The COSMOS Testbed – a Platform for Advanced Wireless, Smart Cities, Edge-cloud, and Optical Experimentation

SIGCOMM Tutorial – Intro to COSMOS

August 22, 2022

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

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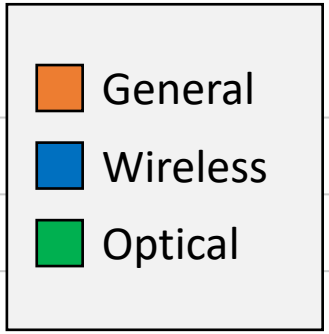
Presenter Intro + Outline

- List of presenters
  - Abhishek Adhikari
  - Julie Raulin
  - Agastya Raj
  - Bob Lantz (Zoom)
  - Zehao Wang (Zoom)
  - Panagiotis Skrimponis (Zoom)
  - Jennifer Shane (Zoom)
- How do you benefit from this tutorial?
  - Go to the wiki
  - Understand high level motivation
  - Try the SDRs
    - Outdoor/indoor at sub-6 and mmWave
  - Try Mininet-optical
    - Vision is to be a digital twin of the cosmos optical testbed



Before	Signup Instructions
1:30PM	Cosmos Testbed Overview
1:50PM	Introduction to Experimentation
2:10PM	Hello World SDR Experiment
2:30PM	Introduction to Mininet-Optical
3:00PM	Mininet-Optical Experiment
3:30PM	Coffee Break with Educational Toolkit Presentation
4:00PM	Massive MIMO
4:20PM	28 GHz and 60 GHz mmWave
4:40PM	Optical Testbed Tutorial

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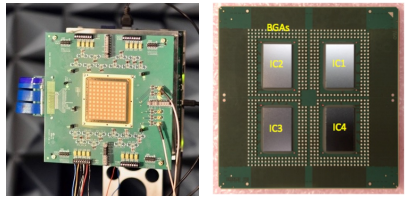
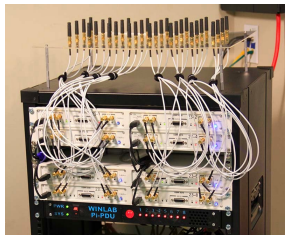
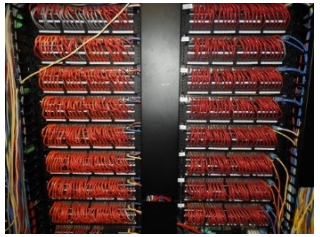
Developing Future Wireless Networks

Researchers' objective: design, prototype, and evaluate technologies for the **wireless edge** to enable novel modes of interaction between **city residents** and the **urban environment**



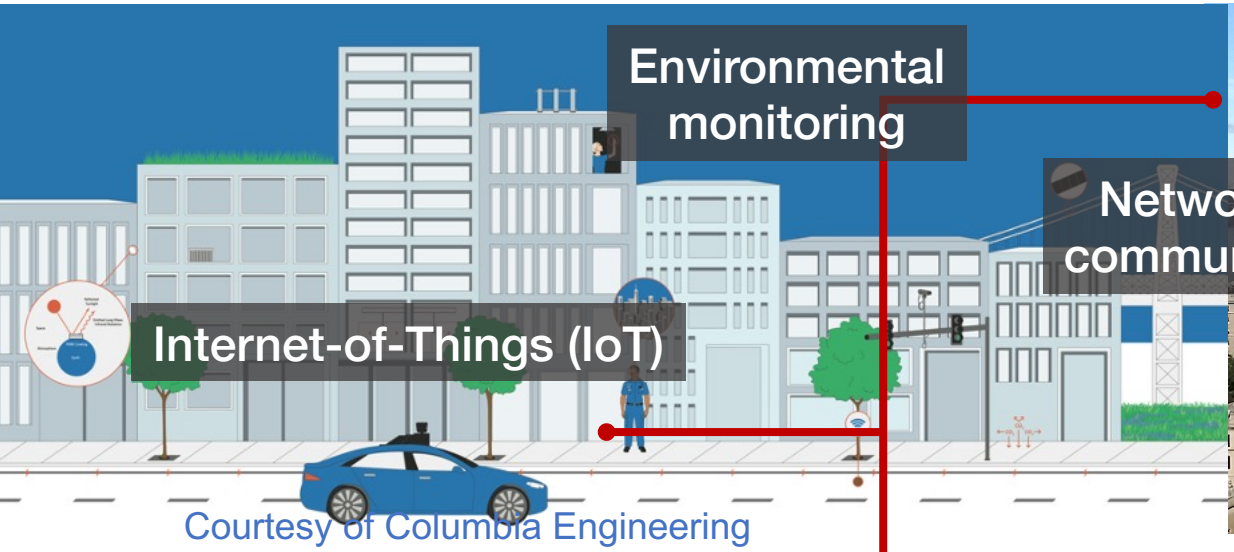


Multi-antenna



Edge cloud

Millimeter-wave



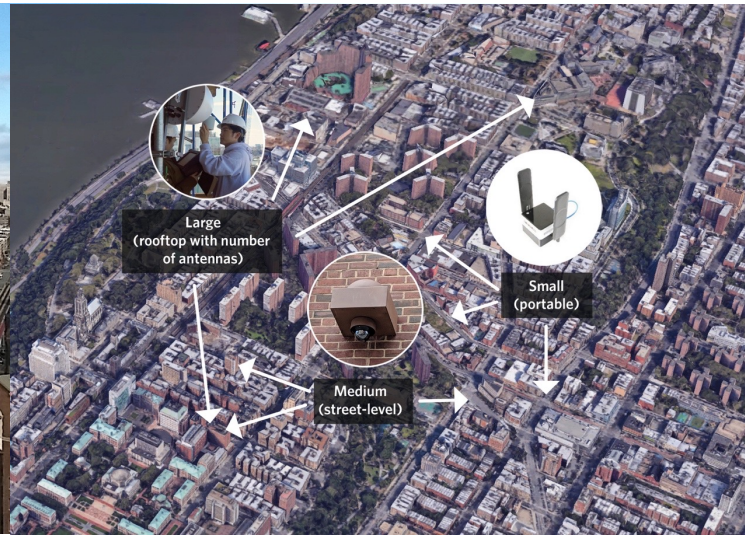
Environmental monitoring

Internet-of-Things (IoT)

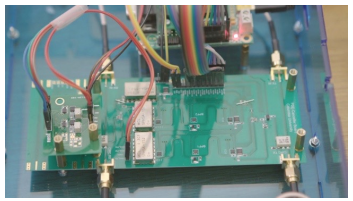
Courtesy of Columbia Engineering

Networking & communications

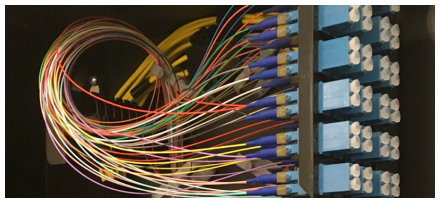
Transportation systems



Full-duplex



Optical x-haul



NSF PAWR COSMOS wireless testbed in West Harlem, NYC

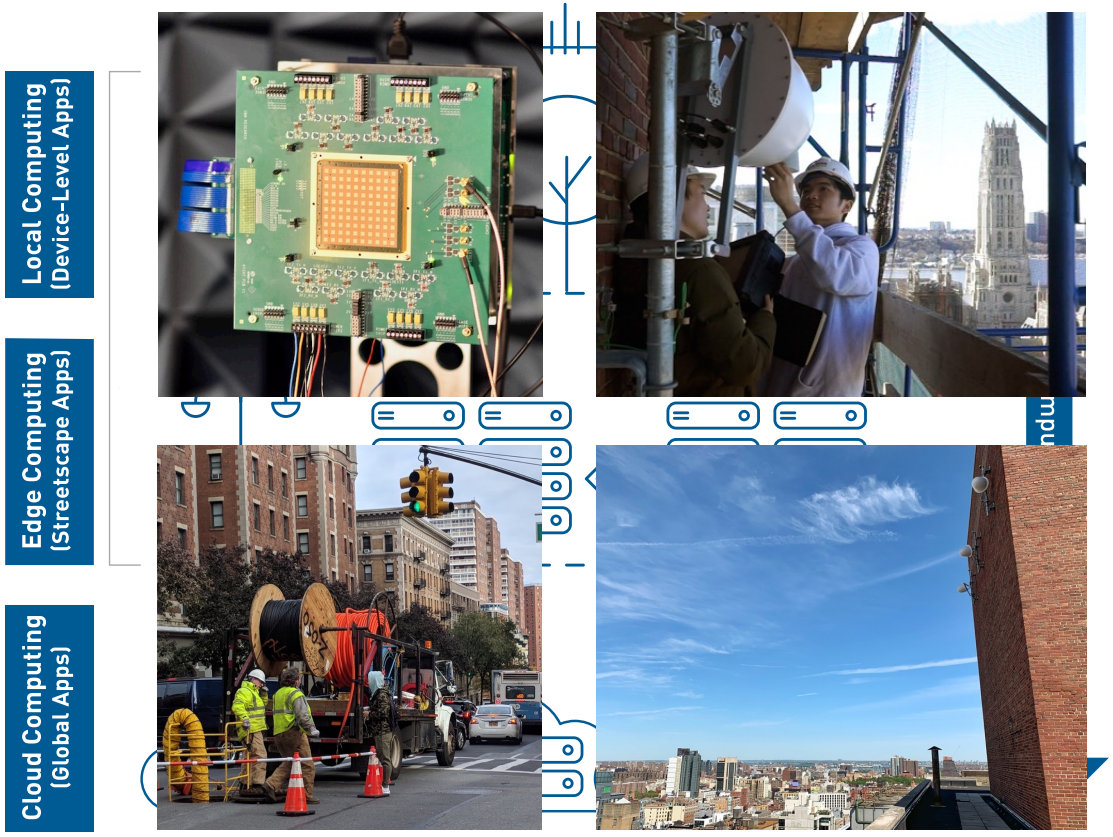
NSF Platforms for Advanced Wireless Research

COSMOS

COSMOS

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
  - Remote-access
  - Programmability



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 city (with high-bandwidth sensing),

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Wireless Testbeds (PAWR)

- Supported by the $100M NSF Platforms for Advanced Wireless Research (PAWR) program

Platforms for Advanced Wireless Research

POWDER-RENEW

Salt Lake City

COSMOS

New York City

AERPAW

Research Triangle

ARA

Central Iowa

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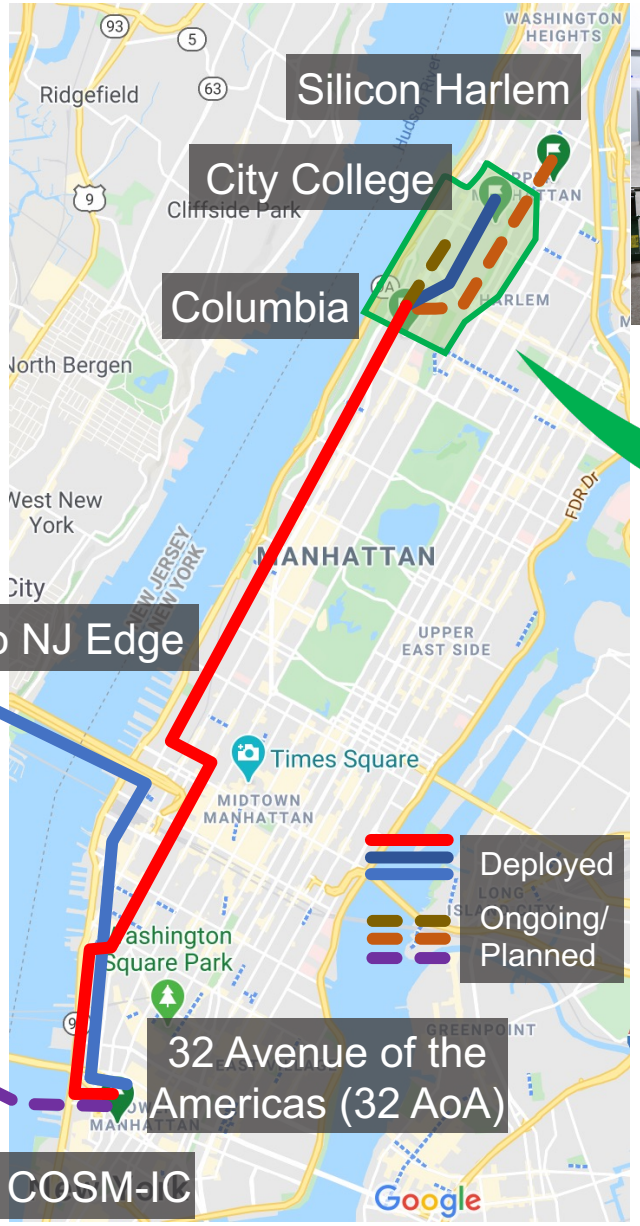
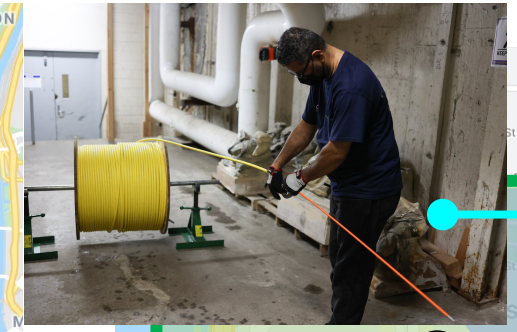
COSMOS: Envisioned Deployment





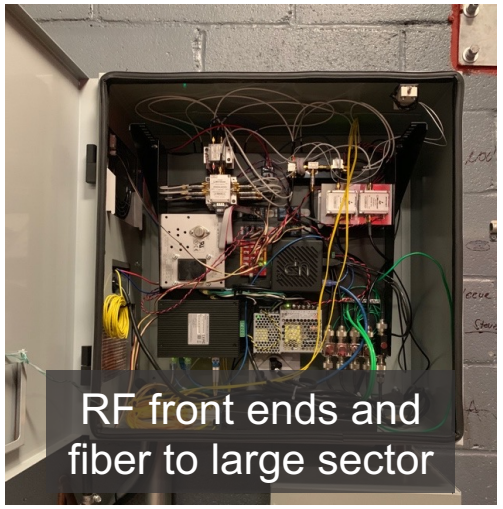
- Large Node
- Medium Node
- Columbia
- CCNY
- Light Poles
- Public Schools
- Public Housing
- Pilot
- Phase 1

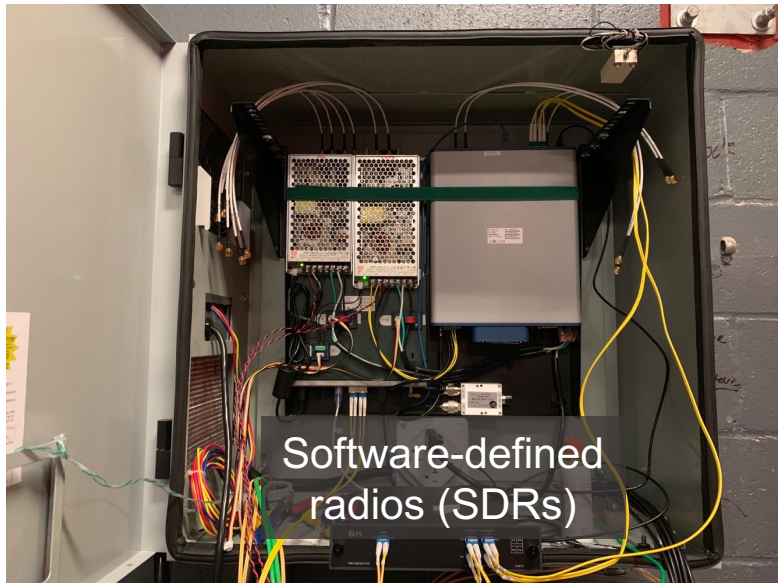
Large (rooftop)

Medium (street-level)

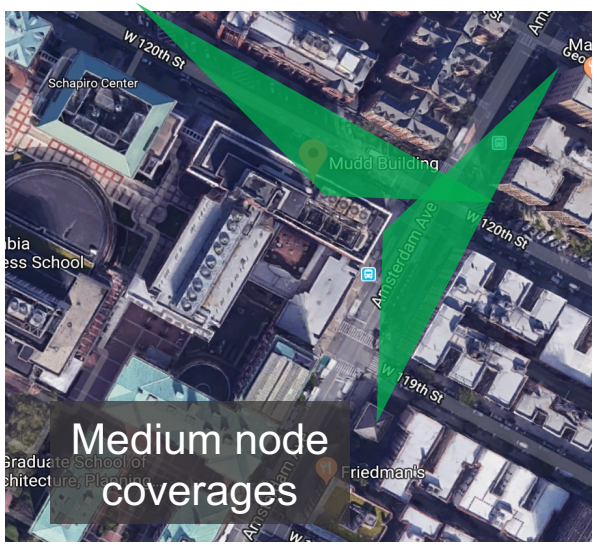
Small (portable)

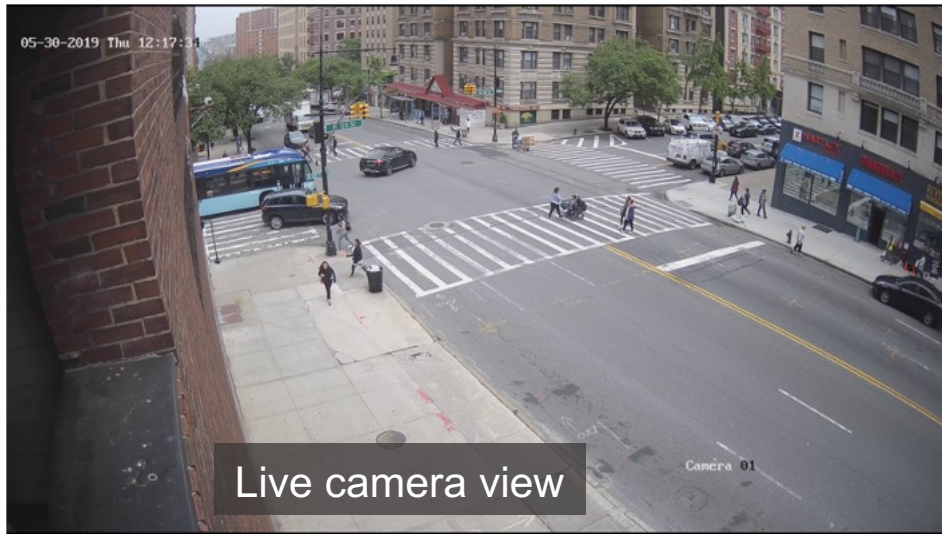
Columbia Large Node (lg1)



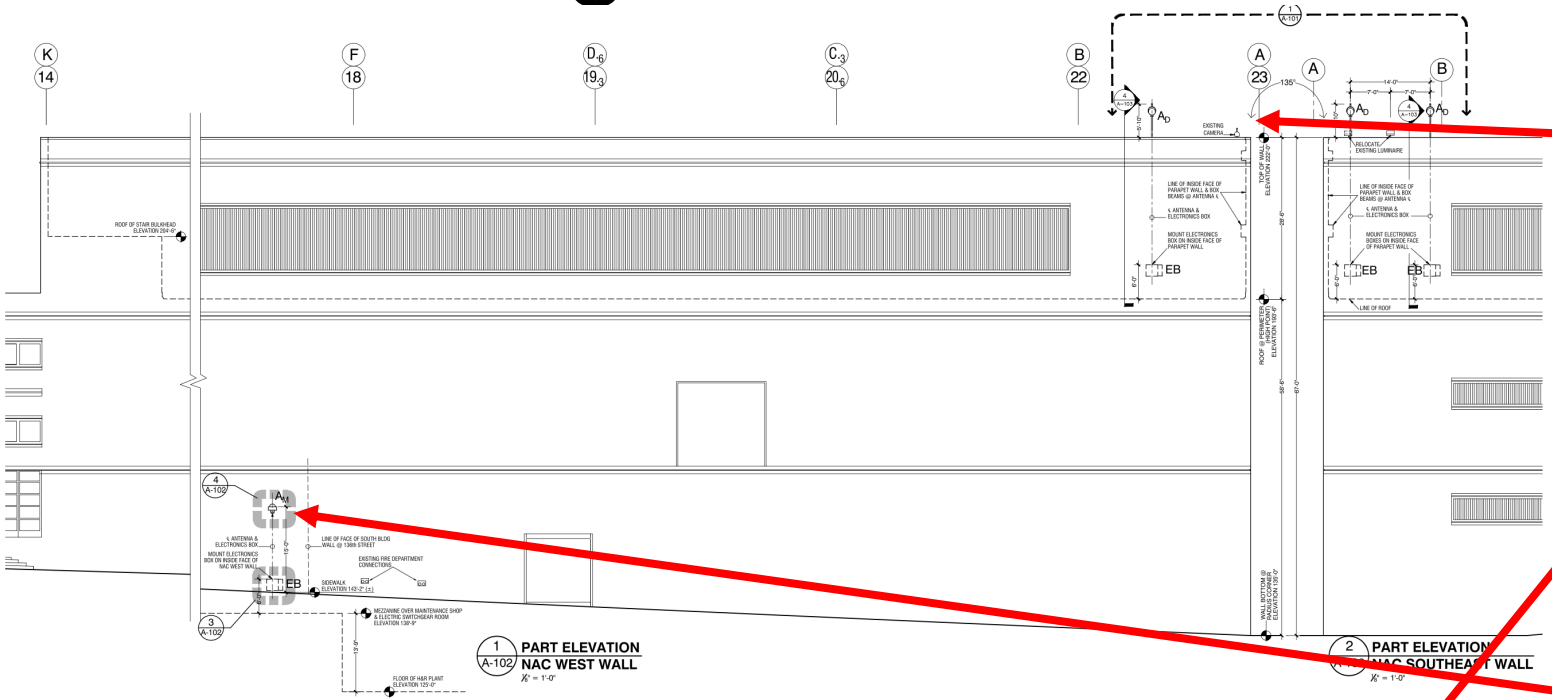


Medium Nodes (md1 and md2)



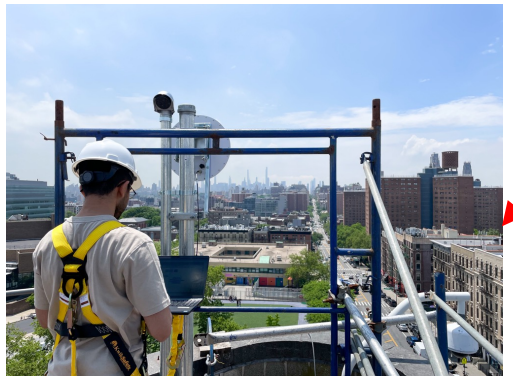


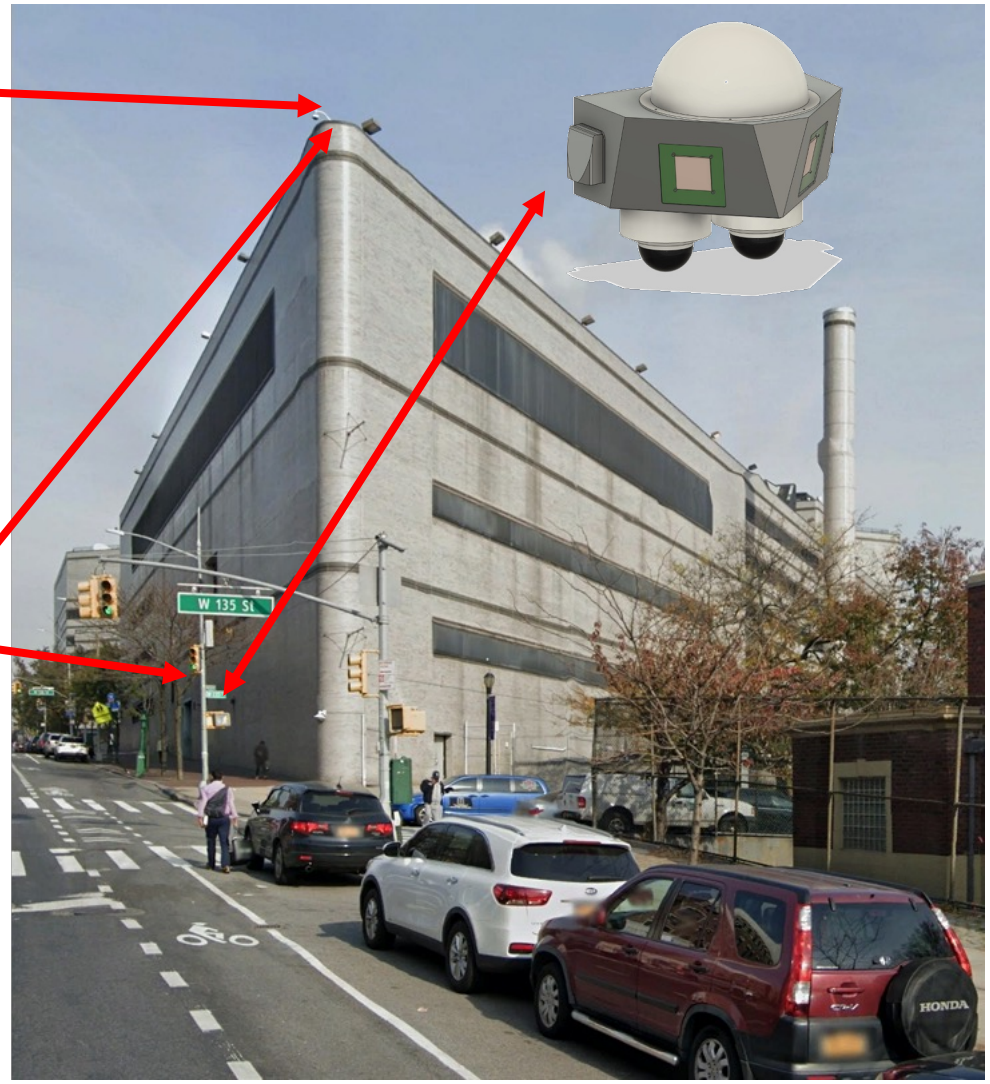
CCNY Large and Medium Nodes (lg2 and md3)



2 MEDIUM NODE | NAC WEST WALL @ 136th STREET

1 LARGE NODE | NAC H&R PLANT ROOF SOUTHWEST CORNER





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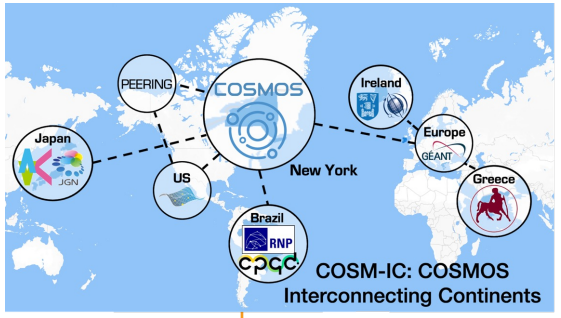
COSMOS: Project Timeline

*Deployments affected by the COVID-19 pandemic and supply chain



Dark fiber b/w Columbia and 32AoA lit up — *Oct. 2017*

Apr. 2018 — Project start

Pilot completion and the first COSMOS workshop/tutorial — *May 2019*

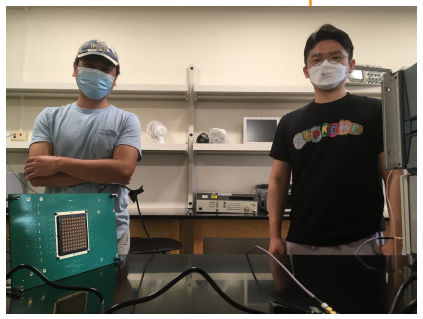
Sept. 2019 — FCC Innovation Zone

IBM 28 GHz PAAM boards delivered — *Sept. 2020*

Nov. 2020 — COSM-IC

Dark fiber b/w Columbia and CCNY lit up — *Dec. 2021*

*During 2022** — Phase 1 completion



COSMOS

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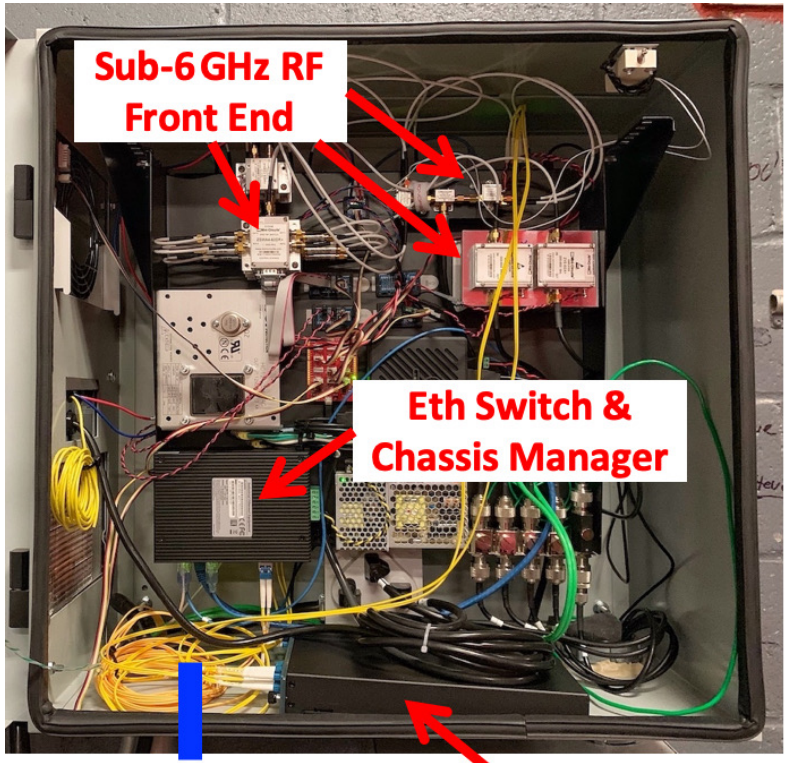
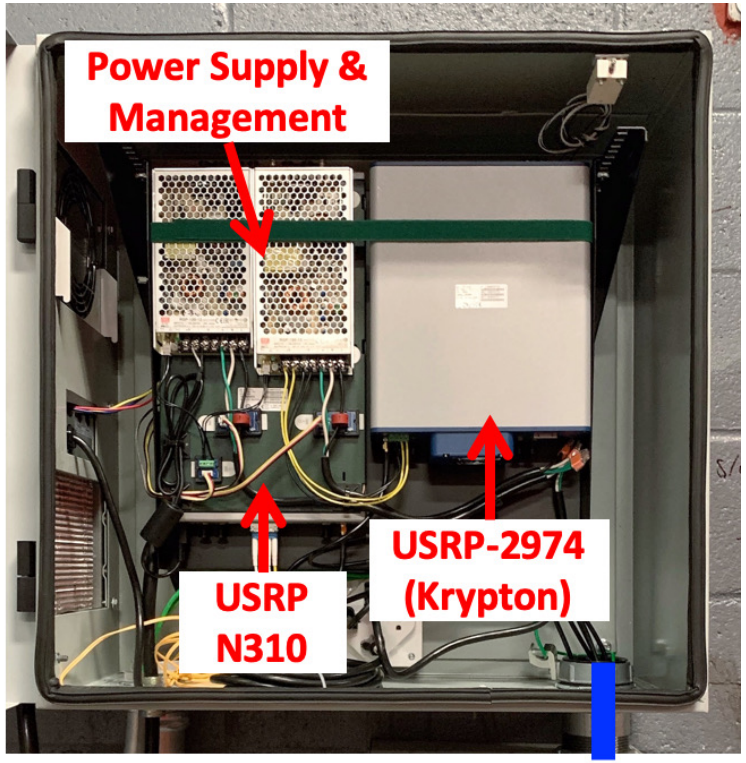
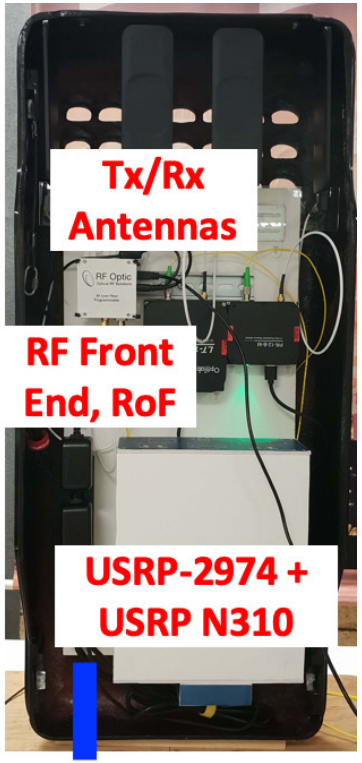
Key Technology: Software-Defined Radios





A large node sector or a medium node



Medium-light node (lightpole-mounted)

Small portable

Hand-held

Small mobile node

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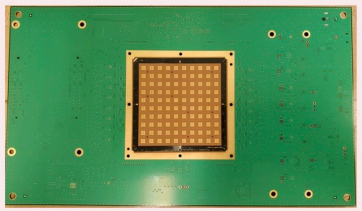
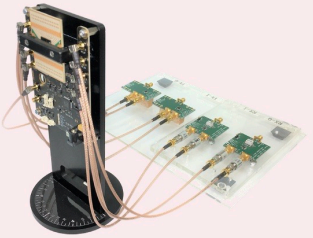
Key Technology: mmWave

- **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

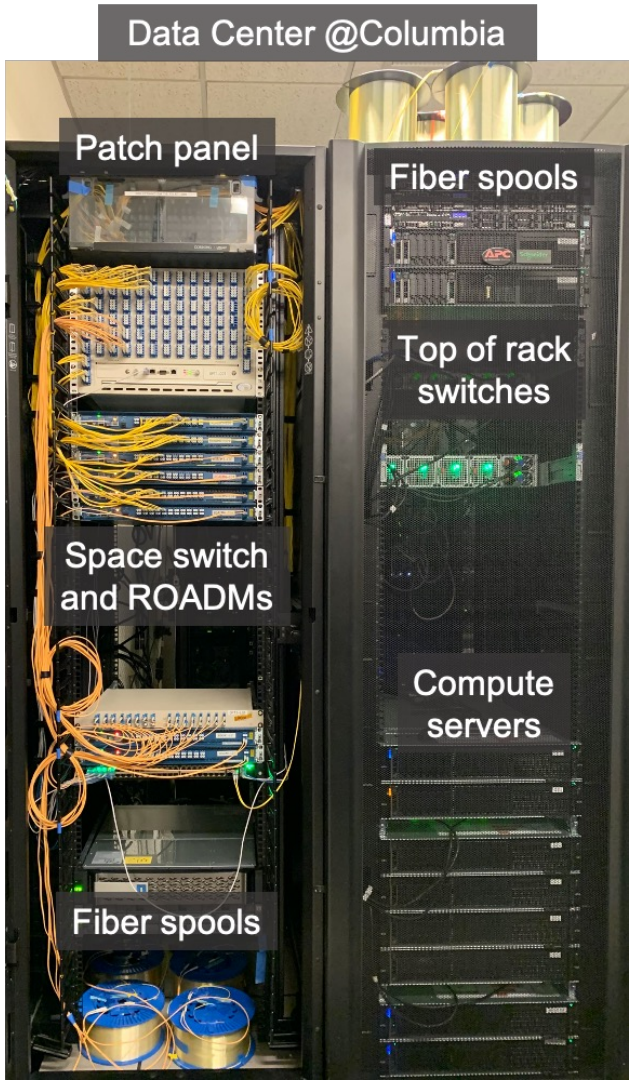
InterDigital 28 GHz 5G NR Platform

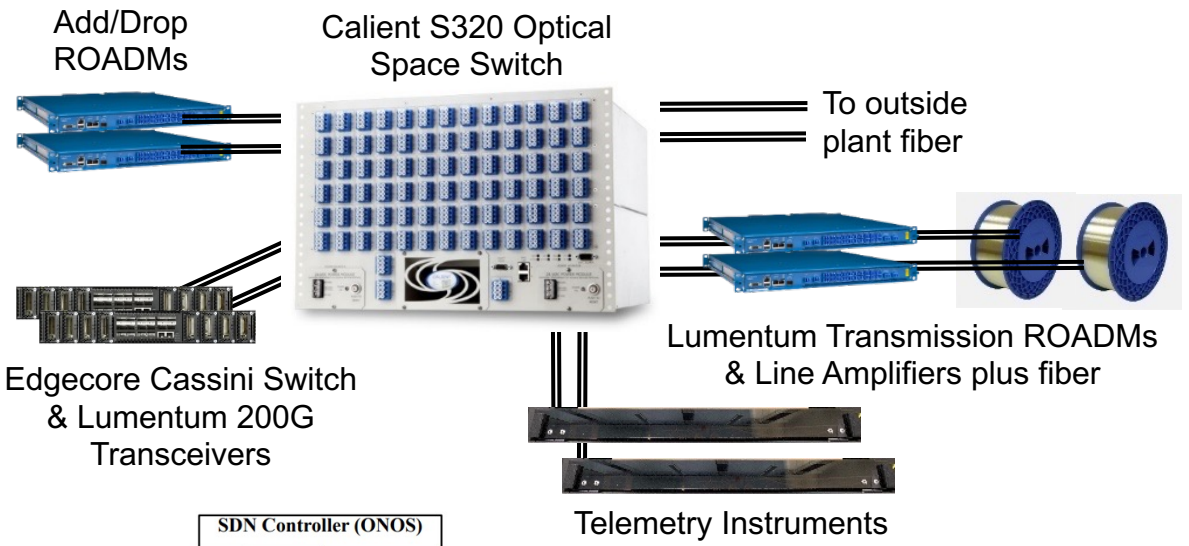
InterDigital 60 GHz EdgeLink Node

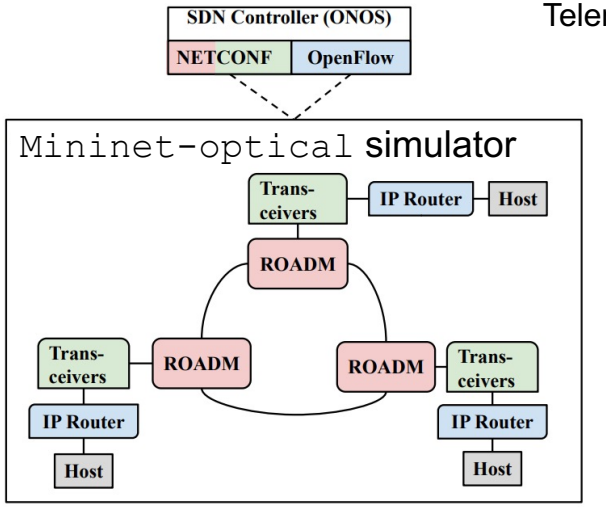
Facebook 60 GHz Terragraph Radio

- T. Chen, P. Maddala, P. Skrimponis, J. 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.
- 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)**

Key Technology: Optical Networking





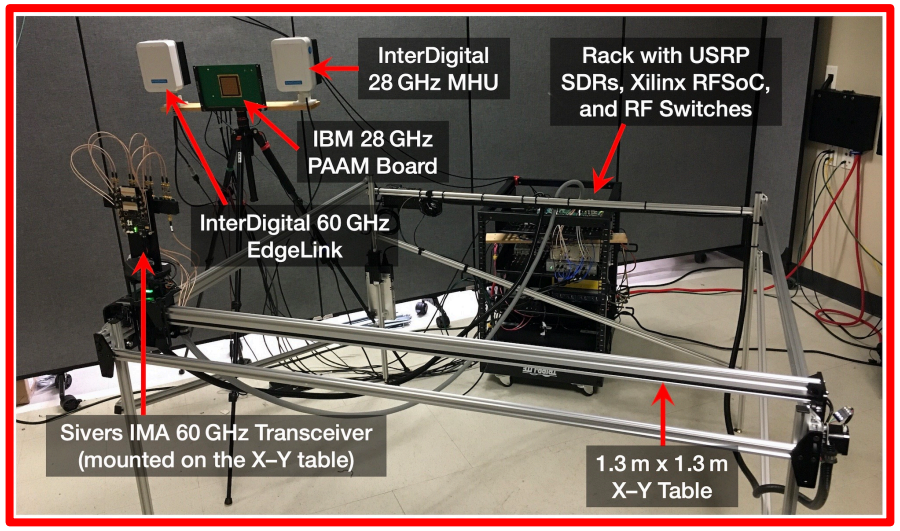


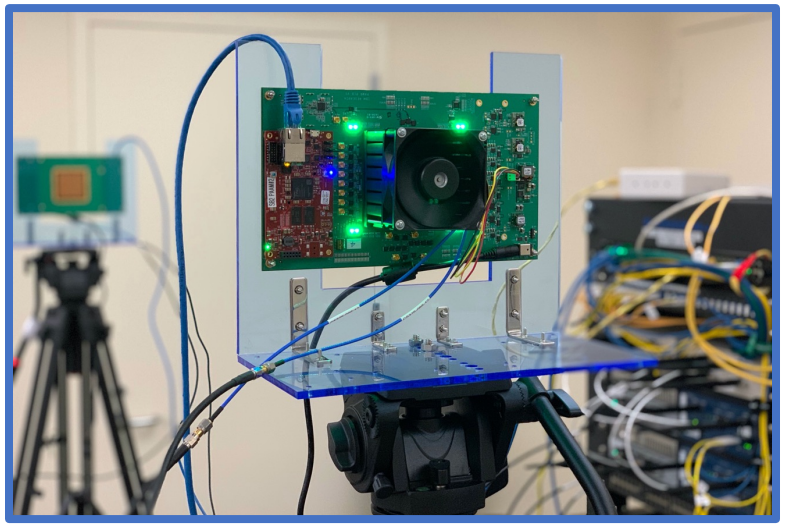
Platforms for Advanced Wireless Research

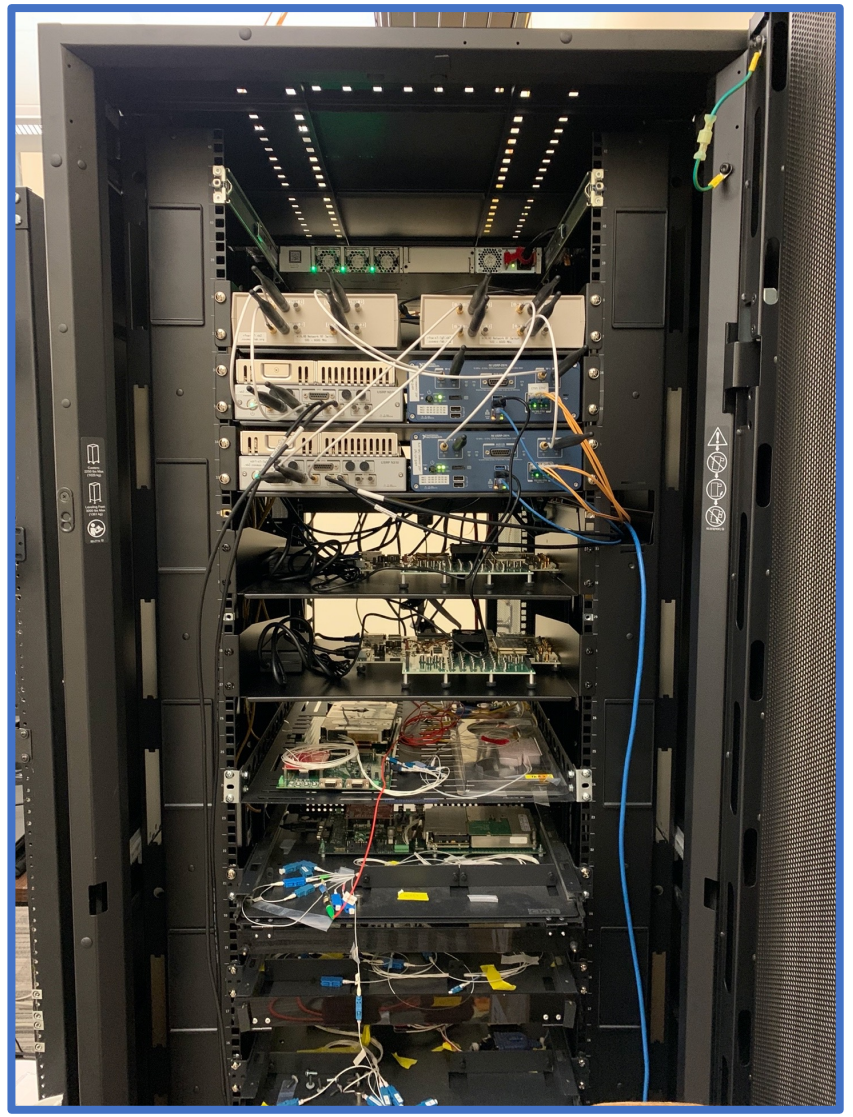
COSMOS

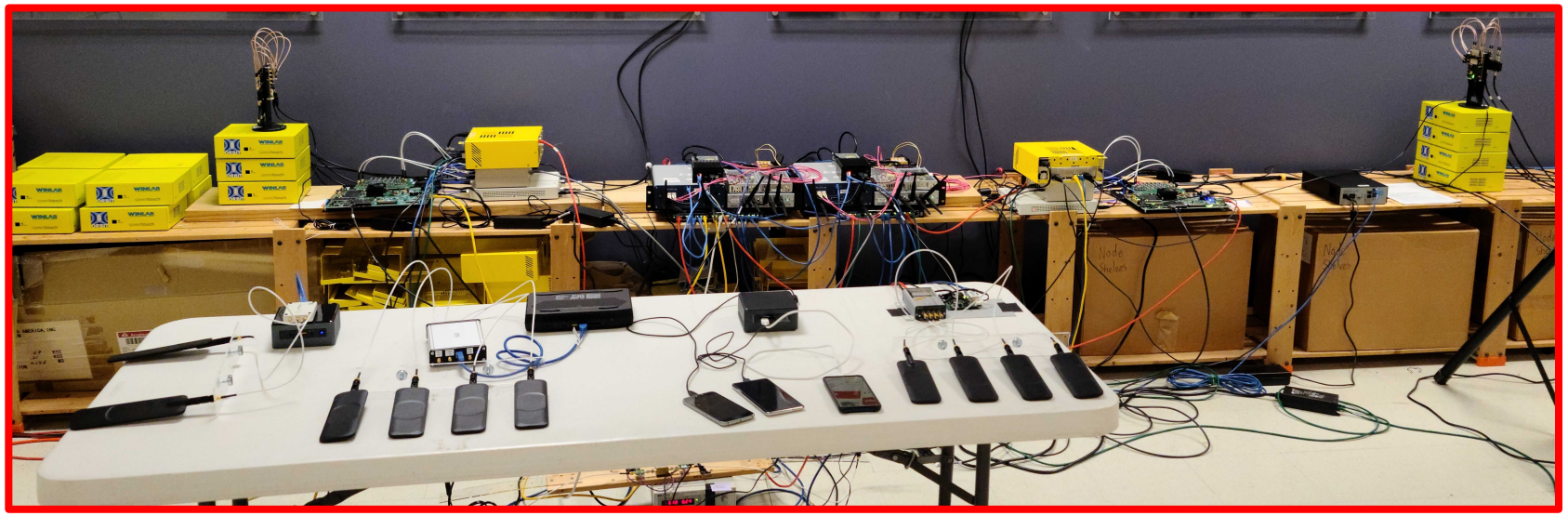
- T. Chen, J. Yu, A. Minakhmetov, C. Gutterman, M. Sherman, S. Zhu, S. Santaniello, A. Biswas, I. Seskar, G. Zussman, and D. Kilper, "A software-defined programmable testbed for beyond-5G optical-wireless experimentation at city-scale," *IEEE Network, Special Issue on Next-Generation Optical Access Networks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

Rutgers and Columbia Sandboxes (sb1 and sb2)







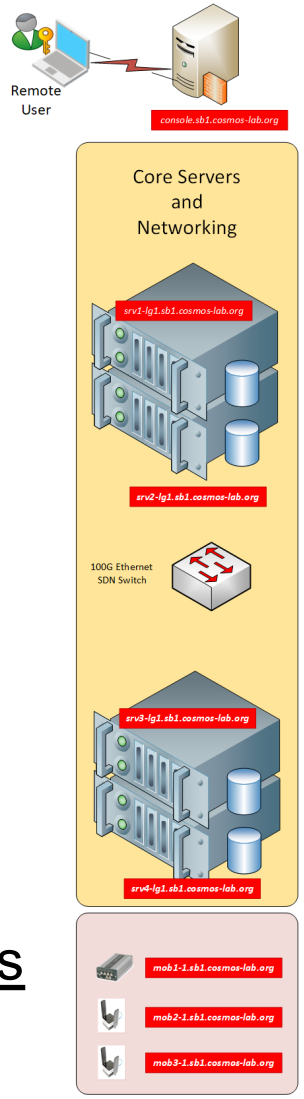


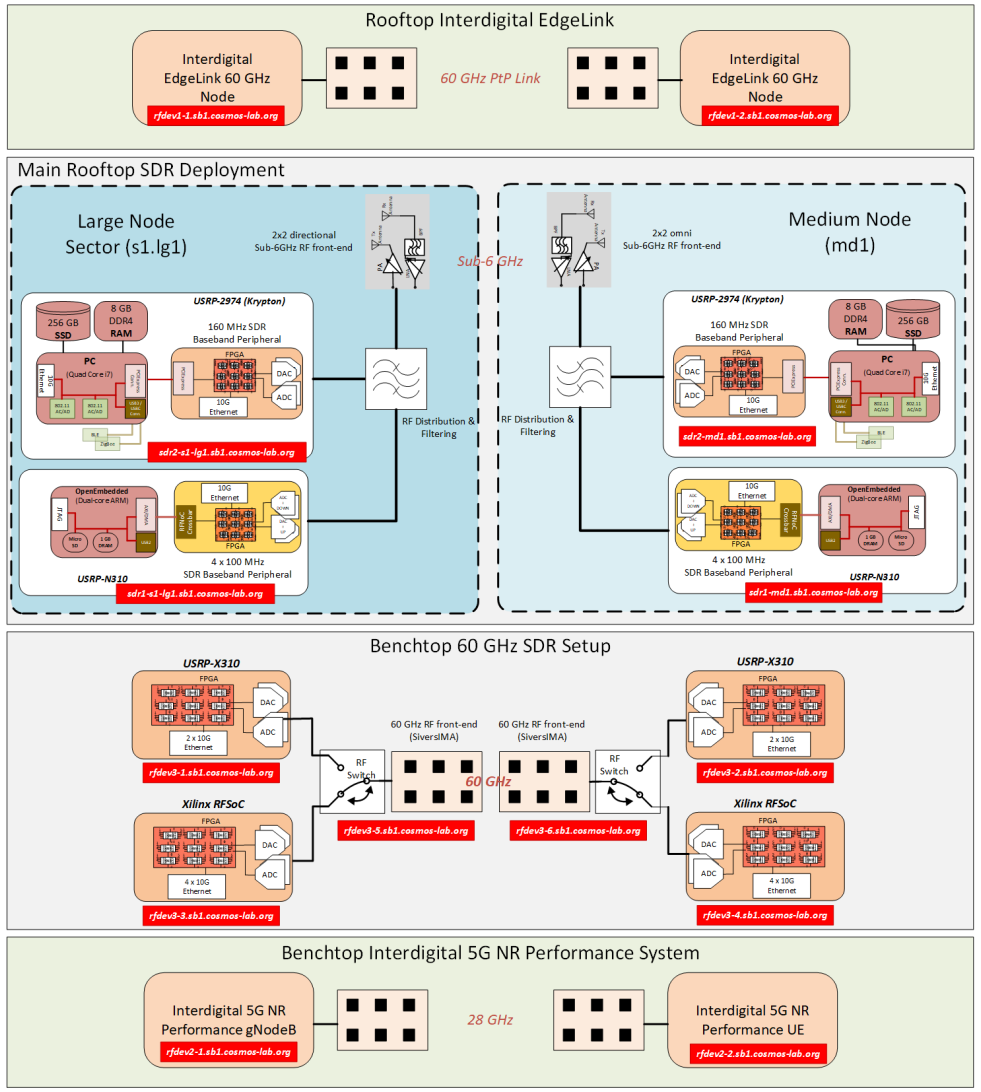
Sandbox1 (sb1) @Rutgers

Sandbox2 (sb2) @Columbia

COSMOS Sandbox1 (SB1)

- 2x USRP-2974
- 2x USRP N310
- 2x Xilinx RFSoC ZCU111
- 2x USRP X310
- Sub-6 GHz RF front-ends
- 2x IBM 28 GHz 64-element PAAM
- 2x Interdigital 5G-NR (28 GHz)
- 2x Interdigital MHU (28 GHz)
- 2x Interdigital EdgeLink (60 GHz)
- 2x Sivers PAAM 60 GHz
- 2x Servers, each with
  - 2x Intel Xeon 12-core, 192 GB RAM
  - Xilinx Alveo FPGA and Nvidia Tesla GPU
- ToR switch, power mgmt., optical mux, …
- X-Y Tables with movable mmWave antennas





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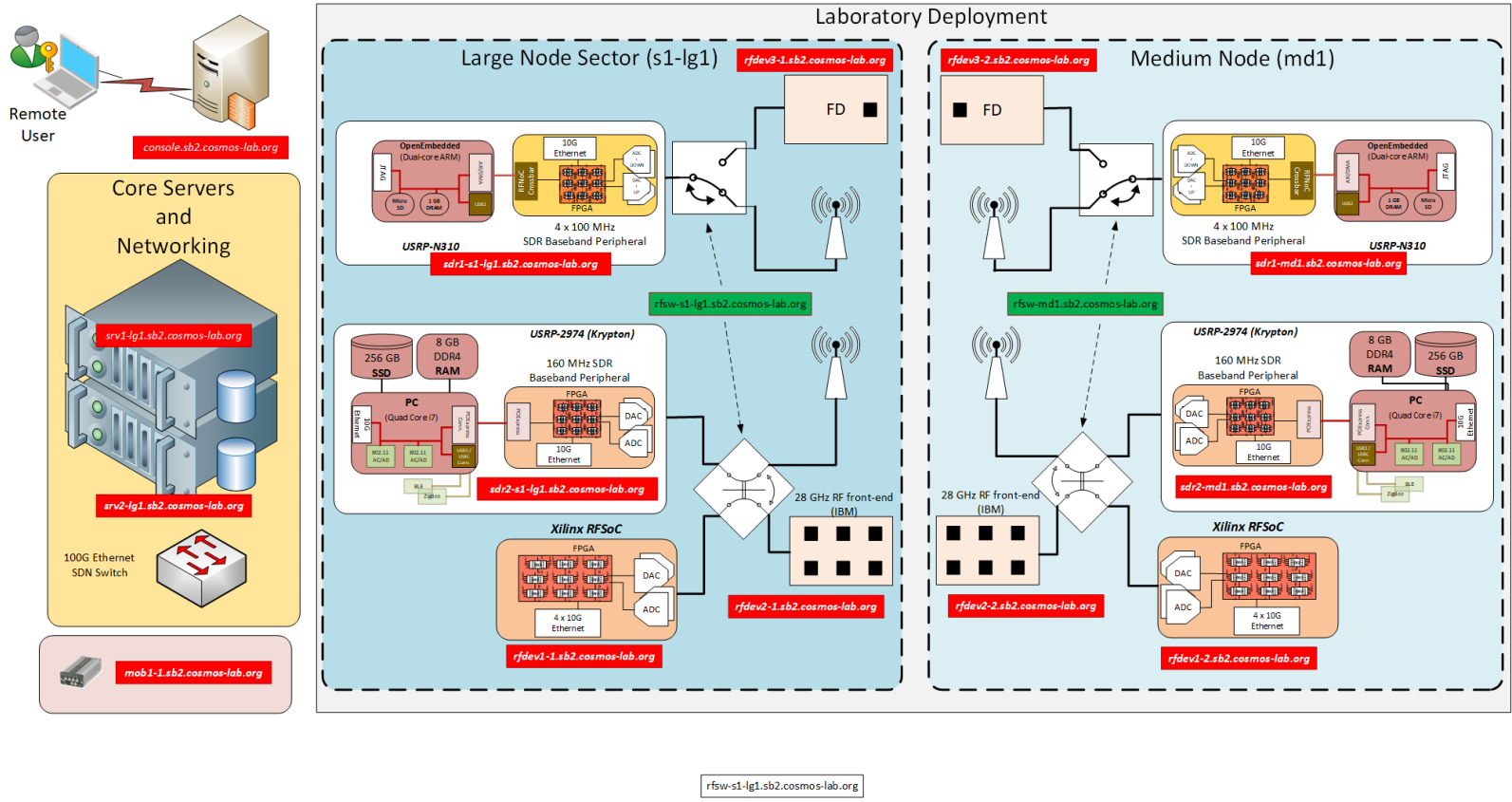
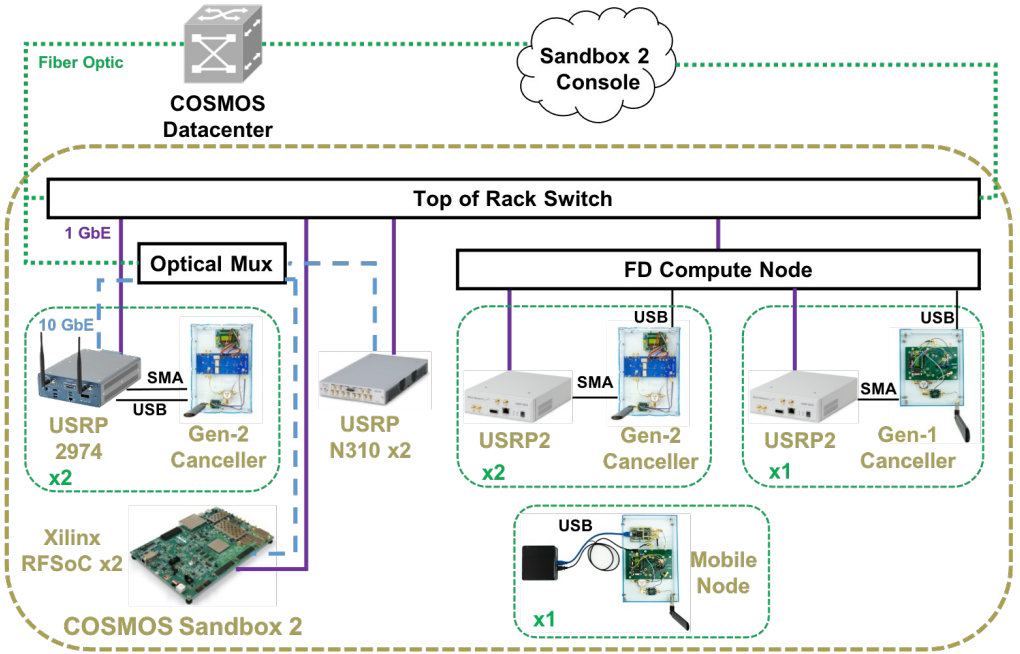
COSMOS Sandbox2 (SB2)

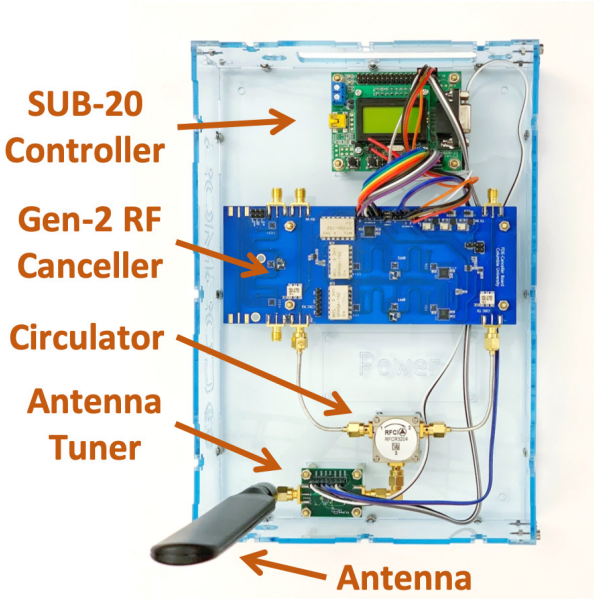
- 2x USRP-2974
- 2x USRP N310
- 2x Xilinx RFSoC ZCU111
- Sub-6 GHz RF front-ends
- 4x FlexICoN full-duplex front-end
- 2x IBM 28 GHz 64-element PAAM
- 2x Servers, each with
  - 2x Intel Xeon 12-core, 192 GB RAM
  - Xilinx Alveo FPGA and Nvidia Tesla GPU
- Comb source, 2x WSS
- ToR switch, power mgmt., optical mux, …



Pilot Experiment: Full-Duplex Wireless

- **Open-access and remotely-accessible wideband full-duplex radios** integrated in the COSMOS sandbox2 with open-sourced hardware, software, and example experiments



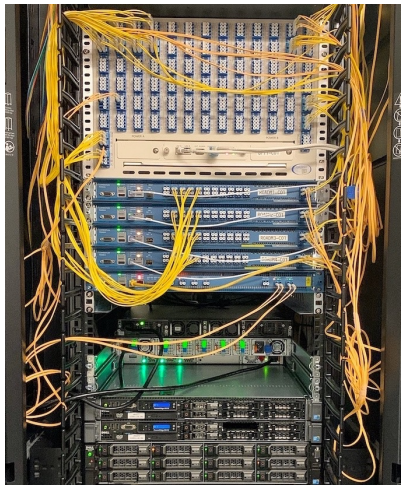


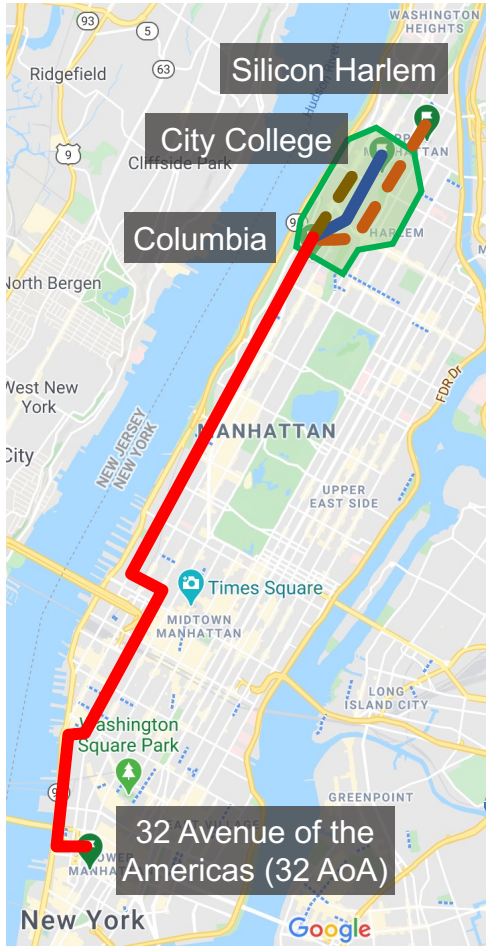
- M. Kohli, T. Chen, M. Baraani Dastjerdi, J. Welles, I. Seskar, H. Krishnaswamy, and G. Zussman, "Open-access full-duplex wireless in the ORBIT and COSMOS testbeds," *Elsevier Computer Networks*, 2021.
- T. Chen, M. Baraani Dastjerdi, J. Zhou, H. Krishnaswamy, and G. Zussman, "Wideband full-duplex wireless via frequency-domain equalization: Design and experimentation," in *Proc. ACM MobiCom'19*, 2019. **ACM MobiCom'19 Student Research Competition (SRC) Winner – First Place.**
- Tutorial available at https://wiki.cosmos-lab.org/wiki/tutorials/full_duplex, code available at https://github.com/Wimnet/flexicon_orbit.

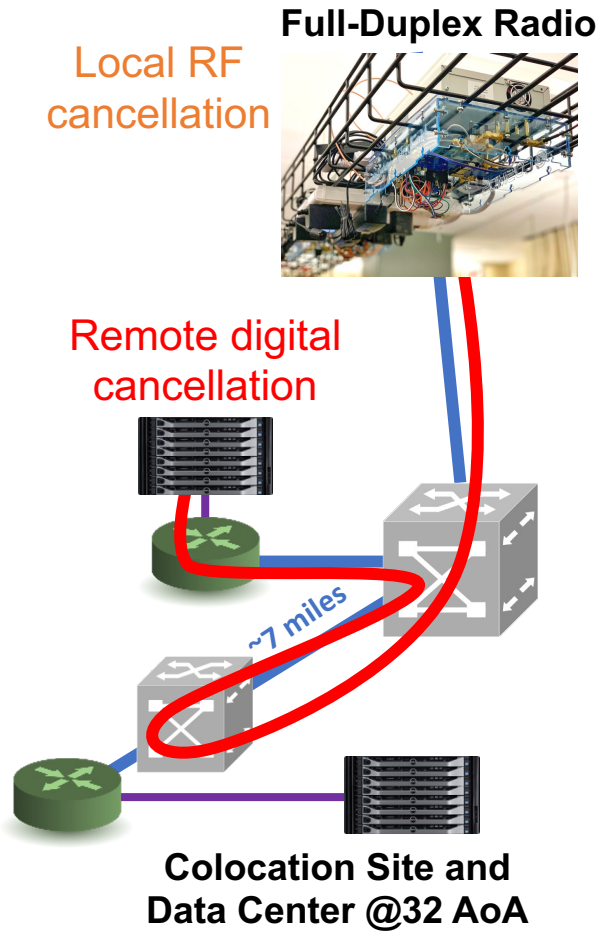
Pilot Experiment: Remote-Processing

- Full-duplex radio integrated with COSMOS' dark fiber-based optical x-haul network

- **Local** RF self-interference cancellation at the full-duplex radio
- **Remote** digital self-interference cancellation at the server (~14 miles away from the radio)





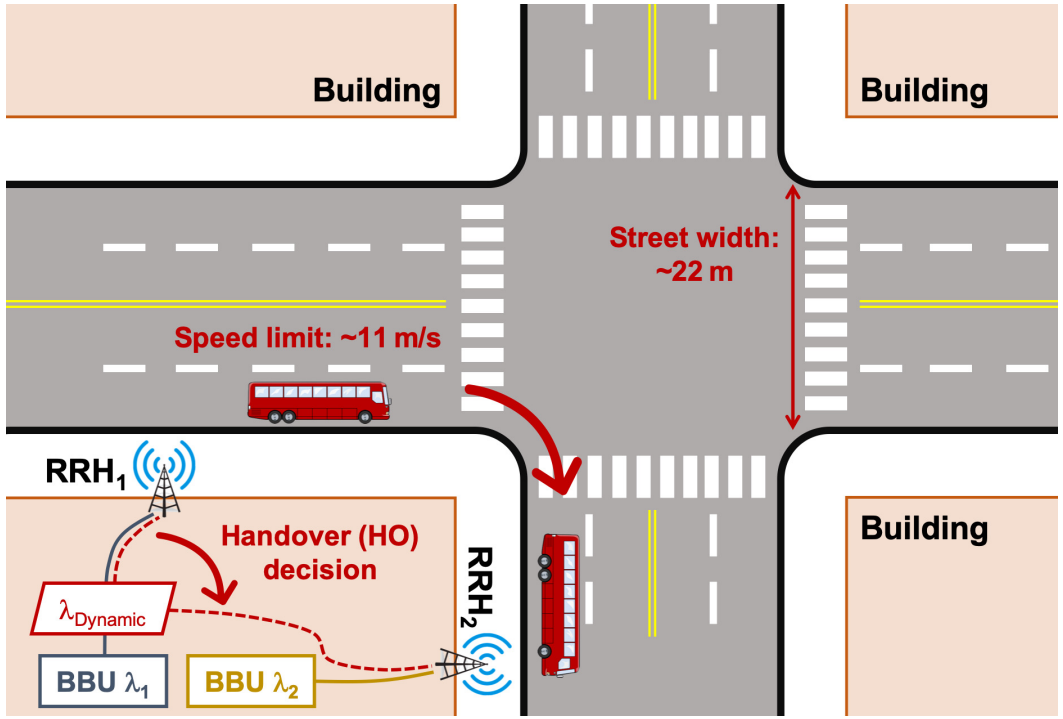


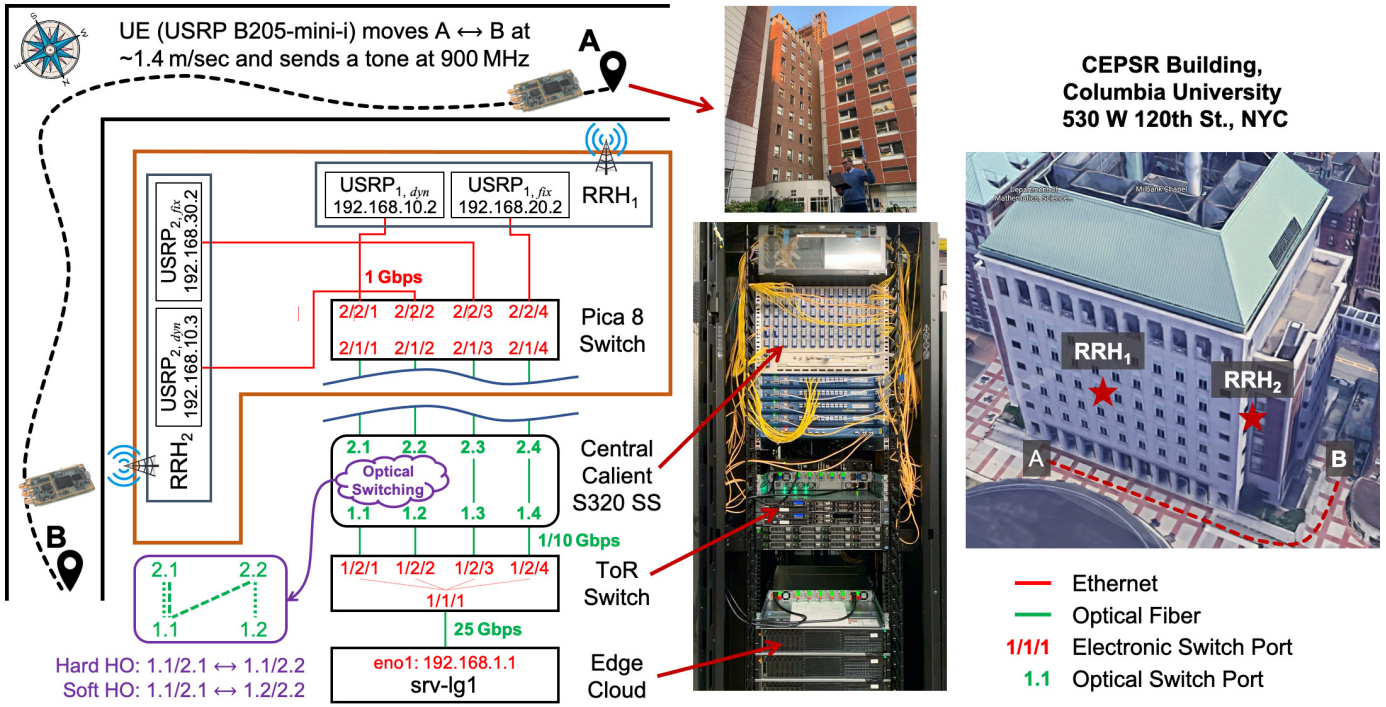
COSMOS dark fiber deployment and the supported Cloud-RAN applications

- J. Yu, T. Chen, C. Gutterman, S. Zhu, G. Zussman, I. Seskar, and D. Kilper, "COSMOS: Optical architecture and prototyping," in *Proc. OSA OFC'19, M3G.3 (invited)*, 2019.

Pilot Experiment: Wireless Handover

- **SDN-based optical switching** to support high bandwidth links with deterministic delay
- A vehicle taking a turn at an intersection receives services from two remote radio heads (RRHs) through dynamic optical switching and wavelength re-allocation.





- A. Minakhmetov, C. Gutterman, T. Chen, J. Yu, C. Ware, L. Iannone, D. Kilper, and G. Zussman, “Experiments on cloud-RAN wireless handover using optical switching in a dense urban testbed,” in *Proc. OSA OFC’20, Th2A.25*, 2020.

Pilot Experiment: mmWave

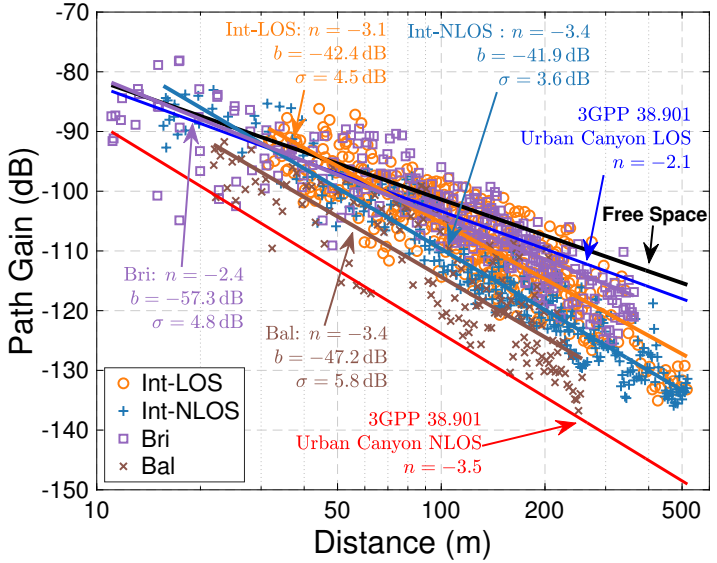
- 28 GHz channel measurements in the COSMOS testbed area in a **dense urban canyon** environment
  - Representative (potential) deployment sites of mmWave BSs (building rooftops, street lightpoles, etc.)
  - Extensive measurements on **long sidewalks** (up to 1,100 m) with **fine-grained link step size**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

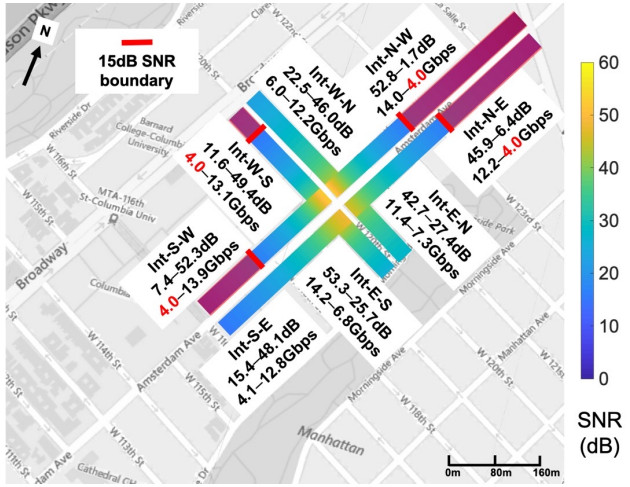
Building rooftop

Cross-avenue bridge

An open-space park



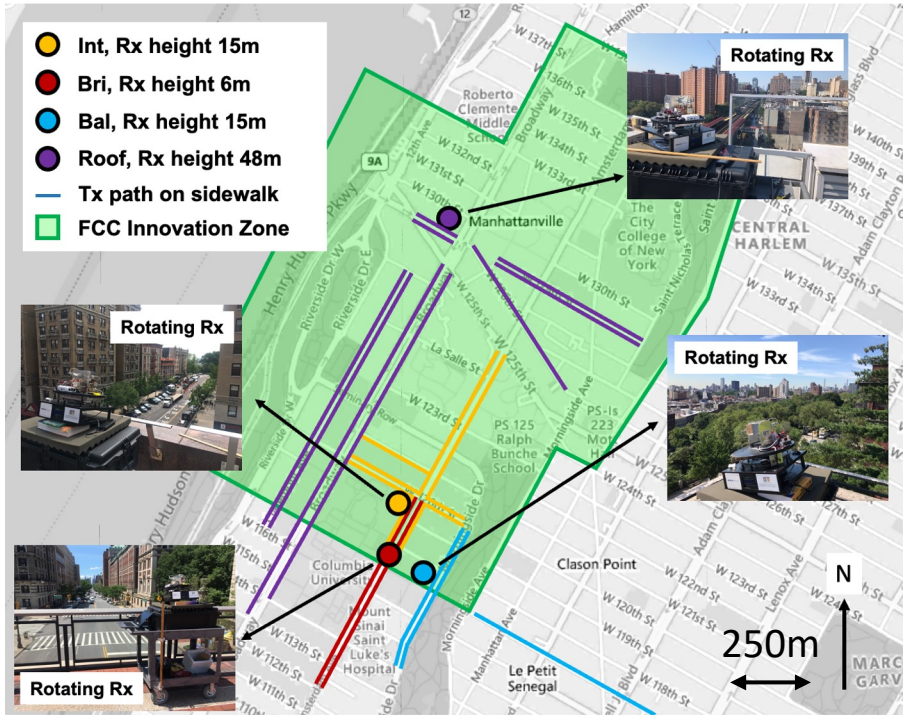
Minimum data rates with >15 dB SNR can be supported for link distances of >200 meters



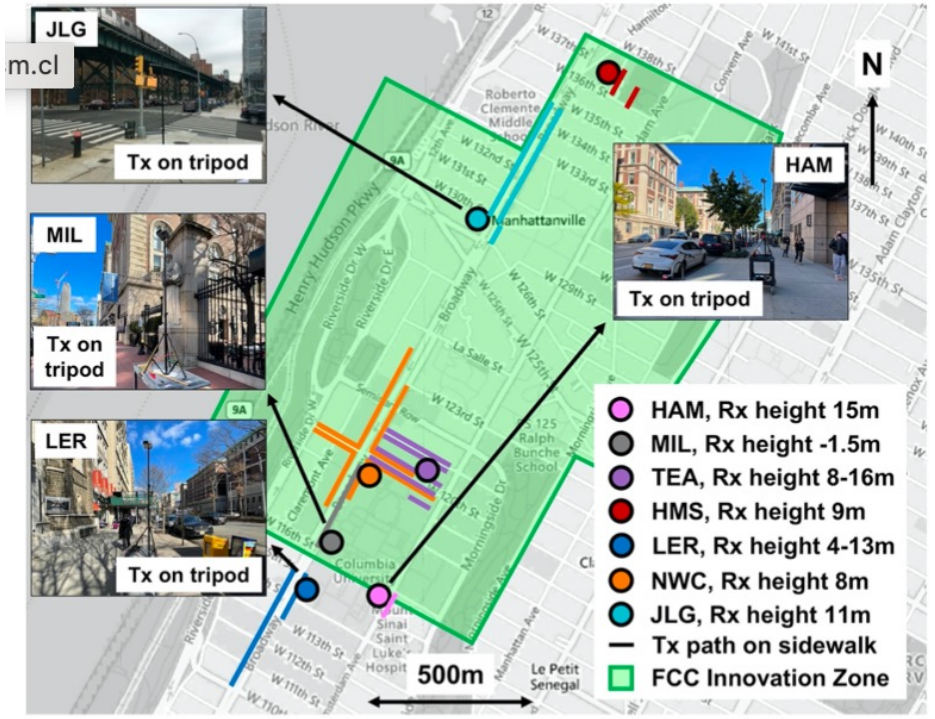
- D. Chizhik, J. Du, R. Valenzuela, "Universal path gain laws for common wireless communication environments", *IEEE Transactions on Antennas and Propagation*, 2021
- J. Du, D. Chizhik, R. Valenzuela, R. Feick, M. Rodríguez, G. Castro, T. Chen, M. Kohli, and G. Zussman, "Directional measurements in urban 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.

Pilot Experiment: mmWave

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



Outdoor-to-outdoor measurements



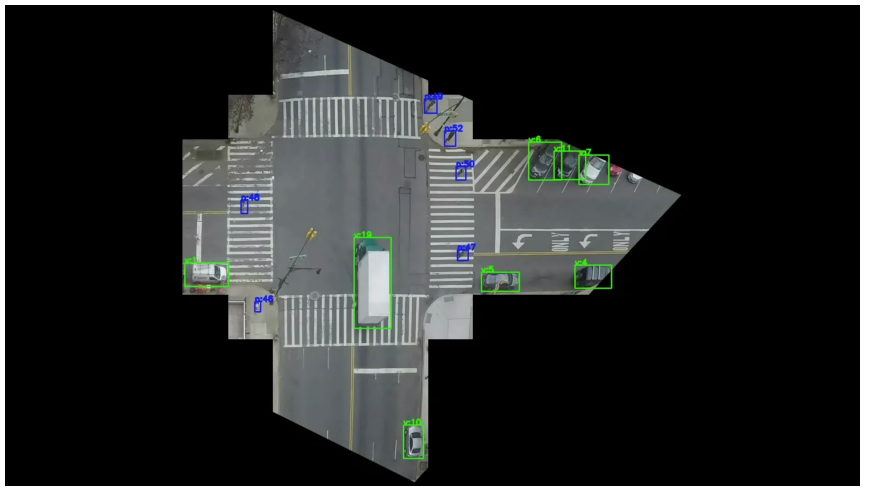
Outdoor-to-indoor measurements

- M. Kohli, A. Adhikari, G. Avci, S. Brent, J. Moser, S. Hossain, A. Dash, I. Kadota, R. Feick, D. Chizhik, J. Du, R. Valenzuela, G. Zussman, “Outdoor-to-Indoor Measurements of 28 GHz Wireless in a Dense Urban Environment,” to appear in MobiHoc’22.

Pilot 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 → ~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

COSMOS pilot site

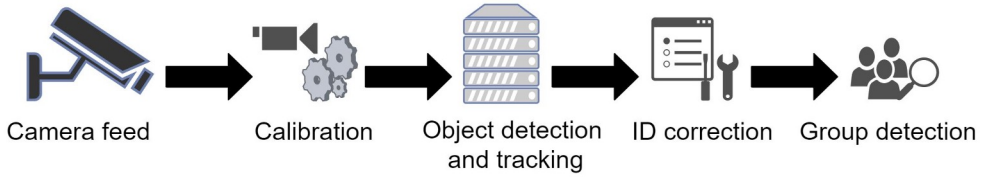


Videos fed into the COSMOS edge node for vehicles/pedestrians detection and classification

- S. Yang, E. Bailey, Z. Yang, J. Ostrometzky, G. Zussman, I. Seskar, and Z. Kostic, “COSMOS smart intersection: Edge compute and communications for bird’s eye object tracking,” in *Proc. 4th International Workshop on Smart Edge Computing and Networking (SmartEdge’20)*, 2020.

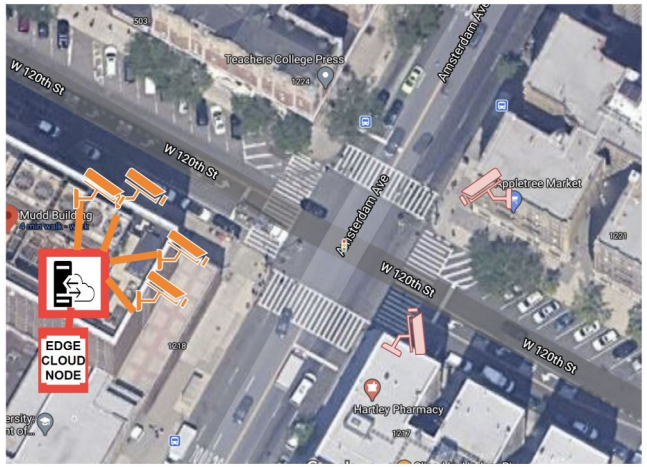
Use Case: Social Distancing Analysis

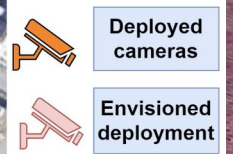
- **Auto**mated video-based **S**ocial **D**istancing **A**nalyzer (**Auto-SDA**)

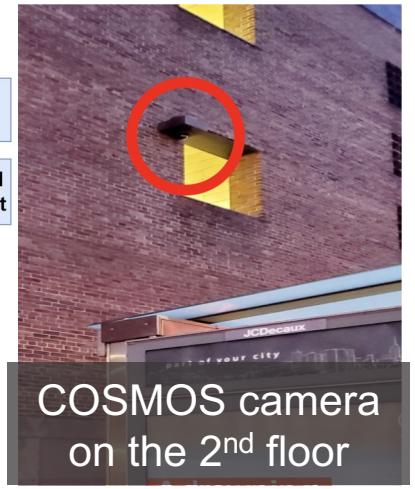


  - **Calibration**: Converts 2D on-image distances to 3D on-ground distances
  - **Object detection and tracking**: Locates the pedestrians and assigns an ID to each of them
  - **ID correction**: Removes the redundant IDs generated by the tracker
  - **Group detection**: Excludes the pedestrians affiliated with a single social group from social distancing violations

- Evaluate compliance of the pedestrians with the social distancing policies







- M. Ghasemi, Z. Kostic, J. Ghaderi, and G. Zussman, “Auto-SDA: Automated Video-based Social Distancing Analyzer,” in *Proc. 3rd Workshop on Hot Topics in Video Analytics and Intelligent Edges (HotEdgeVideo’21)*, 2021.

Support for 5G Experimentation

SDR based 5G:

I. OpenAirInterface & SrsRan:

- Development image with support for agile development (i.e. git-pull-compule-run)
- Tutorial for sub-6 GHz using any of the COSMOS nodes
- Development option (with Interdigital MHU) for FR2 in SB1
- Of-the-shelf UE: Oppo, OnePlus 8 Pro phones and SIMCom USB modems with test SIMs

II. Amarisoft:

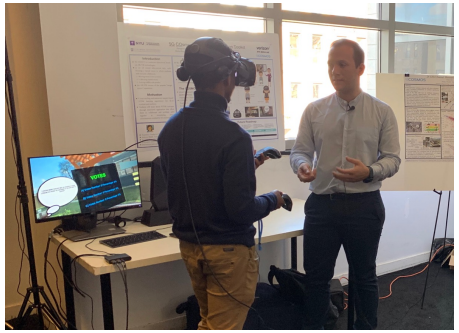
- eNodeB, gNodeB and mme (dNodeB NR release 15 compliant with FDD/TDD FR1 FR2)
- 64 node over-the-air simulator: LTE Release 8 support with features up to Release 14 (FDD/TDD with bandwidths of 1.4, 3, 5, 10, 15 and 20 MHz)
- Of-the-shelf UE: Oppo, Samsun S10 and OnePlus 8 Pro phones and and SIMCom USB modems with test SIMs

ORAN and SMO/Orchestration (SB10 – reserved for ONAP/ORAN members)

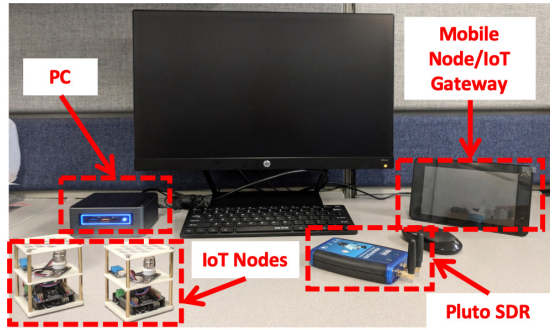
- ONAP Tutorials
- OSM Tutorials
- ORAN Tutorials

Education and Outreach

- COSMOS education toolkit: A small pre-configured COSMOS node (developed/used in Summers 2018–2022 programs for teachers) offering 100+ K–12 educational labs in Math/Science/CS
- Numerous education and outreach activities

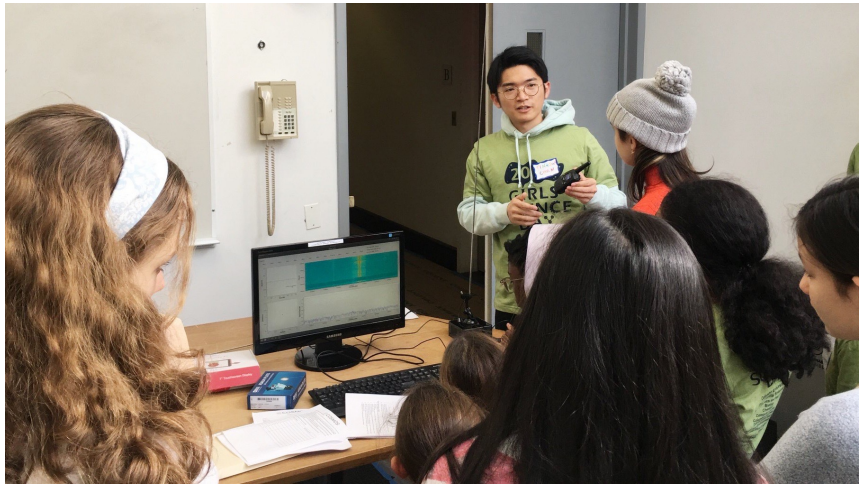


5G COVET



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.

COSMOS Wireless Testbed – Summary

- Focus on ultra-high bandwidth, ultra-low latency, and edge cloud
- Open platform integrating SDRs, mmWave, and optical x-haul
- 1 sq. mile densely populated area in West Harlem
- Industry and local community outreach

COSMOS website: https://cosmos-lab.org
Tutorials: https://wiki.cosmos-lab.org/wiki/tutorials
Twitter: #pawrcosmos

Related links:

- PAWR: https://advancedwireless.org/
- ORBIT: https://www.orbit-lab.org/
- ONAP: https://wiki.onap.org
- ORAN: https://www.o-ran.org/

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