Using the COSMOS testbed for measurement-based wireless, optical, edge-cloud, and smart cities research

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

COSMOS: Project Vision

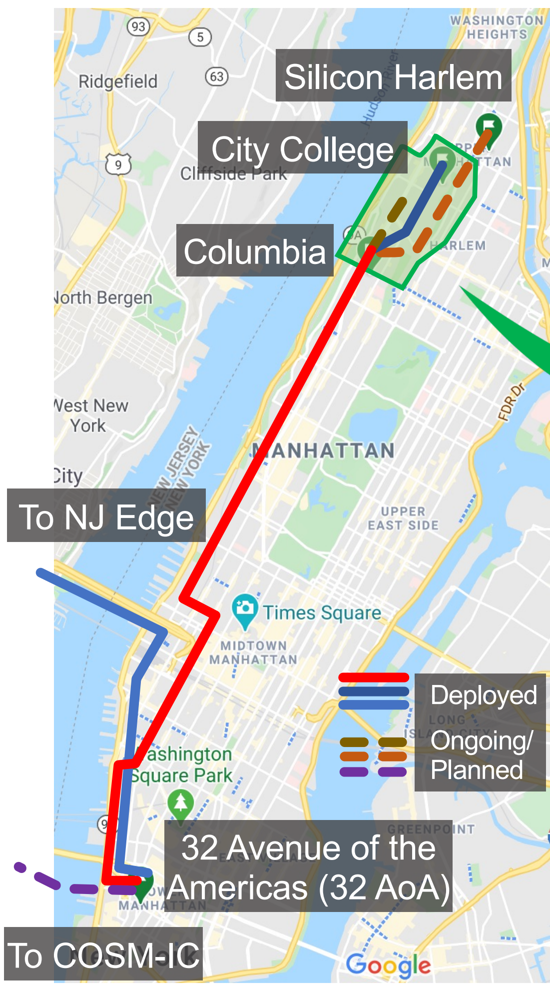
Cloud enhanced **O**pen **S**oftware-defined **MO**bile wireless testbed for city-**S**cale deployment

- **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
  - Cameras and Lidars
  - Remote-access
  - Programmability

The infrastructure can enable data collection and evaluation of algorithms for real-time applications in domains such as AR/VR, connected cars, and smart city

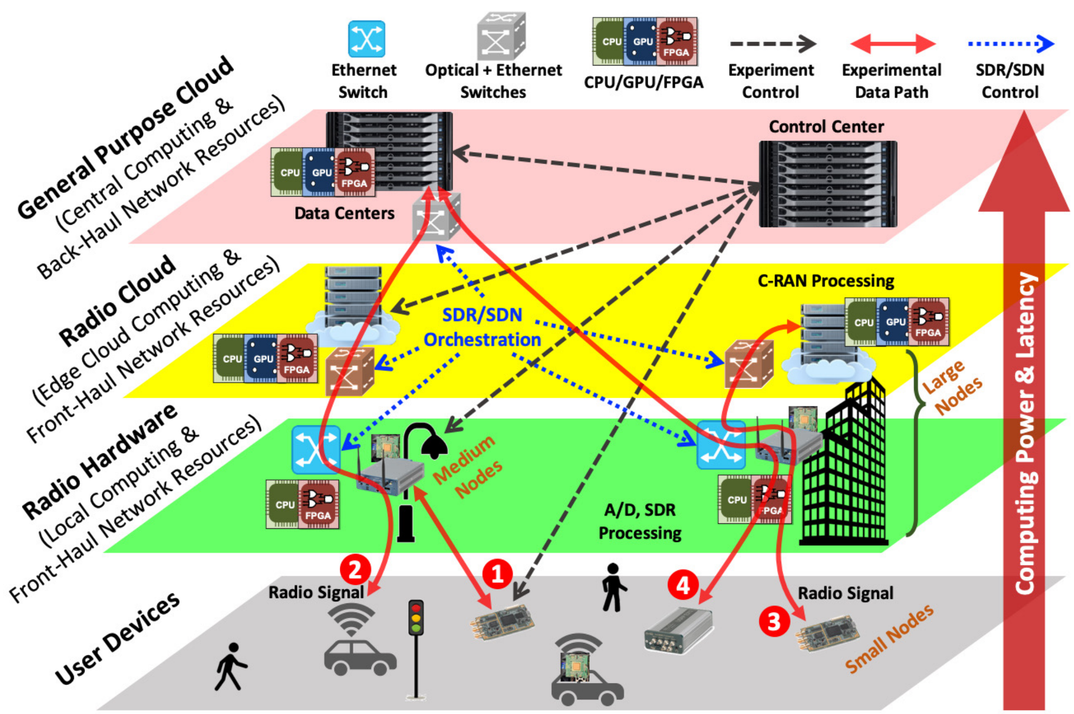
- D. Raychaudhuri, I. Seskar, G. Zussman, T. Korakis, D. Kilper, T. Chen, J. Kolodziejski, M. Sherman, Z. Kostic, X. Gu, H. Krishnaswamy, S. Maheshwari, P. Skrimponis, and C. Gutterman, "Challenge: COSMOS: A city-scale programmable testbed for experimentation with advanced wireless," in *Proc. ACM MobiCom'20*,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

COSMOS: Deployment



COSMOS: Design and Architecture

- **Key design challenge**: Gbps+ performance and full programmability from the radio level to the central/edge cloud
  - Fully programmable multi-layered computing architecture for flexible experimentation
- **Key technologies**:
  - Software-define radios (SDRs)
  - Millimeter-wave (mmWave) radios
  - Optical x-haul networks
  - Edge cloud
  - Control and management software
- **Experiment examples**:
  - Open-access full-duplex wireless 1 2
  - Optical-wireless x-haul networking 3 4
  - Smart intersections 3



COSMOS's multi-layered computing architecture

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NYU
NYC
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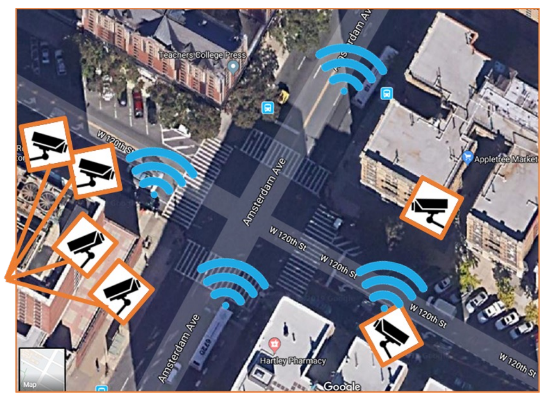
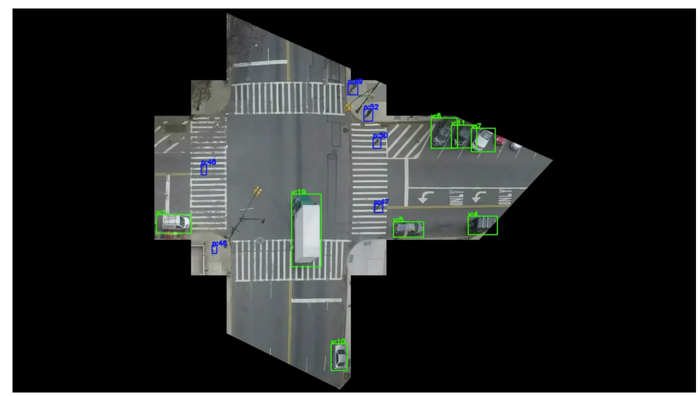
IBM

Example Experiment: Smart Intersection (with Kentyou)

- Edge cloud computing and inference for support of cloud assisted vehicles
- Sensor data acquisition: low latency & high bandwidth wireless links
- **Real-time** (latency) – useful for traffic interaction/management
  - Vehicle speed: 10 km/h → ~3 m/s → **~0.1 m in 1 frame of a video** (@30 fps)
  - Useful to prevent accidents, target round-trip latency = 1/30 second



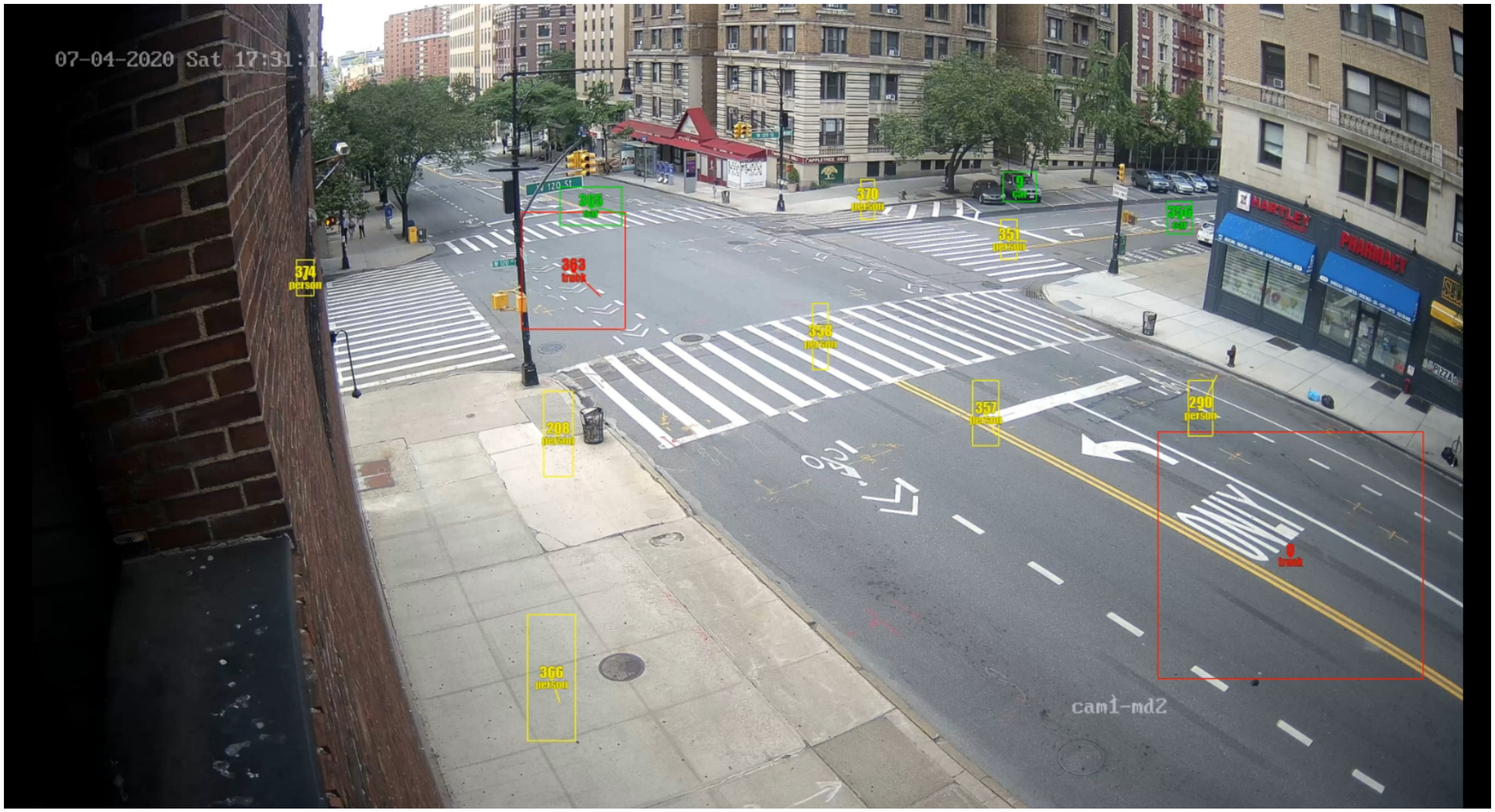
120th St and Amsterdam



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

- Z. Kostic, 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 (to appear)*, Dec. 2022.

Visualization on Kentyou User Interface



Only obtained information (the raw video **will not** be sent to preserve privacy) is sent to **Kentyou UI.**

M. Ghasemi, S. Kleisarchaki, T. Calmant, J. Lu, S. Ojha, Z. Kostic, L. Gürgen, G. Zussman, and J. Ghaderi, "Demo: **Real-time Multi-Camera Analytics** for Traffic Information Extraction and Visualization," *Proc. IEEE PerCom'23*, Mar. 2023.

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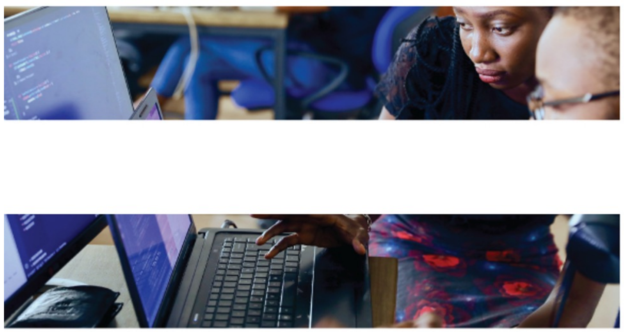

NSF ENGINEERING RESEARCH CENTER FOR SMART STREETSCAPES (CS3)

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mmWave Measuements

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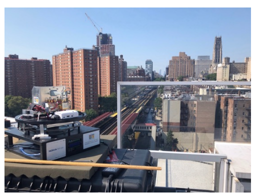
- 28 GHz channel measurements in the COSMOS testbed area in a **dense urban canyon** environment
  - Representative (potential) deployment sites of mmWave BSs (building rooftops, street lightpoles, etc.)
  - Extensive measurements on **long sidewalks** (up to 1,100 m) with **fine-grained link step size** (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

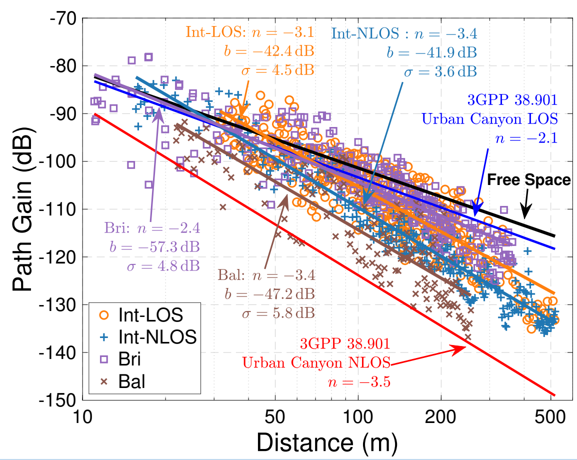
4-way city intersection



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 Measuements

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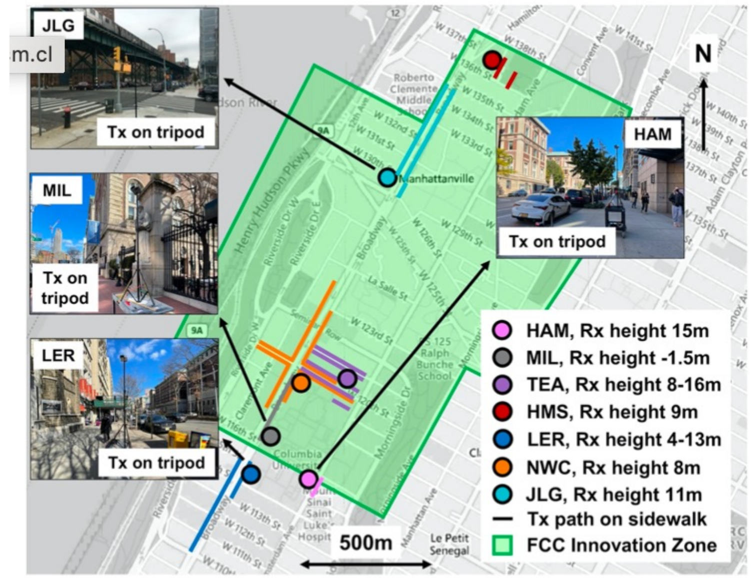
- Extensive outdoor-to-indoor measurements within different buildings: **29+ million** measurements were collected from over **2,200 links** in **7 different sites**

Outdoor-to-outdoor measurements

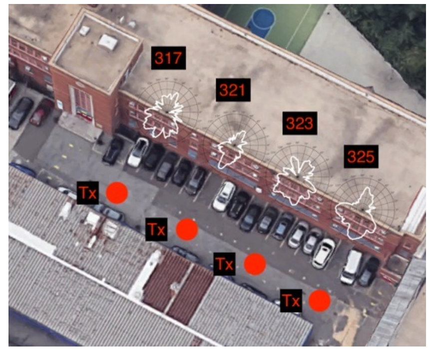


Outdoor-to-indoor measurements

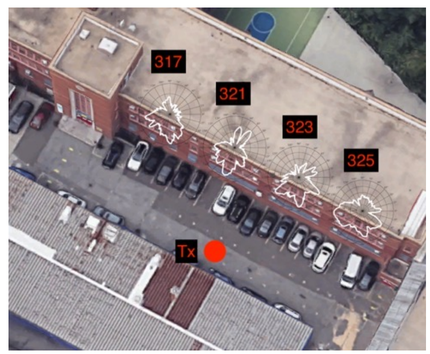
- M. Kohli, A. Adhikari, G. Avci, S. Brent, A. Dash, J. Moser, S. Hossain, I. Kadota, C. Garland, S. Mukherjee, R. Feick, D. Chizhik, J. Du, R. Valenzuela, and G. Zussman, "Outdoor-to-indoor 28 GHz wireless measurements in Manhattan: Path loss, environmental effects, and 90% coverage," *Proc. ACM MobiHoc*, Oct. 2022.

Case Study at a Middle School

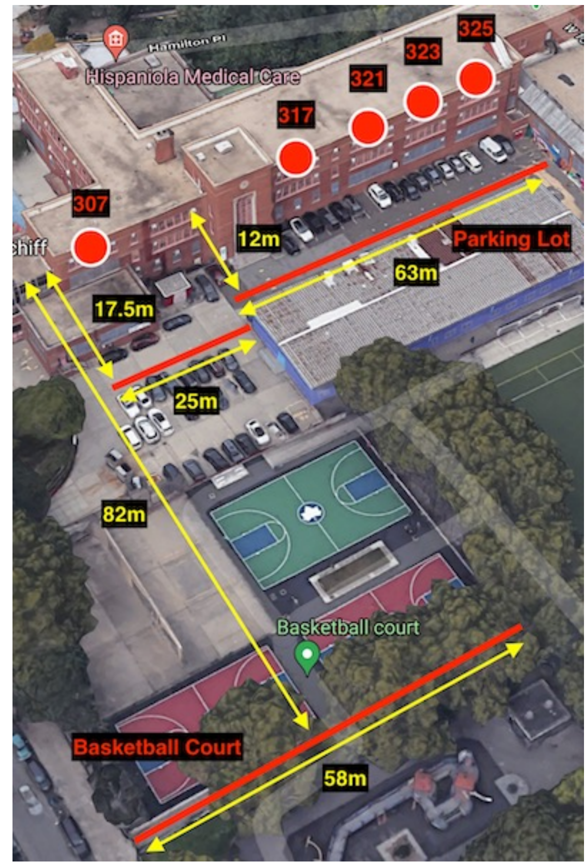
- Hamilton Grange Middle School in West Harlem, NYC
- Measurements taken from transmitter locations in school parking lot and basketball courts to five different classrooms
- Classroom measurements show the feasibility of coverage from an outdoors mmWave transmitter
  - Worst-case Shannon capacity of 1.3 Gbps
- Dataset publicly available



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

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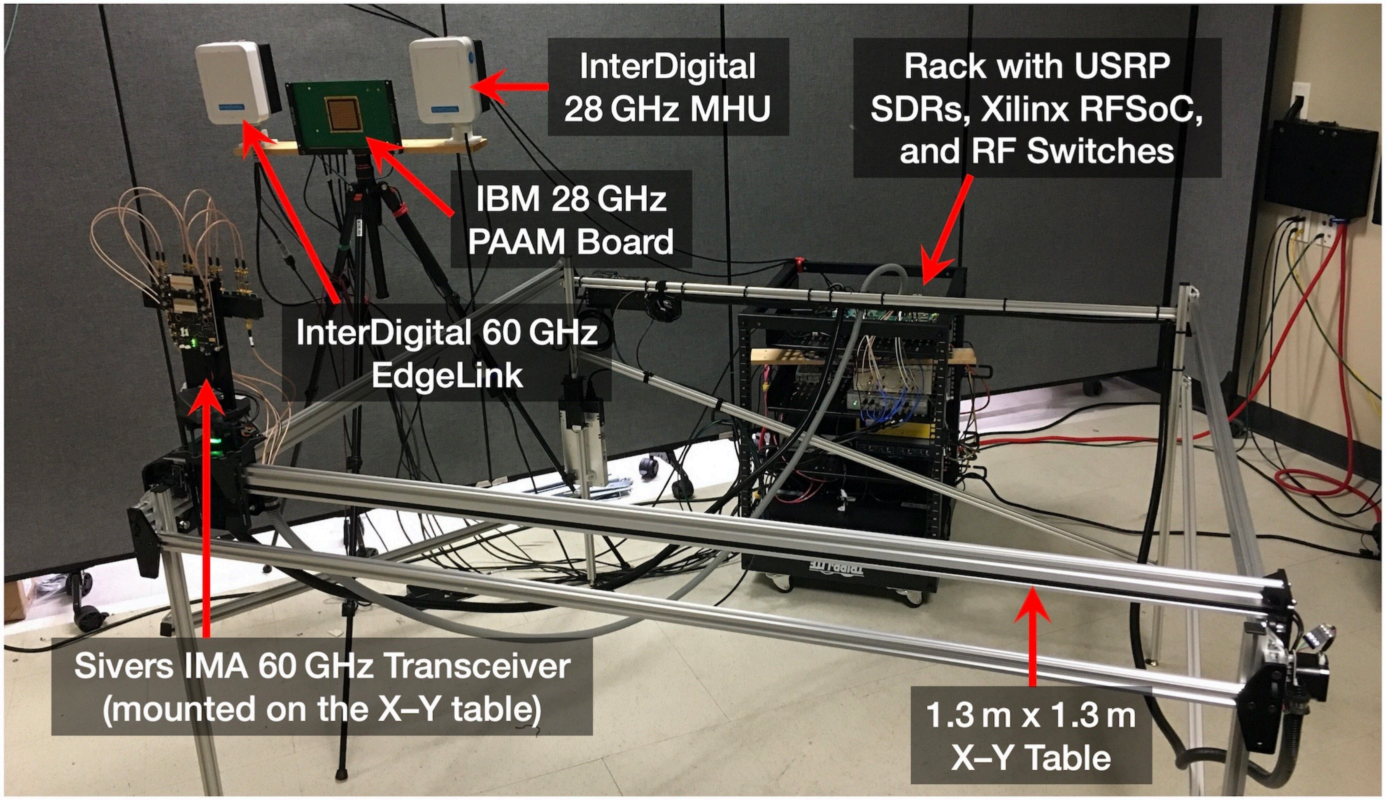
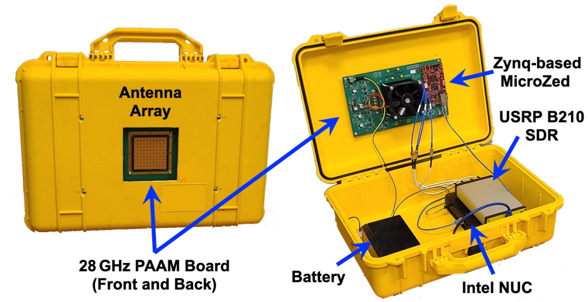
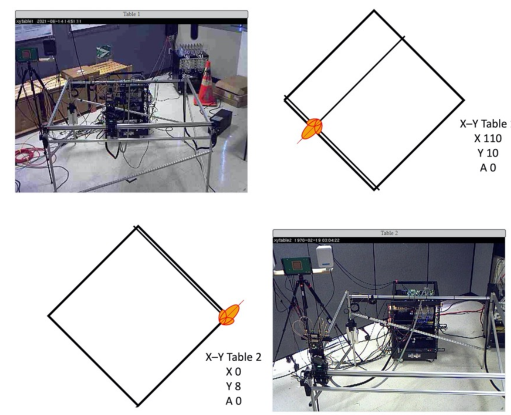
Key Technology: mmWave



Programmable mmWave radios and end-to-end mmWave systems in Sandbox 1 @Rutgers



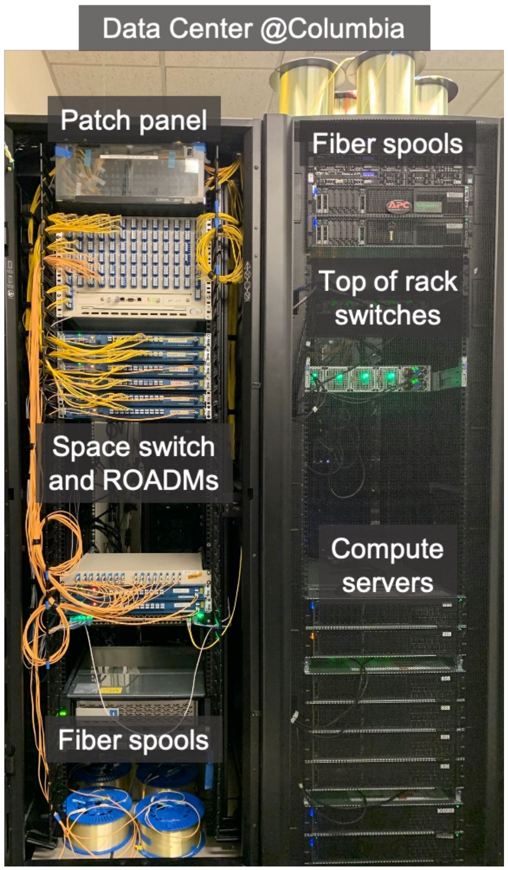
A programmable mobile 28 GHz radio

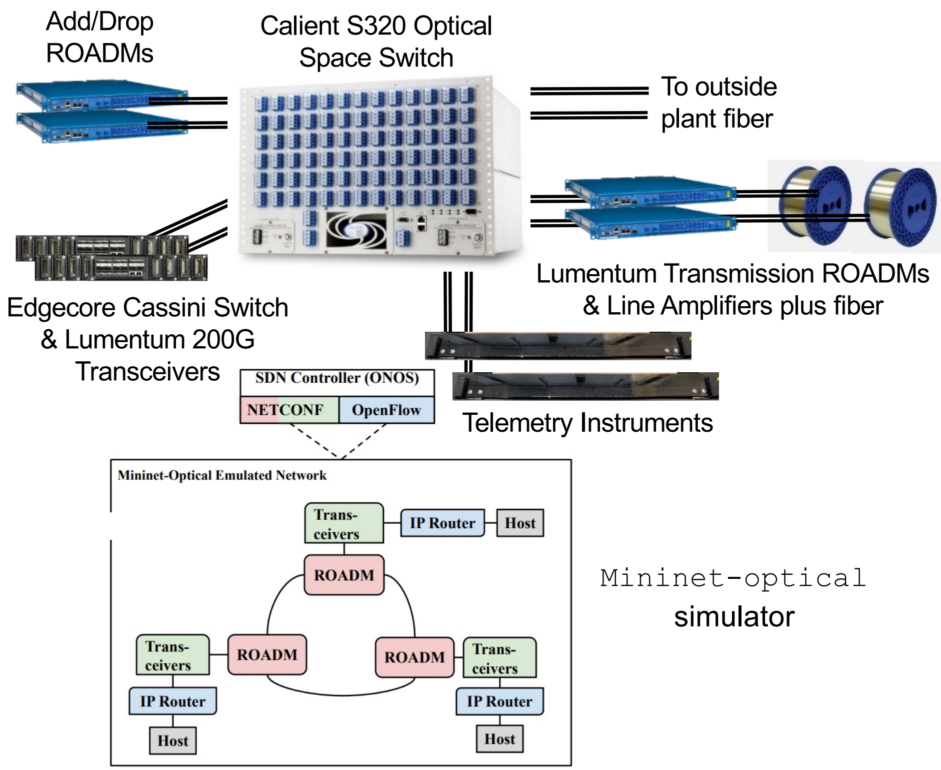


Remote control of the X-Y Table

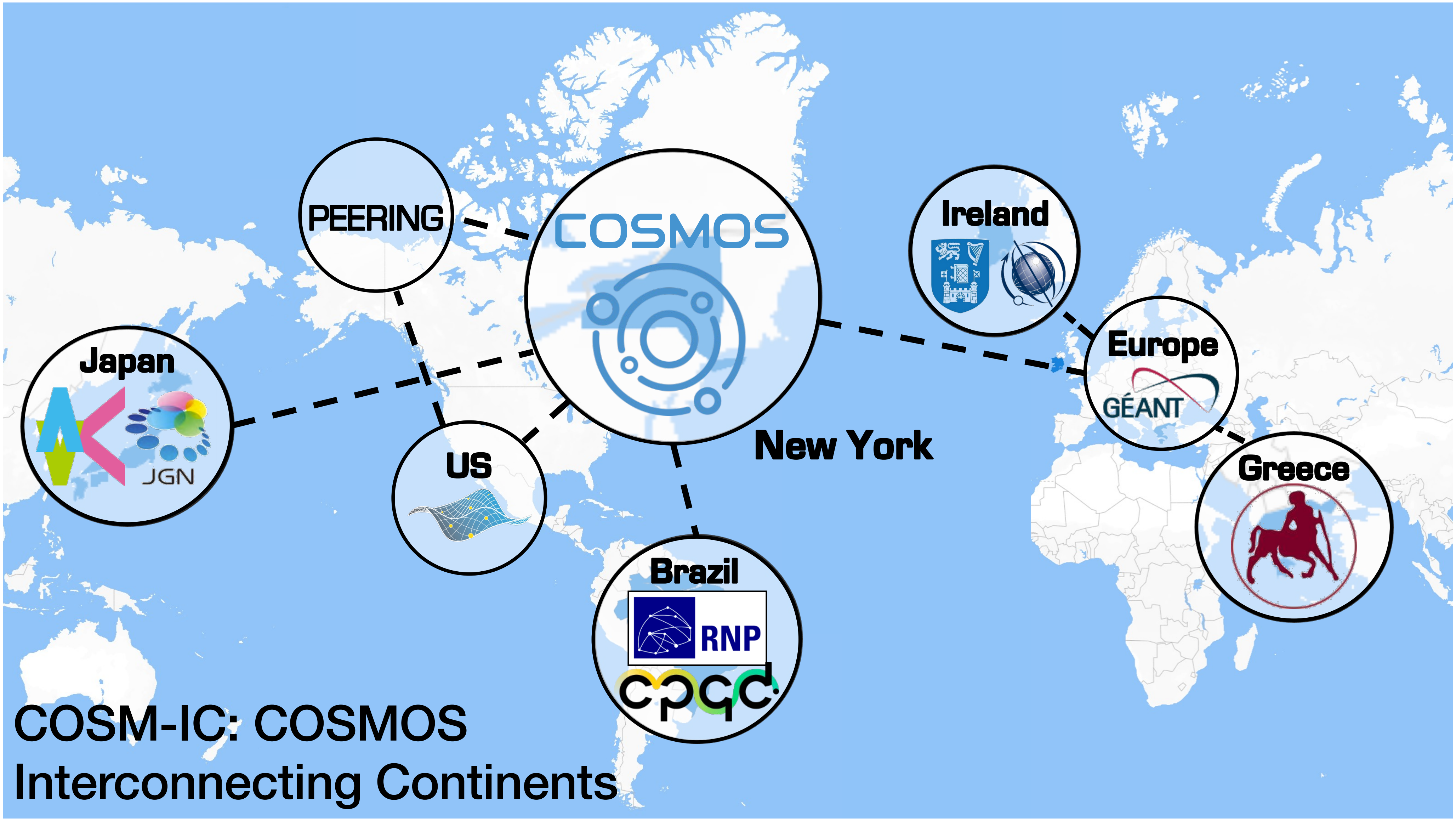
- T. Chen, P. Maddala, P. Skrimponis, J. Kolodziejski, X. Gu, A. Paidimarri, S. Rangan, G. Zussman, and I. Seskar, "Programmable and open-access millimeter-wave radios in the PAWR COSMOS testbed," in *Proc. ACM MobiCom'21 Workshop on Wireless Network Testbeds, Experimental evaluation & CHaracterization (WiNTECH'21)*, 2021.

Optical Networking





- 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.
- K. Huang, Z. Wang, E. Ip, Z. Qi, G. Zussman, D. Kilper, K. Asahi, H. Kageshima, Y. Aono, and T. Chen, "Field trial of coexistence and simultaneous switching of real-time fiber sensing and 400GbE supporting DCI and 5G mobile services," in *Proc. IEEE/OSA Optical Fiber Communication Conference (OFC'23)*, W3H.4, Mar. 2023, **Top scored paper**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Tutorials and Datasets

COSMOS Cameras Data-set

- 1st-floor videos (anonymized): https://drive.google.com/drive/u/0/folders/1QXrfsLXEKfRfQyc6qzvtg37A0Z1i0io5
- 2nd-floor videos (anonymized): https://drive.google.com/drive/u/0/folders/1LR7H4theRazz2_uYHvCFGVVewQmKbWSF
- 12th-floor videos (120th St.): https://drive.google.com/drive/u/0/folders/1SEsocAAIReepdjE4XyVyT4kiqrunv7BU
- 12th-floor videos (Amsterdam Ave.): https://drive.google.com/drive/u/0/folders/1qC-62s8ohTGg-odyzo7BNw2GDv1OIeoK

The 12-th floor cameras capture images of cars and pedestrians such that neither faces nor license plates can be recognized. Therefore there is no need for post-processing for privacy protection.

Anonymization Workflow for 1st and 2nd-floor Cameras

The annonymization workflow is described in the following paper and also described briefly below. We would app datasets above.

A. Angus, Z. Duan, G. Zussman, and Z. Kostic, "Real-Time Video Anonymization in Smart City Intersections," i

Videos from the 1st and 2nd floor, saved in this directory, are the outputs of the COSMOS YOLOv4 blurring pipeli

Faces and license plates are anonymized with Gaussian blurred areas defined by bounding box detection coordin

1. Frames are read individually from a video file.
2. Each frame is:

Datasets

This wiki page includes information about the datasets collected using the COSMOS testbe

Wireless Datasets

- COSMOS large and medium node coverage measurements
- Outdoor-to-indoor 28GHz wireless measurements in manhattan

Optical Datasets

- COSMOS ROADM EDFA gain spectrum measurement dataset

Smart City Datasets

- COSMOS camera dataset

IBM 28GHz PAAM Basics

Description

In this tutorial, we demonstrate the basic use of the IBM 28 GHz phased array antenna modules (PAAMs) with USRP N310 software-defined radios (SDRs) in the COSMOS Sandboxes (sb1, sb2).

The following paper describes the integration of the IBM 28 GHz PAAMs (beta-version) with USRP SDRs in the COSMOS testbed. We would appreciate it if you cite this paper when publishing results obtained using the PAAMs deployed in COSMOS.

- T. Chen, P. Maddala, P. Skrimponis, J. Kolodziejski, 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 Mobi Com?'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.

Author: Tingjun Chen, Duke University (tingjun.chen [at] duke [dot] edu)

Last updated: Mar. 26, 2022

More details can be found on https://wiki.cosmos-lab.org

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Summary

- COSMOS – A city-scale programmable advanced wireless testbed in West Harlem
  - Enables ongoing research on wireless/optical networks and smart cities
  - Deployed within an FCC innovation Zone
- Supported experimentation:
  - Full Duplex, mmWave, Optical-wireless x-haul networking, ORAN, Dynamic spectrum access, International experiments (COSM-IC), Smart intersections and edge cloud
- Offers various unique capabilities both in term of data collection and experimentation/deployment
- “Learning for networks” is being studied for smart intersections and edge cloud, full duplex, optics, dynamic spectrum access

Thank You!

More information:

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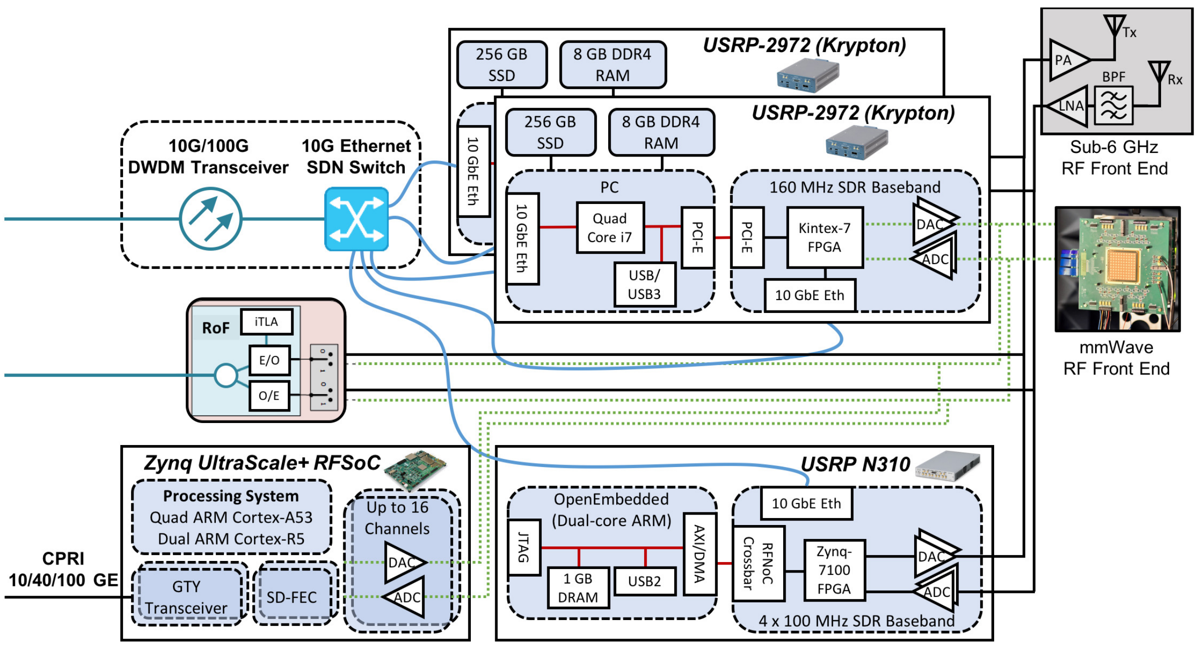
Key Technology: Software-Define Radios

- Software-defined radio (SDR) nodes at various performance levels and form factors:
  - (i) 0.4–6 GHz bands, (ii) 28/60 GHz bands (with up to ~500 MHz bandwidth), Gbps
- Signal processing can be spread between radio node & edge cloud RAN



COSM-IC - Federation of Testbeds

- To scale up
- To use/combine special resources (e.g. mmWave, wireless robots, high-performance computing, etc.)
- To re-use experiments (class exercises, scientifically, …)
- Redundancy (e.g., testbed in maintenance)