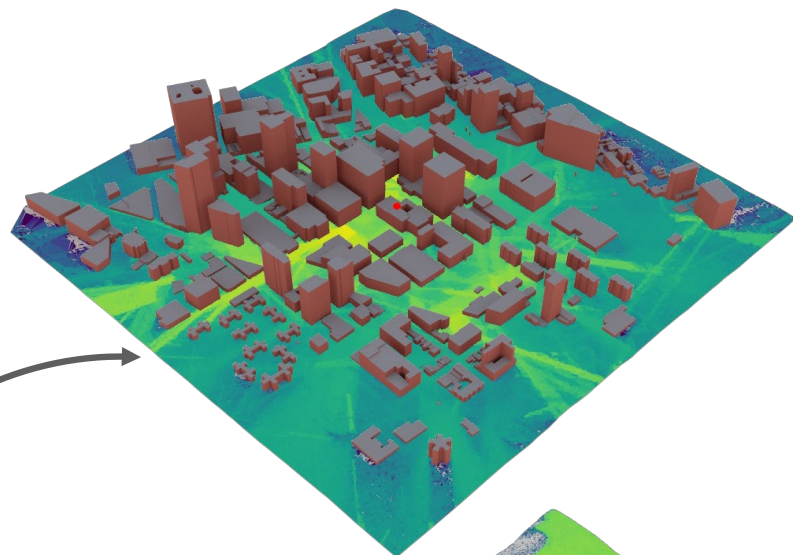
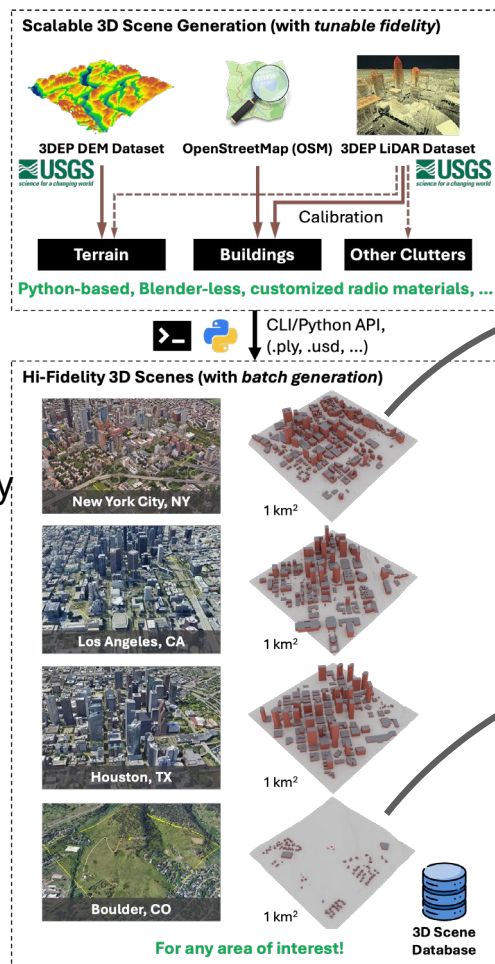
```
> examples
> src/scene_generation
  .gitignore
  LICENSE
  README.md
  pyproject.toml
  requirements.txt
```

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

- 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/>; Code and measurement data: <https://github.com/functions-lab/geo2sigmap>

Geo2SigMap

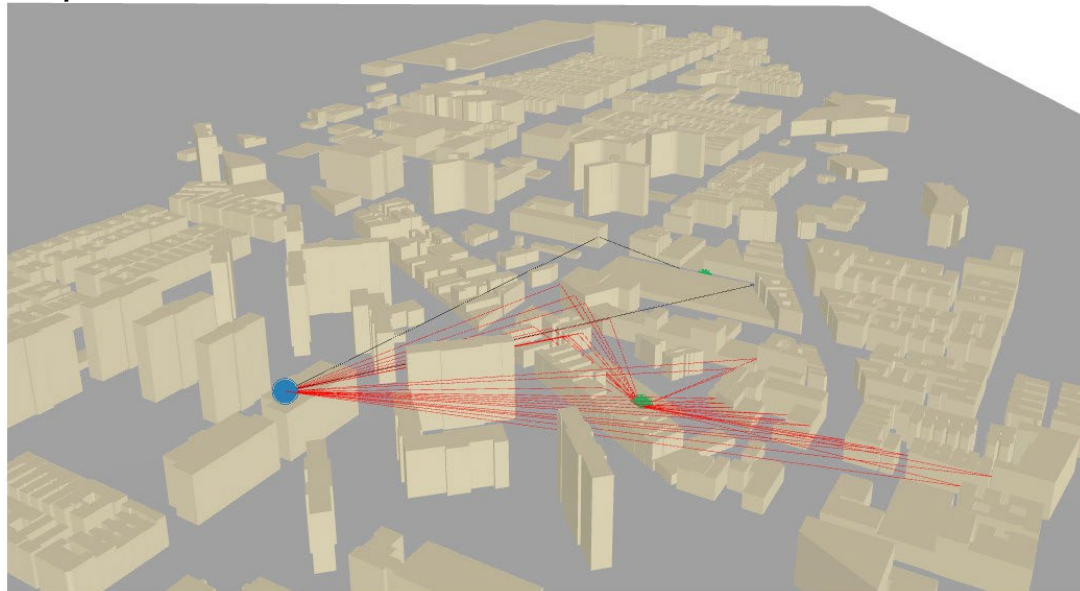
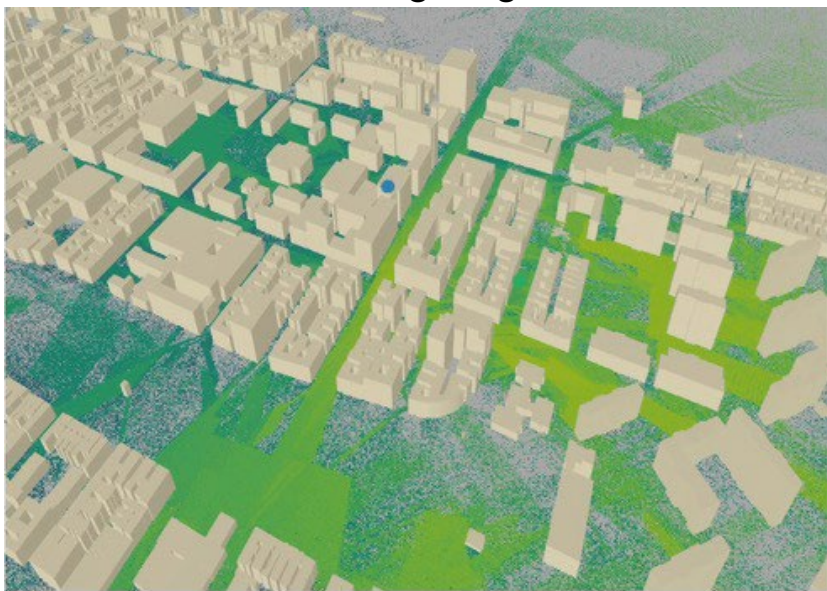
- v2.0 (released Nov. 2025)
 - Support of lidar datasets
 - Support of irregular terrains
 - Tunable scene fidelity
 - Customized radio materials
 - Batch scene generation
 - ...



- Project website: <https://functions-lab.github.io/projects/geo2sigmap/>
- Code and measurement data: <https://github.com/functions-lab/geo2sigmap>

Spectrum DT for the NYC FCC Innovation Zone

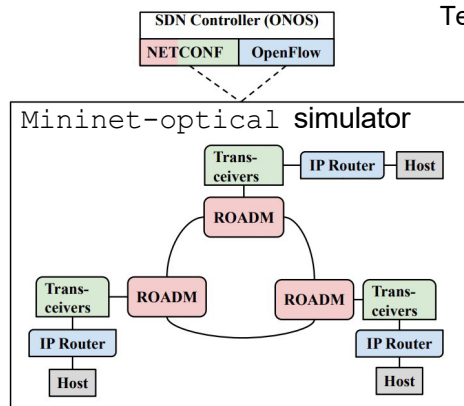
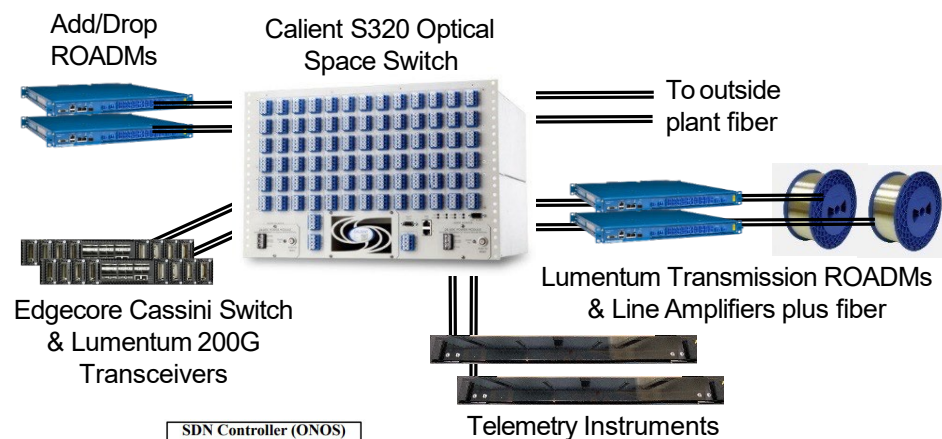
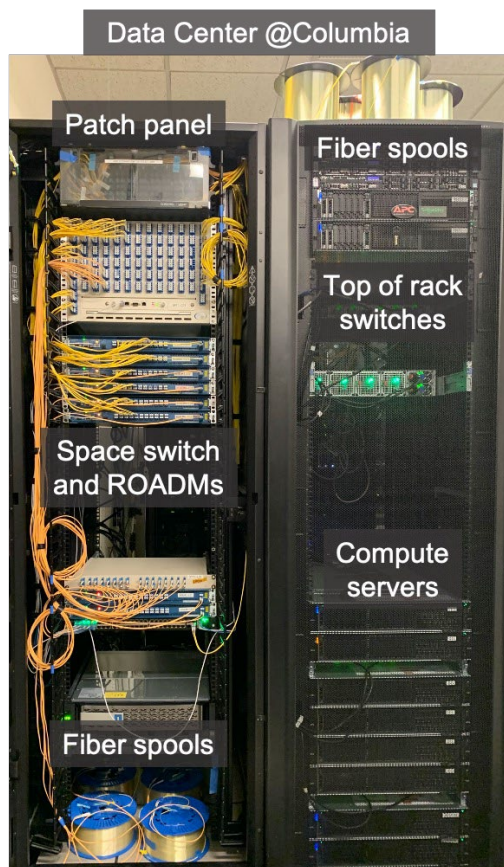
- ~1 sq. mi. area in Upper West, Manhattan, within the PAWR COSMOS platform deployment area
- Accurate building height information from a public NYC LiDAR dataset



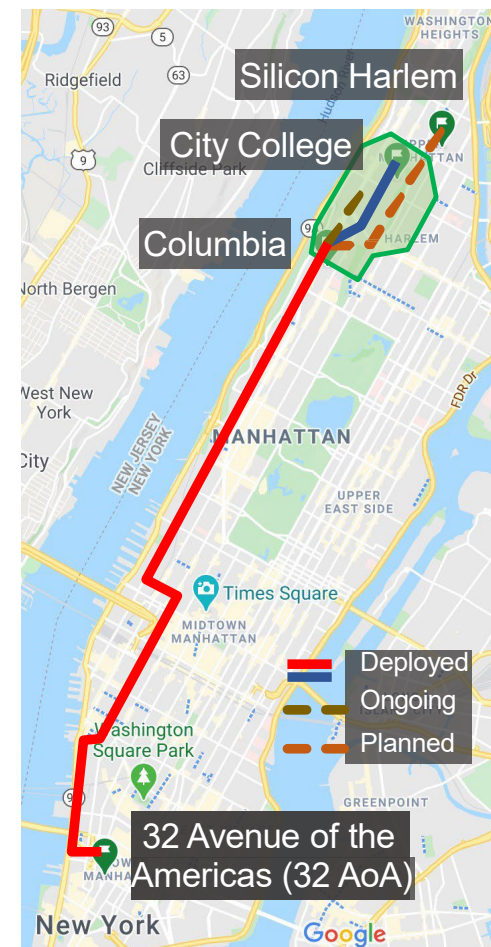
RF signal coverage for a COSMOS large node in FR1 (2.4 GHz, left) and FR2 (28 GHz, right)

► New York State GIS Resources: <https://gis.ny.gov/lidar>.

Key Technology: Optical Networking



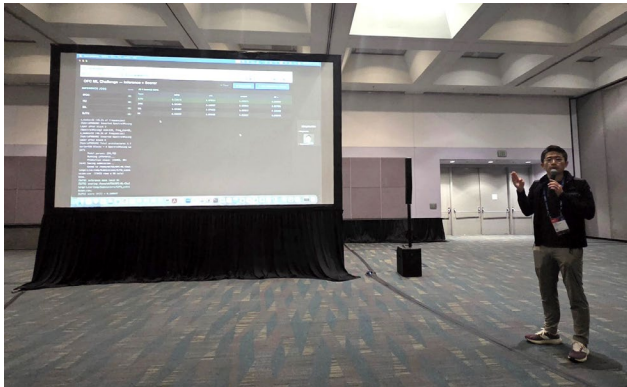
Platforms for Advanced
Wireless Research



- T. Chen, J. Yu, A. Minakhmetov, C. Gutterman, M. Sherman, S. Zhu, S. Santaniello, A. biswas, I. Seskar, G. Zussman, and D. Kilper, "A software-defined programmable testbed for beyond-5G optical-wireless experimentation at city-scale," *IEEE Network, Special Issue on Next-Generation Optical Access Networks to Support Super-Broadband Services and 5G/6G Mobile Networks*, Mar./Apr. 2022.

Dataset Paper Track and ML Challenge at OFC

- Initiated and co-organized the **1st Dataset Paper Submission** and the **1st ML Challenge** (using a large EDFA dataset collected from COSMOS) at OFC 2026. Selected dataset papers and ML Challenge winning team were invited to respective special issues at IEEE/Optica JOCN and JLT
- Led to the formation of a new Dataset Paper Track starting OFC 2027, and the ML challenge will continue at OFC 2027 and beyond



Live ML competition at OFC 2026



Roadmap ahead for OFC 2027 and beyond



- ▶ OFC 2027 Submit a Paper: <https://www.ofcconference.org/submit-a-paper/>
- ▶ COSMOS EDFA dataset: <https://github.com/functions-lab/COSMOS-EDFA-Dataset>

Experimenters/Users (partial list)

- ORAN Alliance
- NSF CS3 ERC
- NSF and DoD 5G Convergence Accelerator: AT&T, Ericsson, Fujitsu, UC Riverside, NYU, Howard, Rutgers, Columbia
- SpectralDSP
- NEC Labs America, NEC Japan
- NTT
- Nokia Bell Labs (Wireless, Optical)
- NGIAtlantic: 3 projects (Kentyou, OpenARCloud, CONNECT)
- NGI Explorer (Tel Aviv U.,)
- Education toolkit: Verizon and AT&T
- NSF NQVL (Stony Brook U, Yale)
- NSF and DOT Cyber Physical Systems: Digital Twin for Transportation
- NTIA Wireless Innovation Fund: AT&T and Verizon, NTIA NOFO1 (Rutgers, NYU)
- Army DURIP: Edge Cloud
- NSF: National Radio Dynamic Zone (Princeton, Syracuse, Rutgers, CCNY, Columbia, Duke); and Associated (Northwestern, MIT)
- ACM SIGMOBILE data collection (Duke)
- NSF: RINGS (MIT)
- NSF PAWR supplements: 5 projects (U. Arizona, Yale, FIU, Duke, Oregon State)
- DARPA/SRC JUMP Cubic Center
- NSF New Spectrum x2 (Syracuse, Rutgers, ND, Yale, Northeastern)
- EC Horizon 6G-XCEL
- NSF-BSF (Tel Aviv U.)
- NSF: Vines (upcoming)



COSMOS Usage: September 2025 – September 2026

Twelve months of approved reservations — *omf_scheduler* database, pulled 17 September 2026

31,067
reservation hours

across twelve testbed subdomains

11,302
reservations

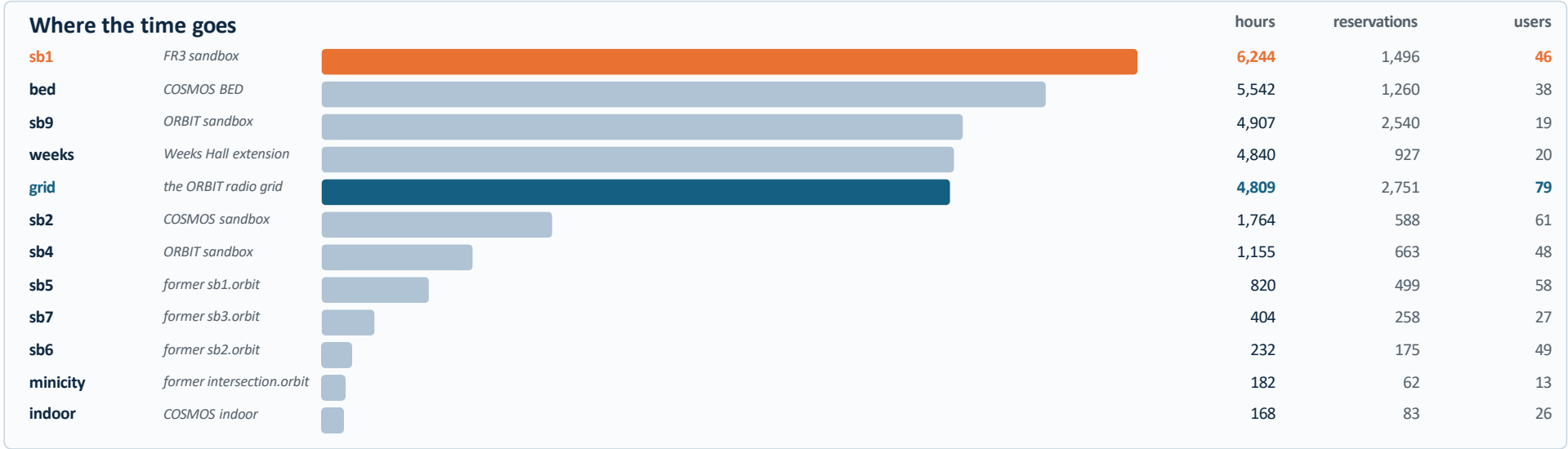
a booking every 46 minutes, year-round

194
distinct users

owners and invited participants

28
research groups

universities, labs and the summer program

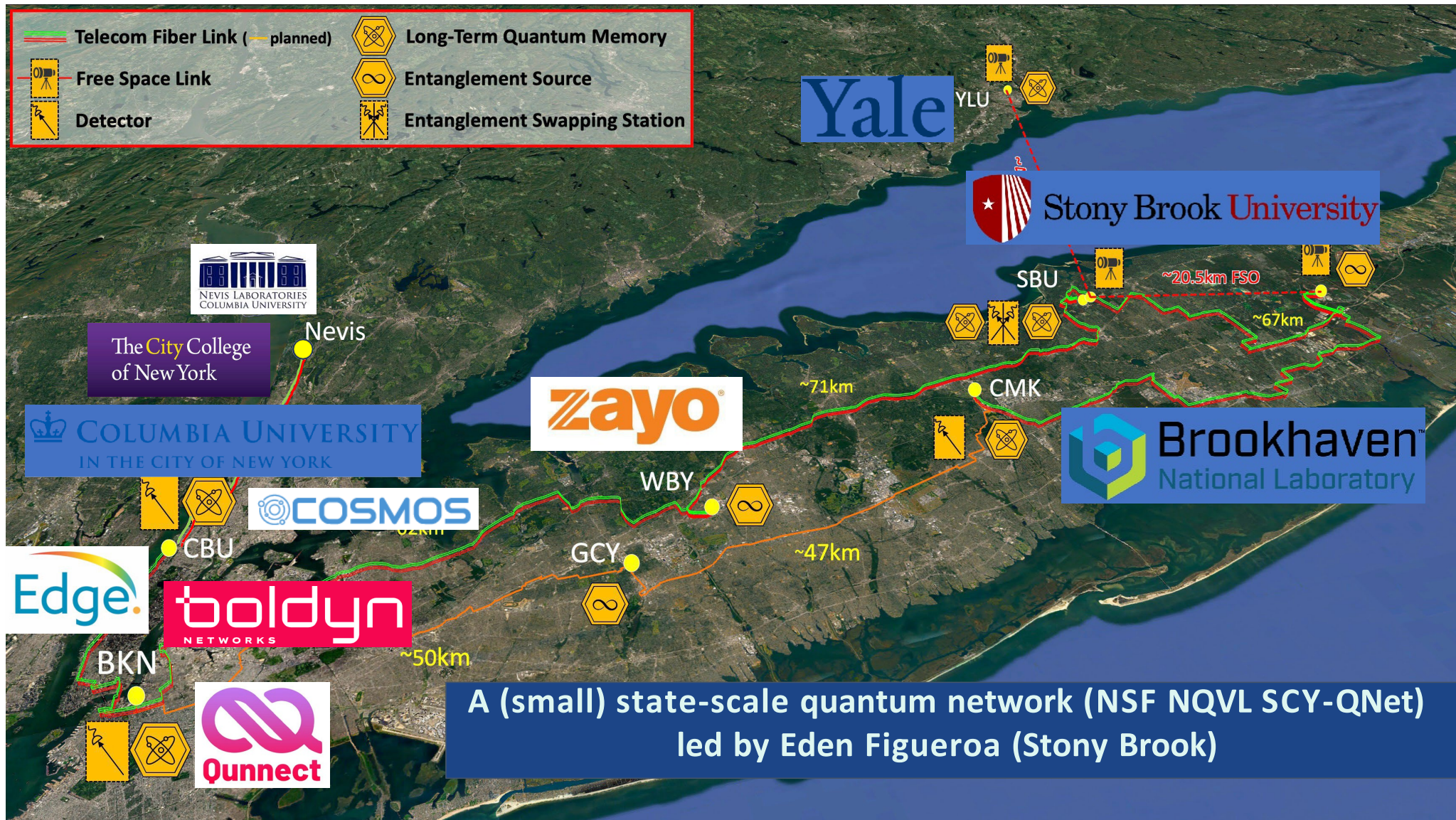


Two different kinds of leader: SB1, the FR3 sandbox, now absorbs the most time on the testbed — 6,245 hours, more than the ORBIT grid — while the grid remains the front door, with 79 users and 2,751 bookings against SB1’s 46 and 1,496. FR3 is where the long experiments are; the grid is where people start.

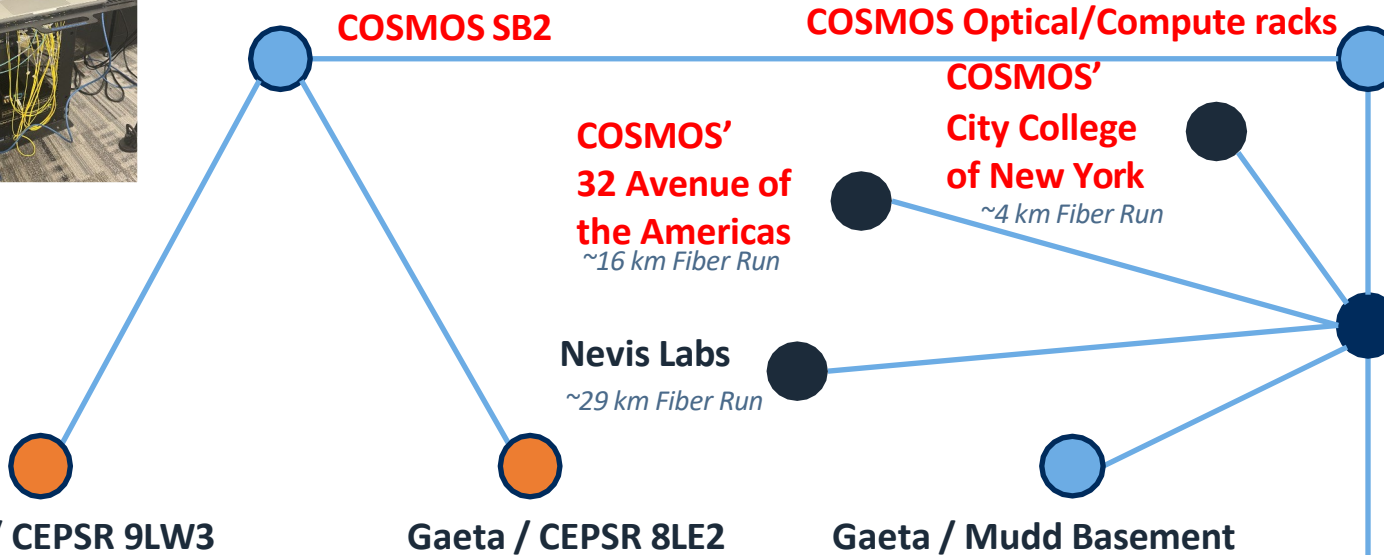
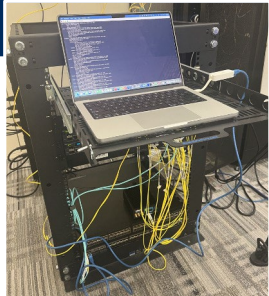
Four dedicated domains (3 O-RAN-focused)

Restricted, research-group-managed, each with its own hardware, group membership and jump host

Domain	Program	What is in it
osc.cosmos-lab.org	O-RAN Software Community (now LFN)	srv1–srv20 bare metal, three tiers: Stable / Development / Experimental. OpenStack on the first two; StarlingX being stood up. Intel ACC100.
rrail.cosmos-lab.org	NTIA energy efficiency (POET)	7 servers including, multi-vendor O-RU devices. BubbleRAN MX-PDK and DPDK stacks, ACC100, PTP, CPU isolation.
accord.cosmos-lab.org	NTIA ACCoRD (AT&T prime)	5 Dell R740 servers, Airspan/Corning O-RUs on a FibroLan PTP grandmaster switch, Keysight O-RAN Studio and VIAVI TM500
durip.cosmos-lab.org	Army funded edge-cloud project	4 Dell Servers with 2 GPUs each



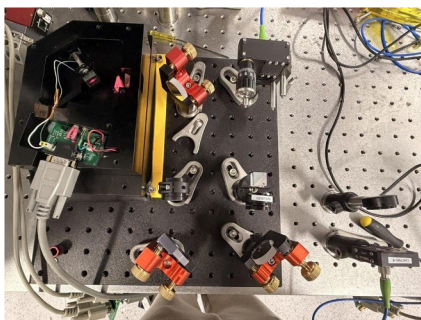
NSF NQVL SCY-QNet – Network of Networks



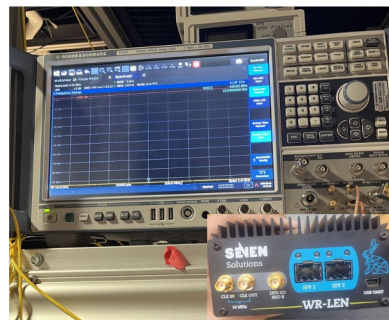
Mudd Fiber Termination
~26 km Fiber Run



Qunnect / Brooklyn Navy Yard



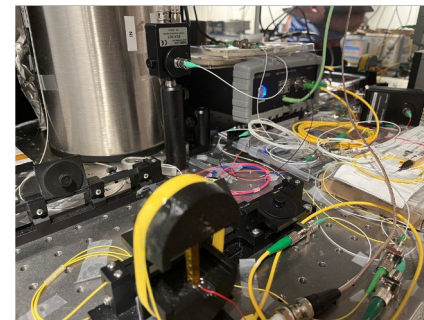
 **COSMOS**



RUTGERS



COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK



Duke

The City College of New York

SCY-QNet Dark Fiber and Traffic Monitoring

Dashboard

Global Map



LIVE

Broadway @ 45 St

Manhattan



LIVE

Broadway @ Morris St

Manhattan



LIVE

Broadway @ Chambers St

Manhattan



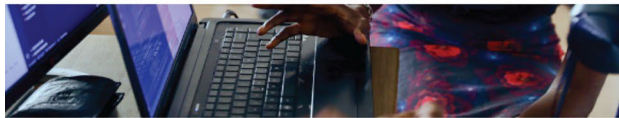
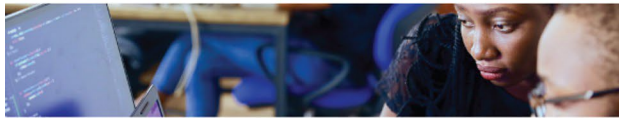
LIVE



LIVE



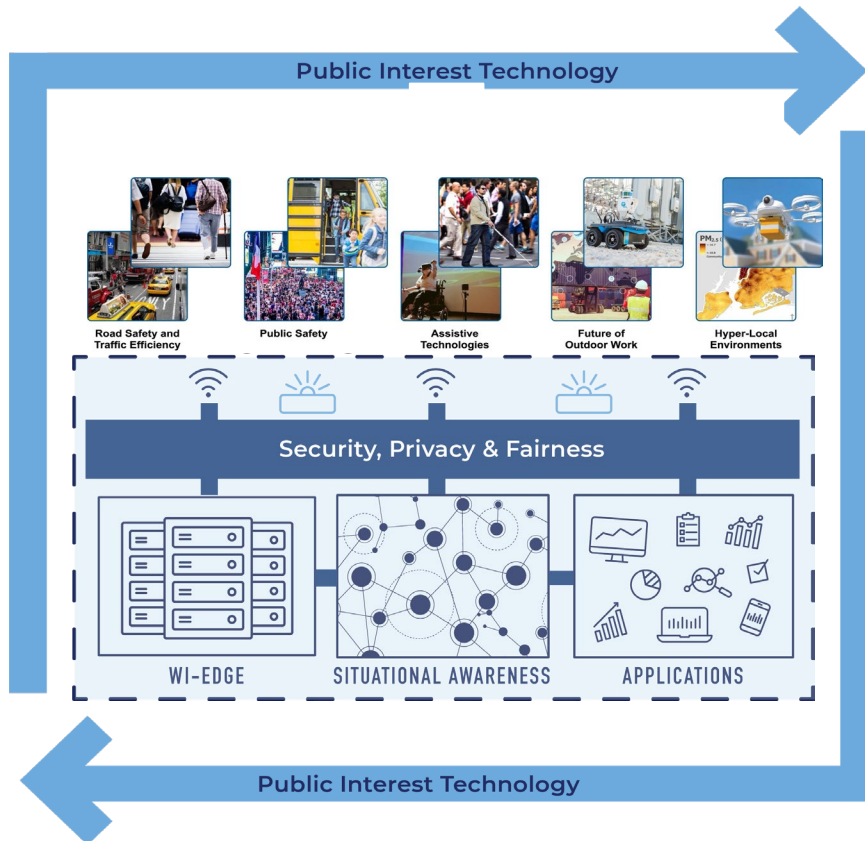
LIVE



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Research Vision & Principles

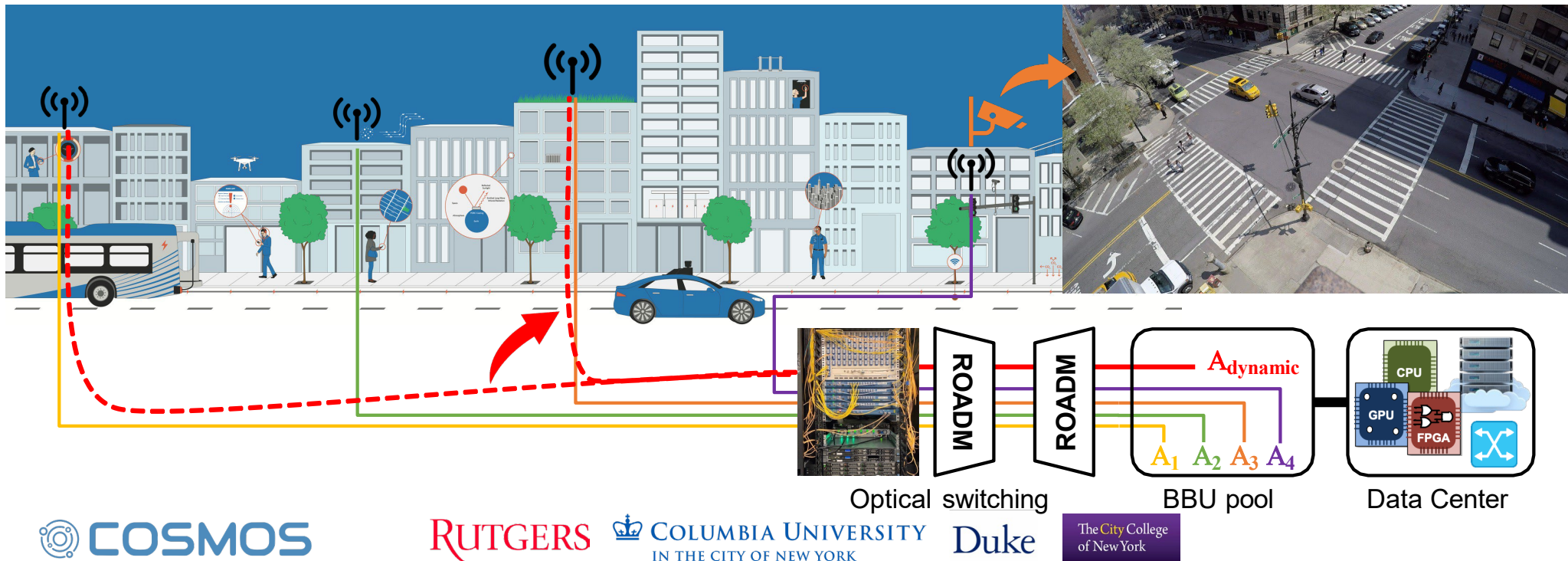


- **Vision:** High-precision, real-time understanding and coordination of streetscapes, to foster **livable**, **safe** and **inclusive** communities.
- **Balance** of public **data collection** with community-defined **benefits**.

Supporting Smart Cities: Wireless-Optical Networking with Edge Cloud

- Joint optical-wireless-compute resource allocation (radios, sensors, LIDARS, cameras, servers, ...) for smart cities and intersections

- Aggregation of high-volume data
- Low-latency and real-time response (with edge cloud and optics)



Experiment: Smart Intersection

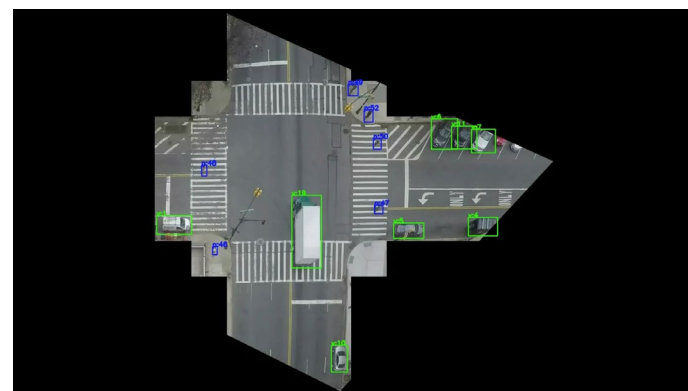
- Smart intersection as a core smart city asset
 - Low latency, high bandwidth wireless links, sensor data acquisition
 - Edge cloud computing and machine intelligence for interaction with pedestrians
- Real-time (latency) – useful for traffic interaction/management
 - Vehicle speed: 10 km/h $\rightarrow$ ~ 3 m/s $\rightarrow$ ~ 0.1 m in 1 frame of a video (@30 fps)
 - Useful to prevent accidents, target round-trip latency = 1/30 second



COSMOS pilot site

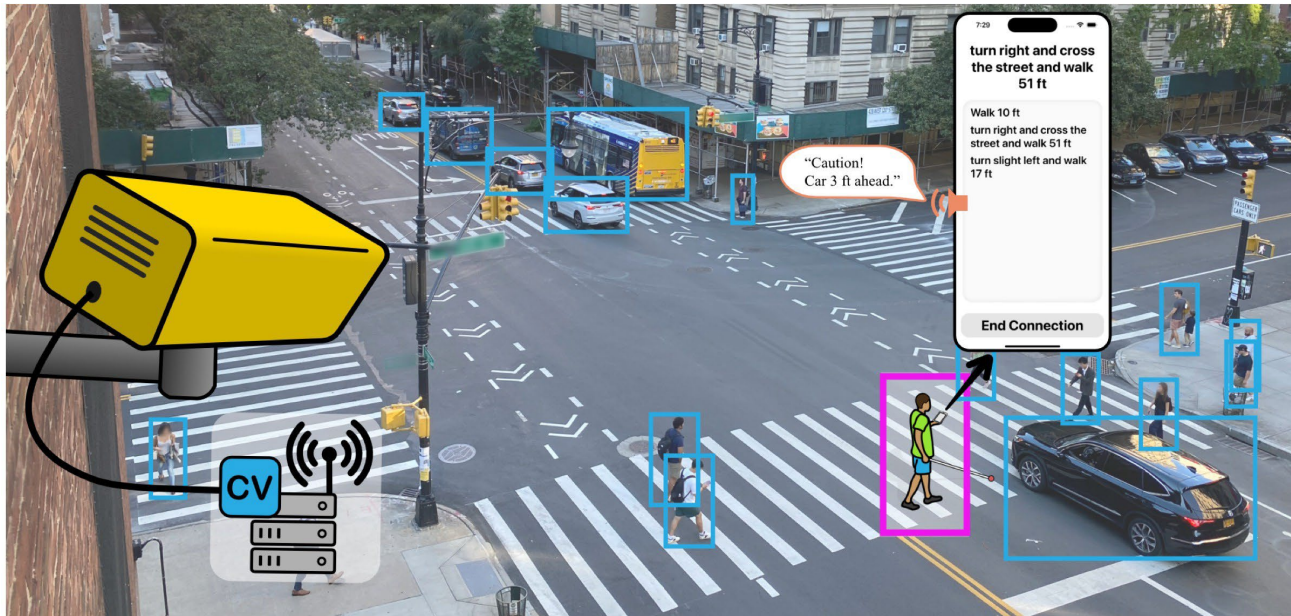


Videos fed into the COSMOS edge node for vehicles/pedestrians detection and classification



- Z. Kotic, A. Angus, Z. Yang, Z. Duan, I. Seskar, G. Zussman, and D. Raychaudhuri, "Smart city intersections: Intelligence nodes for future metropolises," *IEEE Computer, Special Issue on Smart and Circular Cities*, Dec. 2022.

StreetNav: Leveraging Street Cameras to Support Precise Outdoor Navigation for Blind Pedestrians



Example of taking advantage of cameras, edge computing, situational awareness algorithms and communications

<https://youtu.be/JFLiBAm0s-U>

G. Jain, B. Hindi, Z. Zhang, K. Srinivasula, M. Xie, M. Ghasemi, D. Weiner, S. A. Paris, X. Y. T. Xu, M. Malcolm, M. Turkcan, J. Ghaderi, Z. Kostic, G. Zussman, and B. A. Smith, "StreetNav: Leveraging Street Cameras to Support Precise Outdoor Navigation for Blind Pedestrians," in *Proc. ACM UIST'24*, 2024

StreetNav: Leveraging Street Cameras to Support Precise Outdoor Navigation for Blind Pedestrians

Gaurav Jain¹, Basel Hindi¹, Zihao Zhang¹, Koushik Srinivasula¹, Mingyu Xie¹,
Mahshid Ghasemi¹, Dan Weiner², Sophie Ana Paris³, Xinyi Xu⁴, Michael Malcolm⁵,
Mehmet Turkcan¹, Javad Ghaderi¹, Zoran Kostic¹, Gil Zussman¹, Brian A. Smith¹

¹Columbia University, New York, USA

²Lehman College, New York, USA

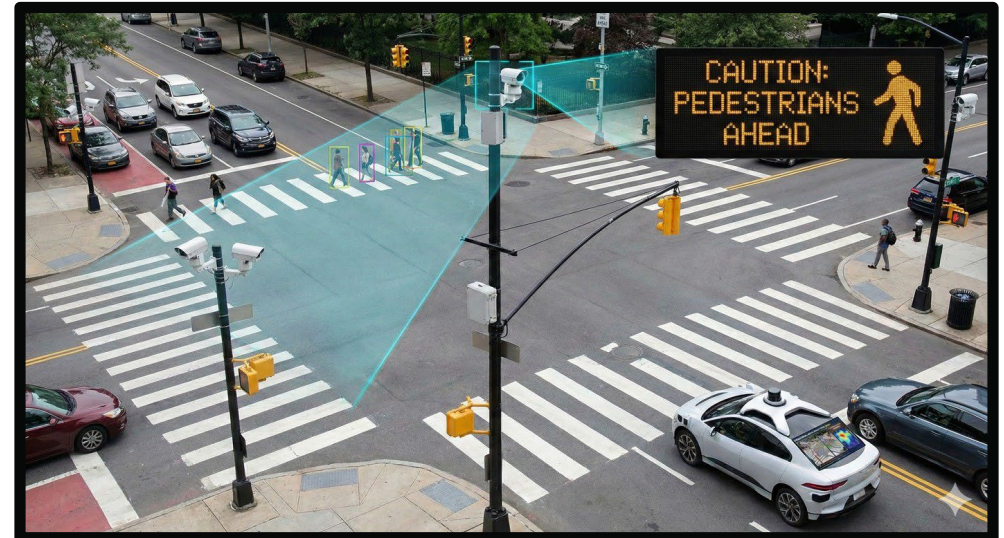
³New York University, New York, USA

⁴Pomona College, California, USA

⁵City Tech College, New York, USA

The Urban Safety Challenges

- ✓ **Goal:** Enhance pedestrian safety at busy urban intersections using existing street cameras.
- ✓ **Constraint:** Latency, limited compute, strict privacy requirements.
- ✓ **Solution:** **PAVE** (Pedestrian Awareness Via Edge analytics).
- ✓ **Approach:**
 - Use **video analytics** + **edge computing** to detect and alert at-risk pedestrians.
 - Ensure privacy preservation — no identifiable data shared.

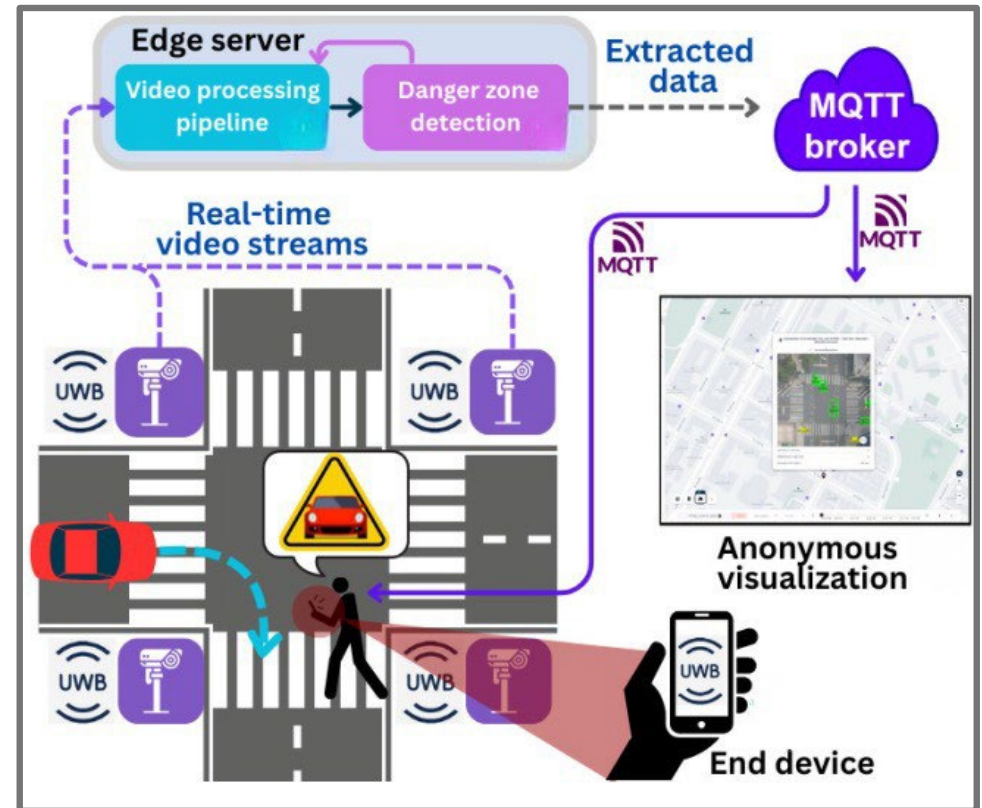


M. Ghasemi, Y. Fu, X. Ouyang, P. Wang, M. Turkcan, J. Tavori, S. Kleisarchaki, T. Calmant, L. Gürgen, Z. Kostic, X. Di, G. Zussman, and J. Ghaderi, "Real-time video analytics for urban safety: deployment over edge and end devices," in *Proc. ACM/IEEE Symposium on Edge Computing (SEC)*, Dec. 2025. **Best Paper Award**

PAVE Architecture

PAVE employs a distributed computing architecture to balance load and ensure privacy.

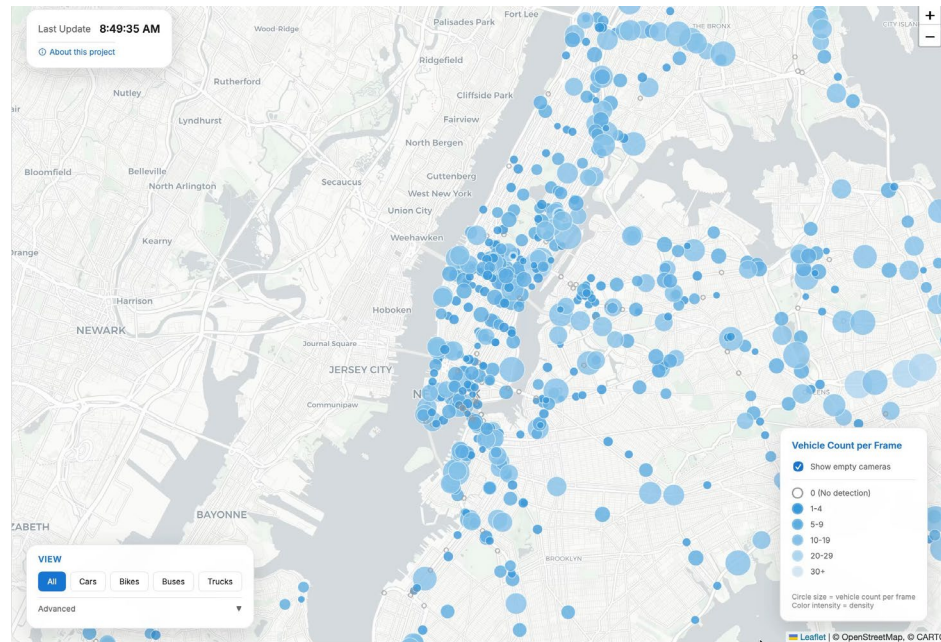
- ✓ **Edge Server:** Handles heavy DNN-based video processing.
- ✓ **End Devices:** Lightweight apps on pedestrians' phones for localization and alerts.
- ✓ **Connectivity:** Uses MQTT for ultra-low latency communication between Edge and End devices.
- ✓ **Privacy:**
 - No data from pedestrians' phones is transmitted to the Edge.
 - Only bounding boxes (not raw images) are shared with the visualization dashboard.



A Vision-Based Analysis of Congestion Pricing in New York City

Computer vision pipeline processes footage from over 900 cameras distributed throughout Manhattan and New York City. Compared traffic patterns from November 2024 through the program's implementation in January 2025 until January 2026.

Datasets available

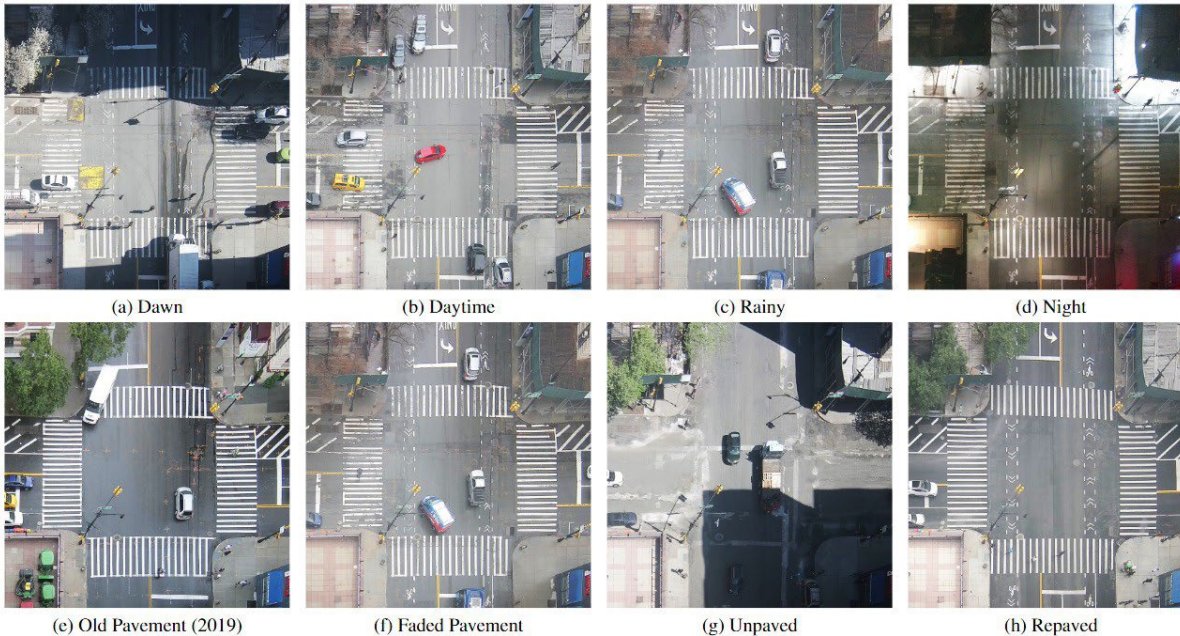


M. K. Turkcan, J. Tavori, J. Ghaderi, G. Zussman, Z. Kostic, A. Smyth. "A Vision-Based Analysis of Congestion Pricing in New York City". arXiv: 2602.03015

<https://huggingface.co/datasets/mehmetkeremturcan/nyc-congestionpricing-cv>

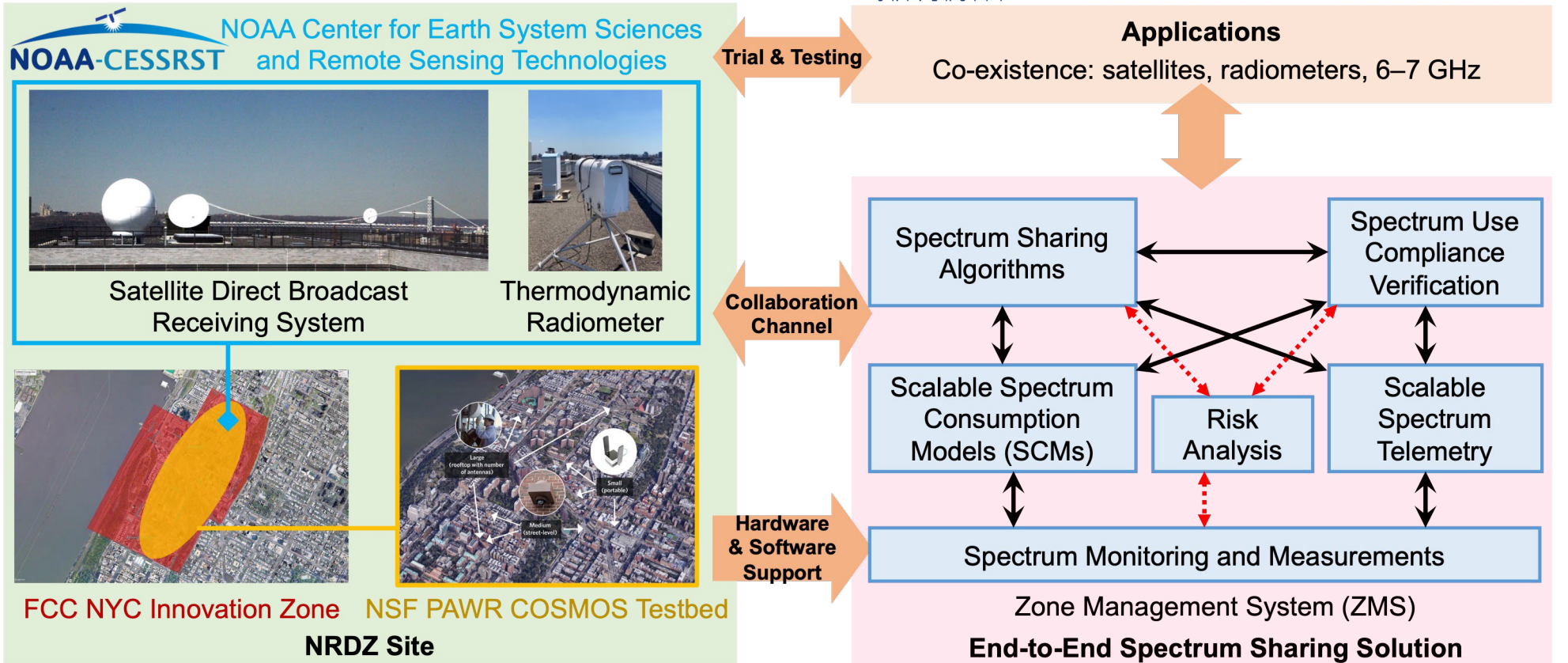
Constellation Dataset: Benchmarking High-Altitude Object Detection for an Urban Intersection

- Dataset of 13K images for research on object detection in dense urban streetscapes from high-elevation cameras across varied temporal conditions.
- Addresses challenges in small object detection, particularly for pedestrians observed from elevated positions with limited pixel footprints



M. Turkcan, C. Zang, S. Narasimhan, G. H. Je, B. Yu, M. Ghasemi, J. Ghaderi, G. Zussman, and Z. Kostic, "Constellation dataset: benchmarking high-altitude object detection for an urban intersection," *Int. J. of Computer Vision*, vol. 134, p. 429, Sept. 2026.

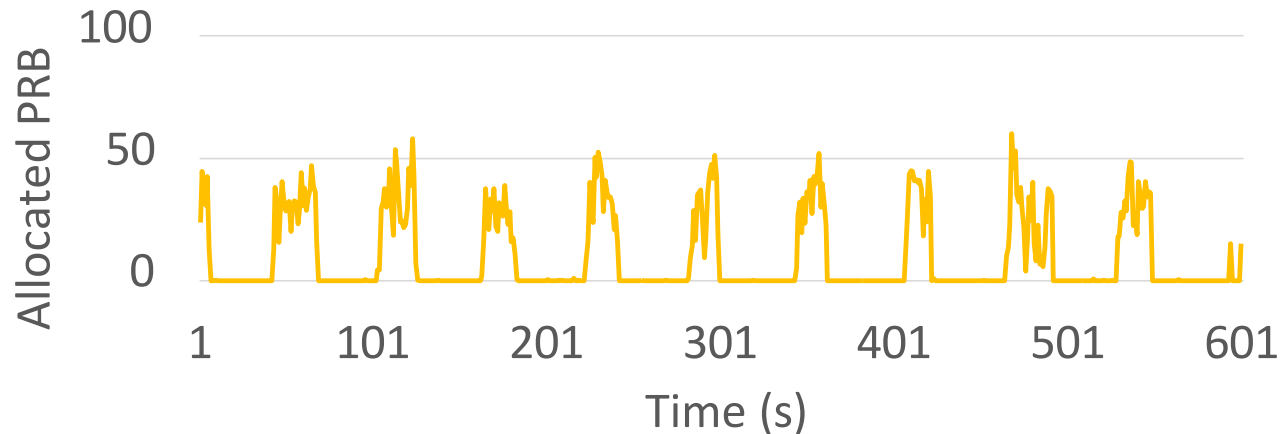
NRDZ - Spectrum Sharing via Consumption Models and Telemetry



Jamieson Group (Princeton): CellScout/NG-Scope/NR-Scope: Fine-grained cellular telemetry

Allocated bandwidth (PRB):

- Varies with the traffic pattern
- Predicting the future traffic pattern of the user



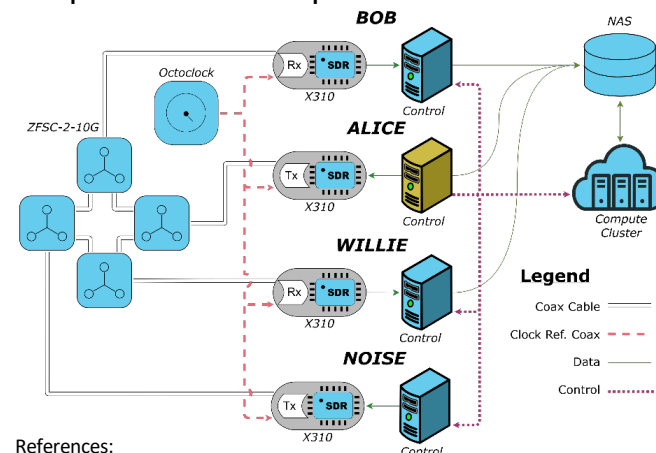
- If the signal layer detects strong cellular activities in certain bands, the PHY layer can be triggered to monitor those bands to obtain the spectrum utilization as a function of network statistics
- Provide input to the **Spectrum Sharing and Interference Management Algorithms**
- Provide input to **Energy Efficiency Analysis/Characterization**

Bash Group (University of Arizona): Experimental Validation of Provably Covert Communication Using Software-Defined Radio



- **Goal:** Demonstrate covert communication over an RF channel that conceals the fact that any transmission is taking place: a stronger form of communication security than cryptographic protection of message content.
- **Prior work:** PI Bash established the information theory of covert communications. Lots of follow-on work from many groups; largely theoretical.
- **Experimental challenges:** signal structure design to ensure covertness. Inadequate COTS solutions necessitate flexibility of SDR.
- **This project:** first known demonstration of covert communication over a physical RF channel, presented at IEEE MILCOM [3] and published in IEEE Journal on Selected Areas in Communication (JSAC) [4]. SDR units on the COSMOS testbed and collaboration with COSMOS team was integral to its success. Initial concept for the experiment was developed in a project funded by an NSF PAWR supplement to CCF-2006679, continued under CNS-2107265.
- **Poster and MERIF demo** by PI Bash and graduate student Rohan Bali.

Experimental setup on COSMOS



References:

- 1 Bash, Goeckel, Towsley "Square root law for communication with low probability of detection on AWGN channels" In Proc. IEEE Int. Symp. Inform. Theory (ISIT) 2012.
- 2 Bash, Goeckel, Towsley "Limits of reliable communication with low probability of detection on AWGN channels" IEEE J. Select. Areas Commun., vol. 31, no. 9, pp. 1921–1930, 2013.
- 3 Bali, Bailey, Bullock, Bash "Experimental Covert Communication Using Software-Defined Radio" In Proc. IEEE Mil. Commun. Conf. (MILCOM) 2025.
- 4 Bali, Bailey, Bullock, Bash "Experimental Validation of Provably Covert Communication Using Software-Defined Radio" IEEE J. Select. Areas Commun., vol. 44, pp. 4382–4396, 2026.

mmWave Measurements: Motivation

- Widely available spectrum at millimeter-wave (mmWave) frequencies compared with sub-6 GHz frequencies can support significantly increased data rates
- Due to the challenging link budget at mmWave frequencies, extensive channel measurements and accurate channel models are needed for the deployment and operation of mmWave networks
 - What happens if mmWave BSs will be deployed at locations with existing 4G/LTE cells?
 - What will be the performance indoors?
 - Impacts on communication and sensing?

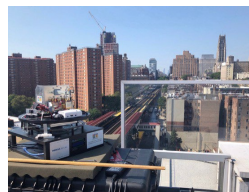


mmWave measurements

- 28 GHz channel measurements in the COSMOS testbed area in a dense urban canyon environment
 - Representative (potential) deployment sites of mmWave BSs (building rooftops, street lightpoles, etc.)
 - Extensive measurements on long sidewalks (up to 1,100 m) with fine-grained link step size (1.5/3 m)
- 41+ million measurements were collected from 2,600+ links on 22 sidewalks in 4 different sites
 - Characterizations of path gain, effective beamforming gain, SNR coverage, and achievable data rates



4-way city intersection



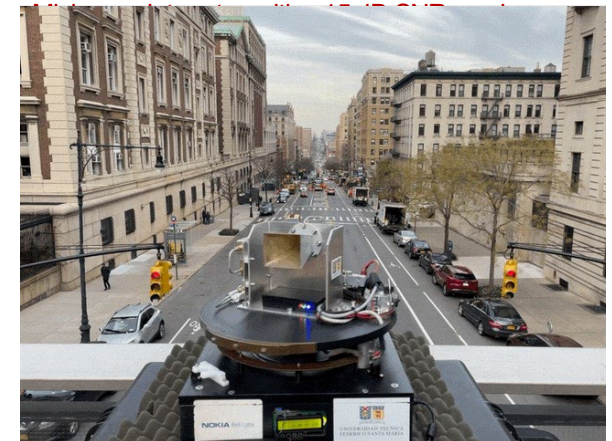
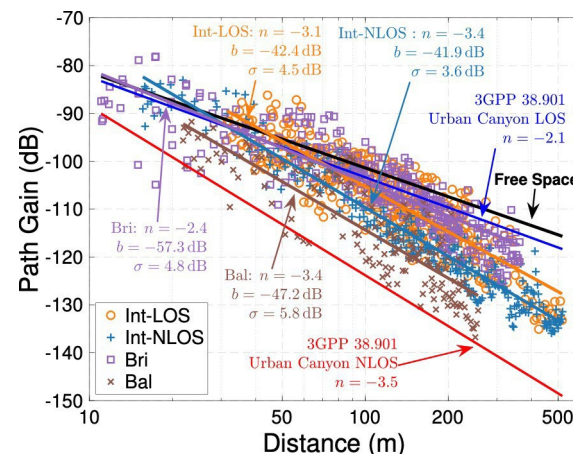
Building rooftop



Cross-avenue bridge



An open-space park



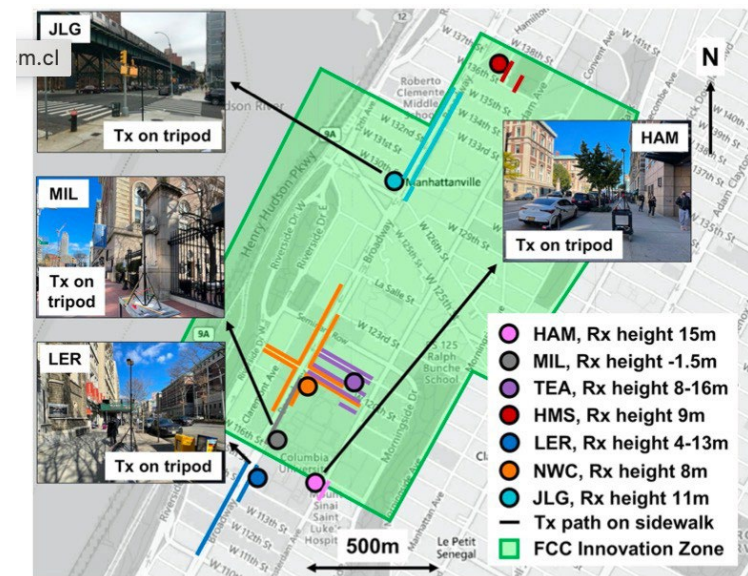
- D. Chizhik, J. Du, R. Valenzuela, "Universal path gain laws for common wireless communication environments", *IEEE Transactions on Antennas and Propagation*, 2021
- J. Du, D. Chizhik, R. Valenzuela, R. Feick, M. Rodríguez, G. Castro, T. Chen, M. Kohli, and G. Zussman, "Directional measurements in urban street canyons from macro rooftop sites at 28GHz for 90% outdoor coverage," *IEEE Transactions on Antenna and Propagation*, vol. 69, no. 6, pp. 3459–3469, June 2021.
- T. Chen, M. Kohli, T. Dai, A. D. Estigarribia, D. Chizhik, J. Du, R. Feick, R. Valenzuela, and G. Zussman, "28GHz channel measurements in the COSMOS testbed deployment area," in *Proc. ACM MobiCom'19 Workshop on Millimeter-Wave Networks and Sensing Systems (mmNets)*, 2019.

mmWave measurements

- Extensive outdoor-to-indoor measurements within different buildings: 29+ million measurements were collected from over 2,200 links in 7 different sites



Outdoor-to-outdoor measurements

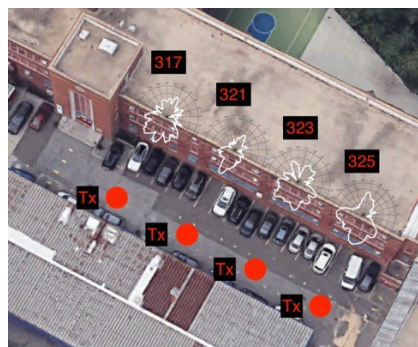


Outdoor-to-indoor measurements

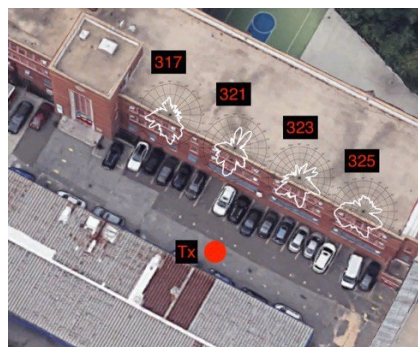
- M. Kohli, A. Adhikari, G. Avci, S. Brent, A. Dash, J. Moser, S. Hossain, I. Kadota, C. Garland, S. Mukherjee, R. Feick, D. Chizhik, J. Du, R. Valenzuela, and G. Zussman, "Outdoor-to-indoor 28 GHz wireless measurements in Manhattan: Path loss, environmental effects, and 90% coverage," *IEEE/ACM Trans. Networking*, 2024.

Case Study at a Middle School

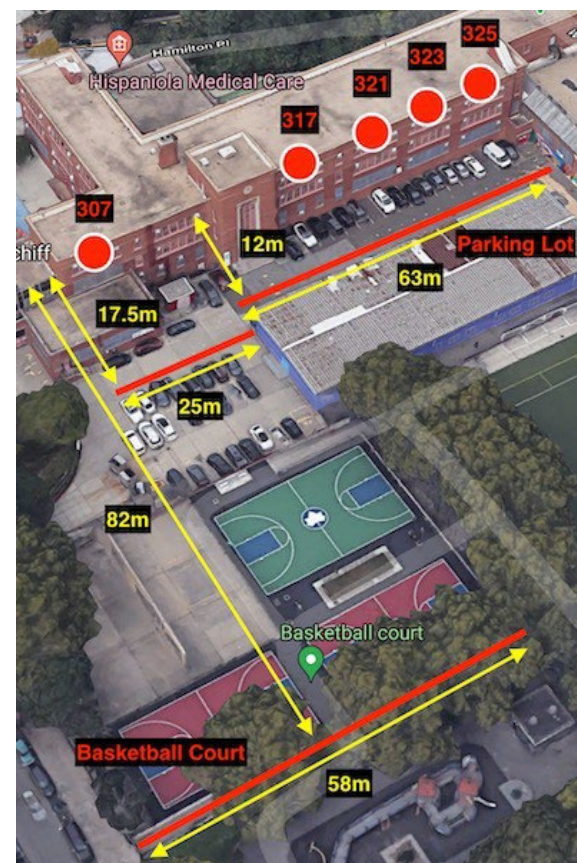
- Hamilton Grange Middle School in West Harlem, NYC
- Measurements taken from transmitter locations in school parking lot and basketball courts to five different classrooms
- Classroom measurements show the feasibility of coverage from an outdoors mmWave transmitter
- Dataset publicly available via NIST



Angular spectra for transmitter placed in front of each classroom



Angular spectra for single transmitter location in middle of classrooms

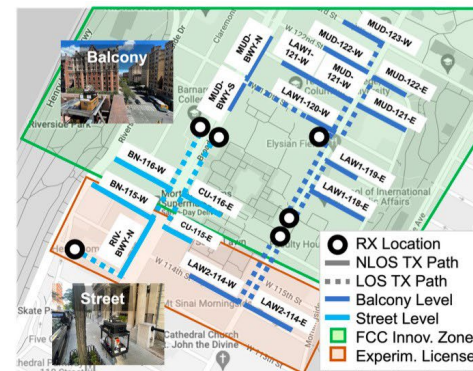
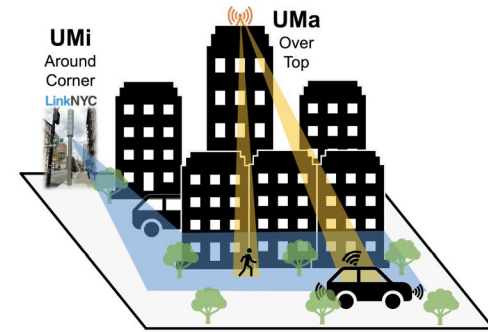


Measurement locations at Hamilton Grange Middle School

mmWave – Around- Corner/Over-Top measurements

- A major challenge of millimeter-wave (mmWave) communication in real-world deployments is the high path loss which limits coverage in dense, urban environments
- In-depth study of non-line-of-sight (NLOS) signal propagation
- Conducted an extensive real-world 28 GHz measurement campaign in Manhattan, NYC, representing over 1,400 links across 35 sidewalks in Upper and Lower Manhattan
- Highly accurate around-the-corner and over-the-top NLOS propagation models

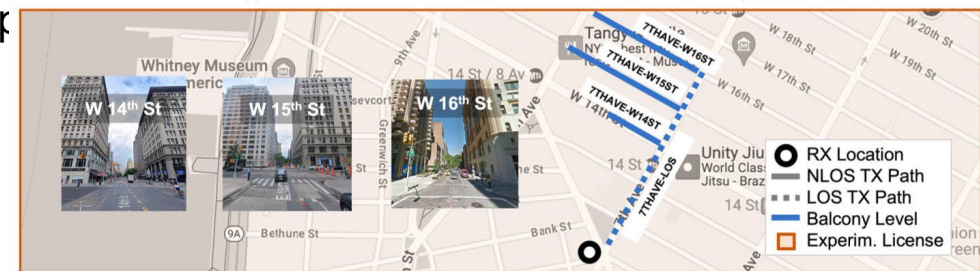
NOKIA
Bell Labs



(a)



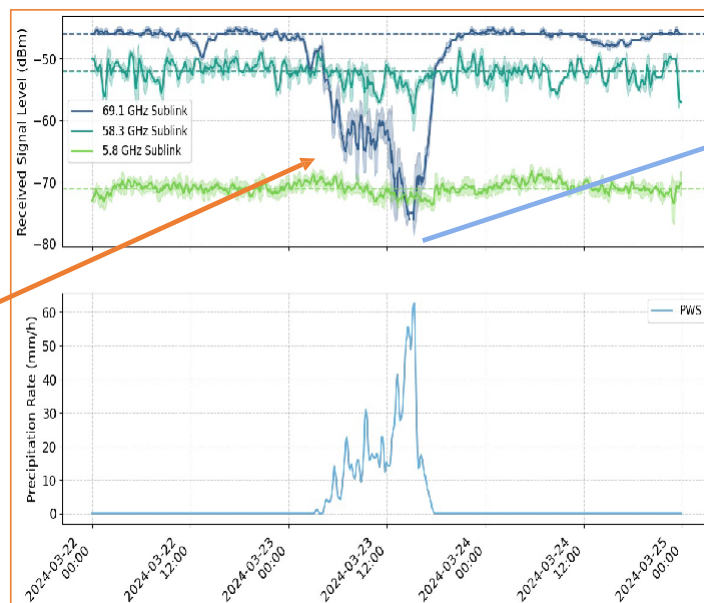
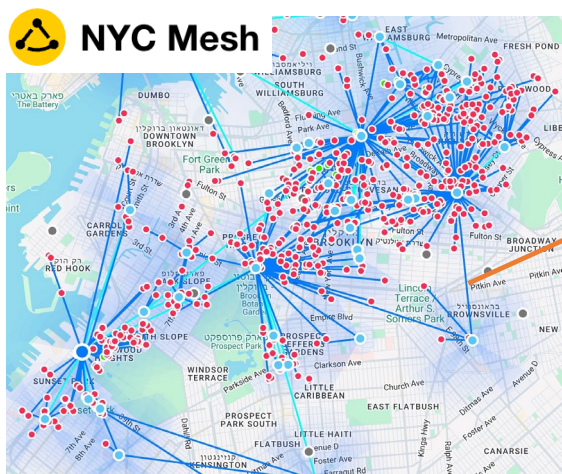
(b)



- A. Adhikari, S. Mukherjee, A. Mehta, M. Kohli, R. Feick, R. Valenzuela, D. Chizhik, J. Du, G. Zussman, "Around-Corner and Over-Top 28 GHz Measurement in Manhattan: Path Loss and AoA for MU-MIMO," *Proc. IEEE INFOCOM'25*, 2025.

Using Backhaul links to Infer the Weather

- Enabled by providing NYCMesh deployment sites in COSMOS nodes
- Transform wireless signal measurements into real-time environmental sensors
- Applications in weather and network resilience
- Extensive dataset available via Zenodo



Wireless Networks currently use high-frequency mmWave signals, challenged by weather-induced attenuation, yet offer high temporal and spatial resolution as real-time environmental sensors.

D. Jacoby, Y. Li, S. Yu, N. Di Cicco, H. Messer, G. Zussman, and I. Kadota, "AWaRe-SAC: Proactive slice admission control under weather-induced capacity uncertainty," in Proc. WiOpt'26, 2026.

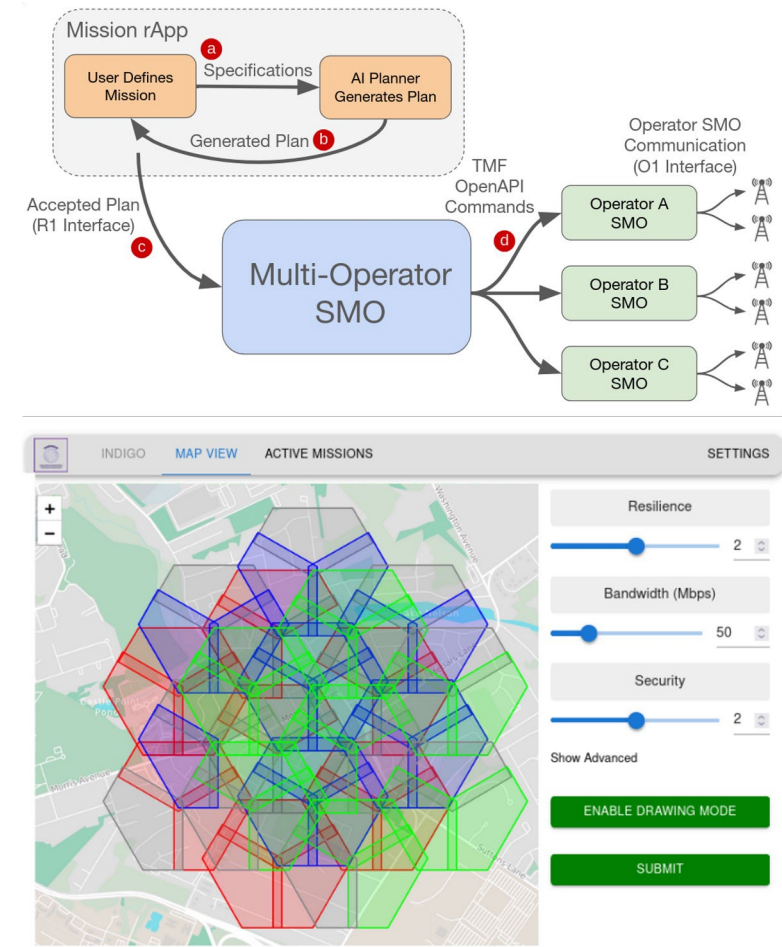
D. Jacoby, S. Yu, Q. Hu, Z. Hine, R. Johnson, J. Ostrometzky, I. Kadota, G. Zussman, and H. Messer, "OpenMesh: wireless signal dataset for opportunistic urban weather sensing in New York City," *Earth System Science Data*, Aug. 2026.

D. Jacoby, S. Yu, Q. Hu, Z. Hine, R. Johnson, J. Ostrometzky, I. Kadota, H. Messer, and G. Zussman, "OpenMesh Dataset, Zenodo." Nov. 2025.

INDIGO

Intelligent Networks Designed and Integrated for Globalized Operations

- **An O-RAN compatible AI-control layer that rapidly recovers** network during disasters by enabling automated interoperability and network adaptation
- **Approach:**
 - Aggregates multi-operator resources into a unified, virtual network slice using open O-RAN and TM Forum standards.
 - An AI-driven planner to decomposes mission requirements into actionable network configurations within seconds.
 - Evaluated a prototype on the COSMOS testbed, emulating a 3-operator urban disaster zone across 21 towers.
- **Successes:**
 - Rapid Usability: Non-expert users successfully generated and deployed complex network coverage plans in under six minutes.
 - Fast Planning: The AI planner returned formatted multi-operator configuration plans in an average of 10.5 seconds.
 - Effective Resource Pooling: Dynamically combined fragmented infrastructure from three separate operators to successfully deliver high-bandwidth services where individual operators failed.



• J. Drogo, A. Trumbach, S. Theiler, S. Mandava, S. Shah, I. Seskar, M. Skorupski, K. K. Ramakrishnan, K. Oikonomou, G. Zussman, and T. van Brakle, "INDIGO: Orchestration Across Multi-Operator, Multi-Vendor, 5G Networks During Civilian Disasters," in Proc. IEEE World Forum on Public Safety Technology (WF-PST), Sep. 2025.

Tutorials and Example Experiments

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Amarisoft 5G NR over FR3 with Pi-Radio Front-Ends

Run a complete Amarisoft 5G NR Stand-Alone network — 5G Core (MME), gNodeB, and UE simulator — on USRP 2974 nodes in COSMOS SB1, then upconvert the sub-6 GHz signal to 12 GHz over-the-air using Pi-Radio FR3 front-ends and verify end-to-end connectivity with an iperf3 throughput test.

Overview

This tutorial sets up a full software-based 5G NR SA network using the Amarisoft stack and COSMOS SB1's Pi-Radio FR3 infrastructure. Amarisoft provides software-defined gNB, 5G Core (MME/AMF), and UE simulator components that run on commodity PCs paired with SDR hardware.

The experiment uses two USRP 2974 nodes (each an embedded X310). One node (sdr1-piradio) runs the Amarisoft 5G Core (MME) and gNodeB; the other (sdr2-piradio) runs the Amarisoft UE simulator. Each USRP 2974 is paired with a Pi-Radio FR3 front-end (rfdev-sdr1-piradio and rfdev-sdr2-piradio respectively).

The signal path is: the USRP 2974 generates a 5G NR waveform in Band n7 (FDD, 2680/2560 MHz, 5 MHz BW). The Pi-Radio front-end on the transmit side upconverts this sub-6 GHz IF signal to ~12 GHz for over-the-air transmission. The Pi-Radio front-end on the receive side downconverts the 12 GHz signal back to the sub-6 GHz band so the USRP 2974 can process it as standard Band n7 5G NR.

Learning outcomes

After completing this tutorial you will be able to:

- ▶ Configure Pi-Radio FR3 front-ends via their web UI for frequency upconversion/downconversion.
- ▶ Launch the Amarisoft 5G Core (MME), gNodeB (SA), and UE simulator on COSMOS testbed nodes.
- ▶ Verify UE registration with the Amarisoft interactive console commands (`ue`, `gnb`, `power_on`, `cell phy`, `t`).
- ▶ Run an iperf3 UDP throughput test over a simulated 5G NR link operating at 12 GHz.
- ▶ Interpret Amarisoft link-quality telemetry (SINR, RSRP, MCS, bitrate).

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> Amarisoft 5G NR over FR3 with Pi-Radio ...

> Overview

> Learning outcomes

> At a glance

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> Resources required

> Topology

> Setup

> Instructions

> Step 1 — Configure the Pi-Radio fr...

> Step 2 — Run the 5G Core (MME) ...

> Step 3 — Run the gNodeB on sdr1-...

> Step 4 — Run the UE simulator on ...

> Step 5 — Verify UE registration in t...

> Step 6 — Run an iperf3 throughput...

> Step 7 — Inspect link-quality tele...

> Verification

> Cleanup

> Troubleshooting

> References

TAGS

tutorial

fr3

TALK

View Discussion

Education and Outreach

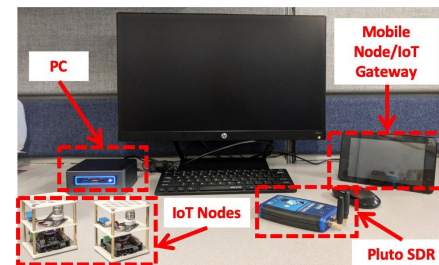


AT&T verizon

- COSMOS education toolkit: A small pre-configured COSMOS node (developed in Summers 2018–2023 RET programs by ~50 teachers) offering 100+ K–12 educational labs in Math/Science/CS
- Numerous education and outreach activities



5G COVET



COSMOS education toolkit



COSMOS Research Experiences for Teachers (RET) program



Columbia Girls' Science Day



Students in Frederick Douglass Academy using the COSMOS toolkit

- P. Skrimponis, N. Makris, K. Cheng, J. Ostrometzky, Z. Kostic, G. Zussman, T. Korakis, and S. Borges Rajguru, "Evaluation: A teacher professional development program using wireless communications and NGSS to enhance STEM teaching & learning," in *Proc. ASEE Annual Conference*, 2020.
- P. Skrimponis, N. Makris, S. Borges Rajguru, K. Cheng, J. Ostrometzky, E. Ford, Z. Kostic, G. Zussman, and T. Korakis, "COSMOS educational toolkit: Using experimental wireless networking to enhance middle/high school STEM education," *ACM SIGCOMM Computer Communication Review*, vol. 50, no. 4, pp. 58–65, 2020.

Summary

- COSMOS: A ~1 sq. mile city-scale programmable advanced wireless testbed in West Harlem, NYC
- COSMOS offers various unique capabilities:
 - A large number of sub-6GHz, FR3, and mmWave SDRs with different form factors
 - Integrated sensing and communications
 - A unique programmable optical/quantum transport network using long-range multi-hop dark fiber
 - Core and edge cloud equipped with programmable heterogeneous computing resources
 - Support for a wide range of research and experiments at-scale within an FCC Innovation Zone
- Supported experiments: smart streetscapes, dynamic spectrum, quantum networks, Full-duplex, ORAN, optical sensing, (bring your own experiment)





Thank You!

More information:

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gil@ee.columbia.edu



COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Duke

