



Challenge: COSMOS: A City-Scale Programmable Testbed for Experimentation with Advanced Wireless

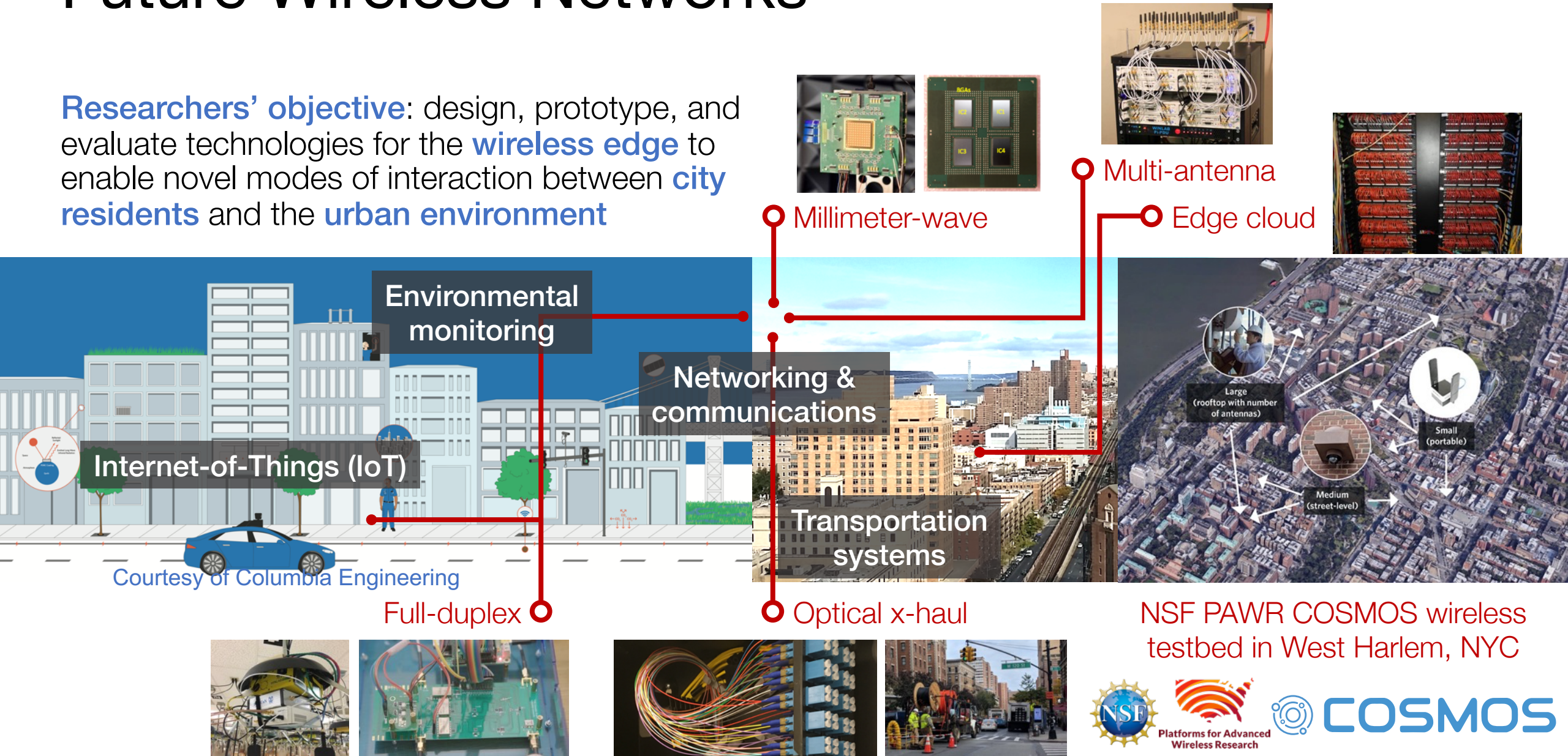
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Harish Krishnaswamy, Sumit Maheshwari, Panagiotis Skrimponis, and Craig Gutterman

<https://cosmos-lab.org/>

Sept. 22, 2020

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**

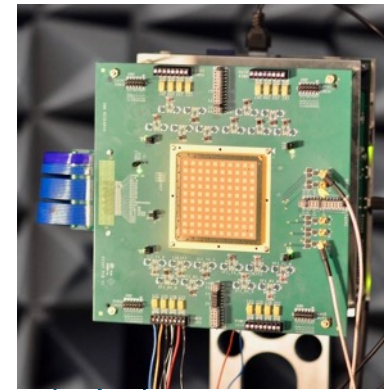


COSMOS: Project Vision

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 (~10–100 GIPS)
- **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, smart city (with high-bandwidth sensing), and industrial control

Wireless Testbeds

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

POWDER-RENEW



Salt Lake City

COSMOS



New York City

AERPAW



Research Triangle

- Colosseum: A massive RF channel emulator from DARPA SC2
- Other testbeds: 5TONIC, ADRENALINE, Arena, Bristol Is Open, CORNET, FED4FIRE+, FIT, ...

Outline

- COSMOS: A city-scale programmable advanced wireless testbed
 - Objective, architecture, and deployment
- COSMOS' key technologies:
 - Software-defined radios (SDRs) for advanced wireless research
 - Millimeter-wave (mmWave) radios
 - Optical transport network
 - Software-defined networking and edge cloud
 - Control and management software
- COSMOS' pilot experiments
- Education and outreach



COSMOS Wireless Testbed

Videos

<https://www.cosmos-lab.org/>

Objective: Take it Outside



Objective: Take it Outside



COSMOS: Envisioned Deployment

- West Harlem with an area of ~1 sq. mile
 - ~15 city blocks and ~5 city avenues
- ~9 **Large** sites
 - Rooftop base stations
- ~40 **Medium** sites
 - Building side- or lightpole-mounted
- ~200 **Small** nodes
 - Including vehicular and hand-held

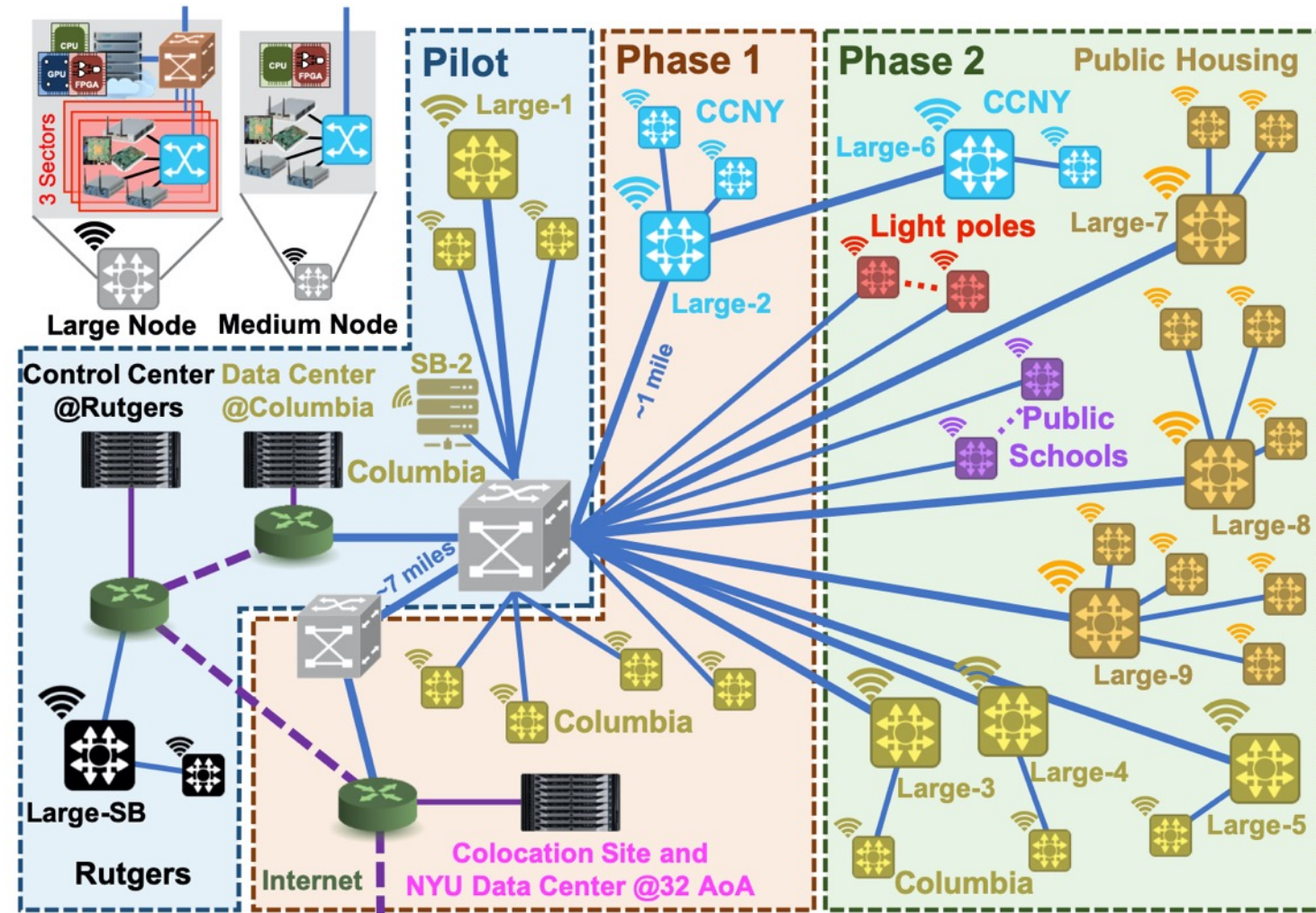


COSMOS: Envisioned Deployment

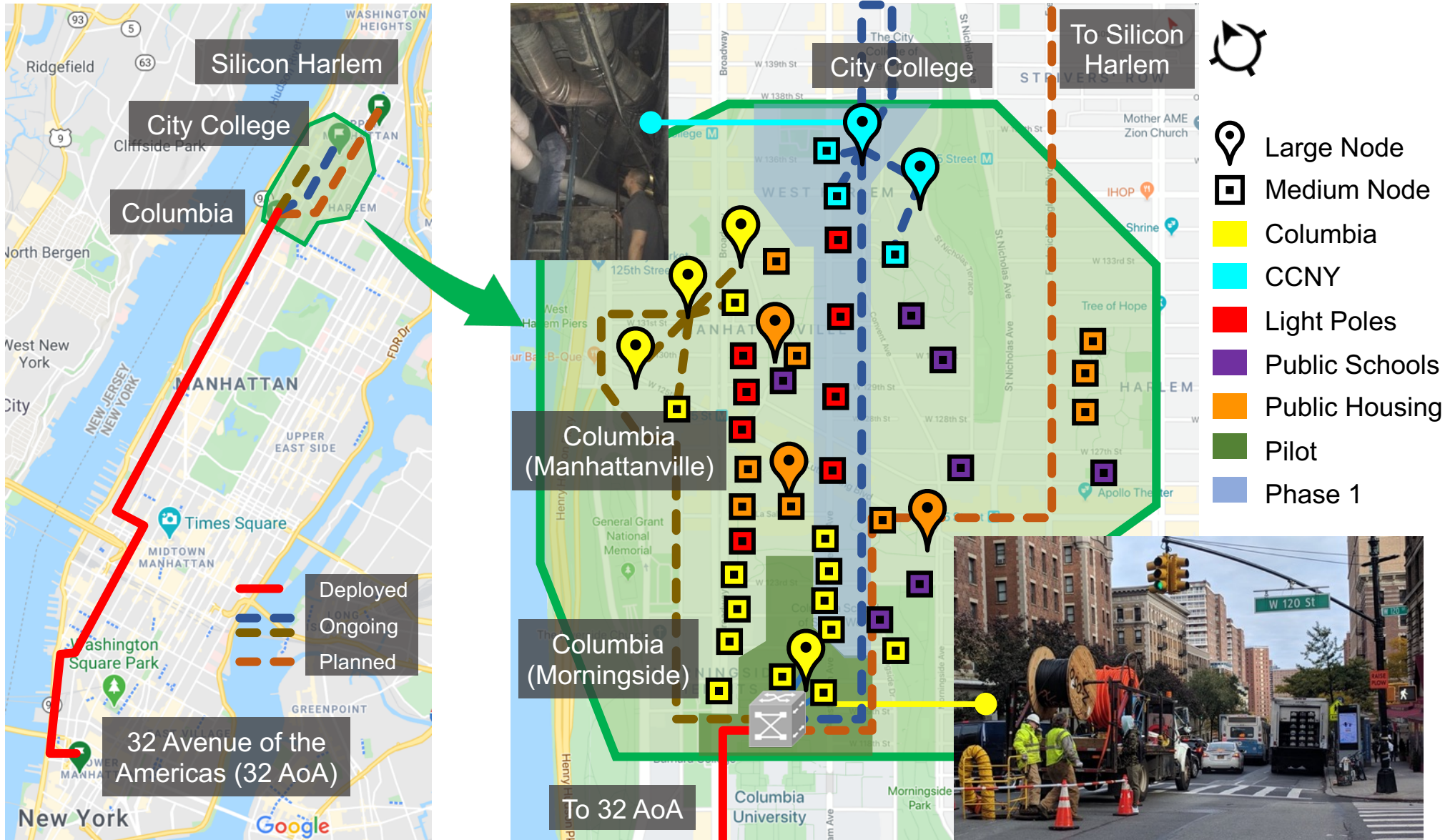
- A phased approach:
 - May 2019: Pilot completion
 - Sept. 2019: FCC Innovation Zone
 - June 2020: General Available
 - During 2021*: Phase 1 completion

*Deployments affected by the COVID-19 pandemic

- Fiber optic connection from most sites
- Fiber connection to Rutgers, NYU Data Center (at 32 Ave. of Americas), GENI, and Internet2, etc.



COSMOS: Envisioned Deployment



**Large
(rooftop)**



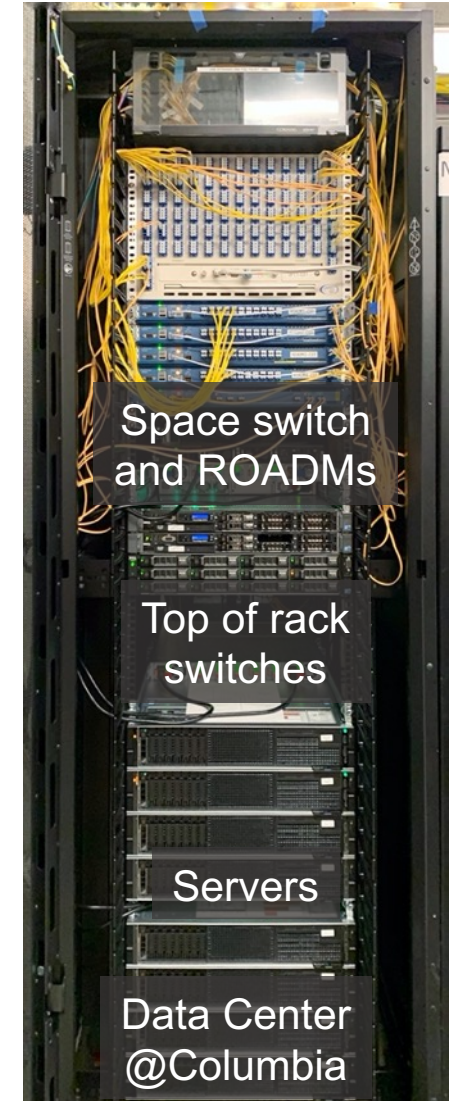
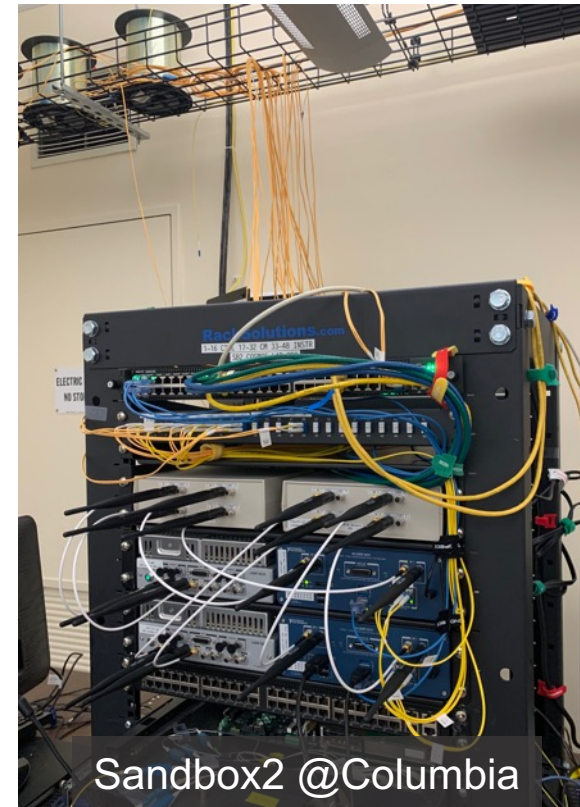
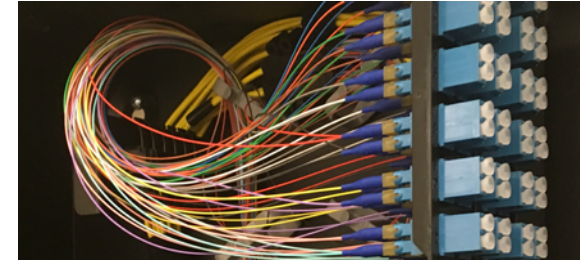
**Medium
(street-level)**



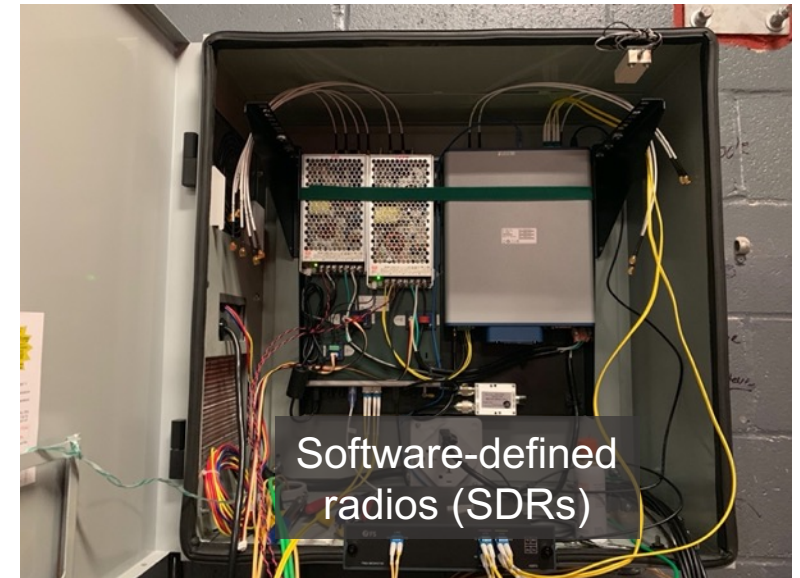
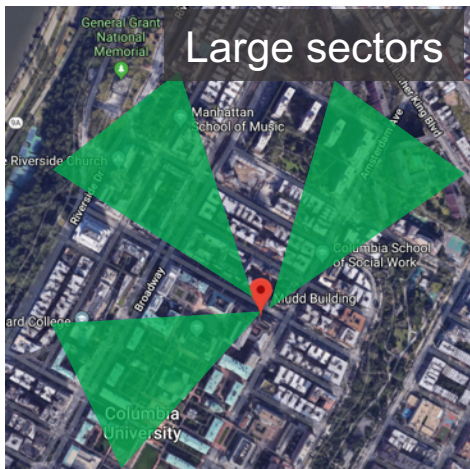
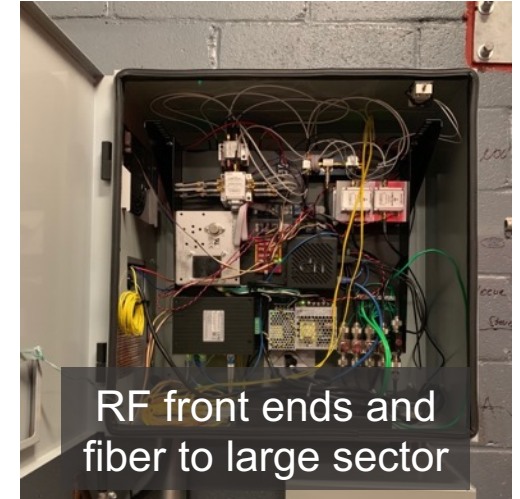
**Small
(portable)**

Pilot (May 2019): Fiber & Optical Core

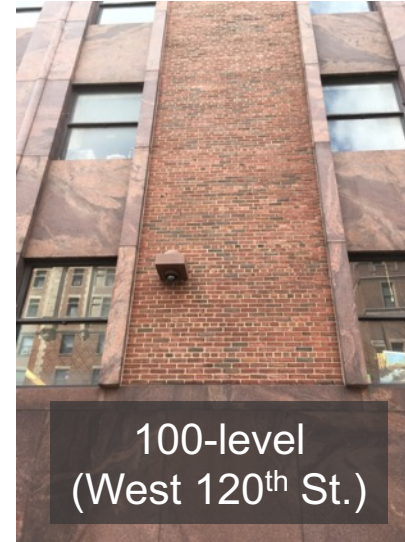
- Fiber connections: internally and to/from downtown Manhattan
- Core optical switching and compute



Pilot (May 2019): Large Node

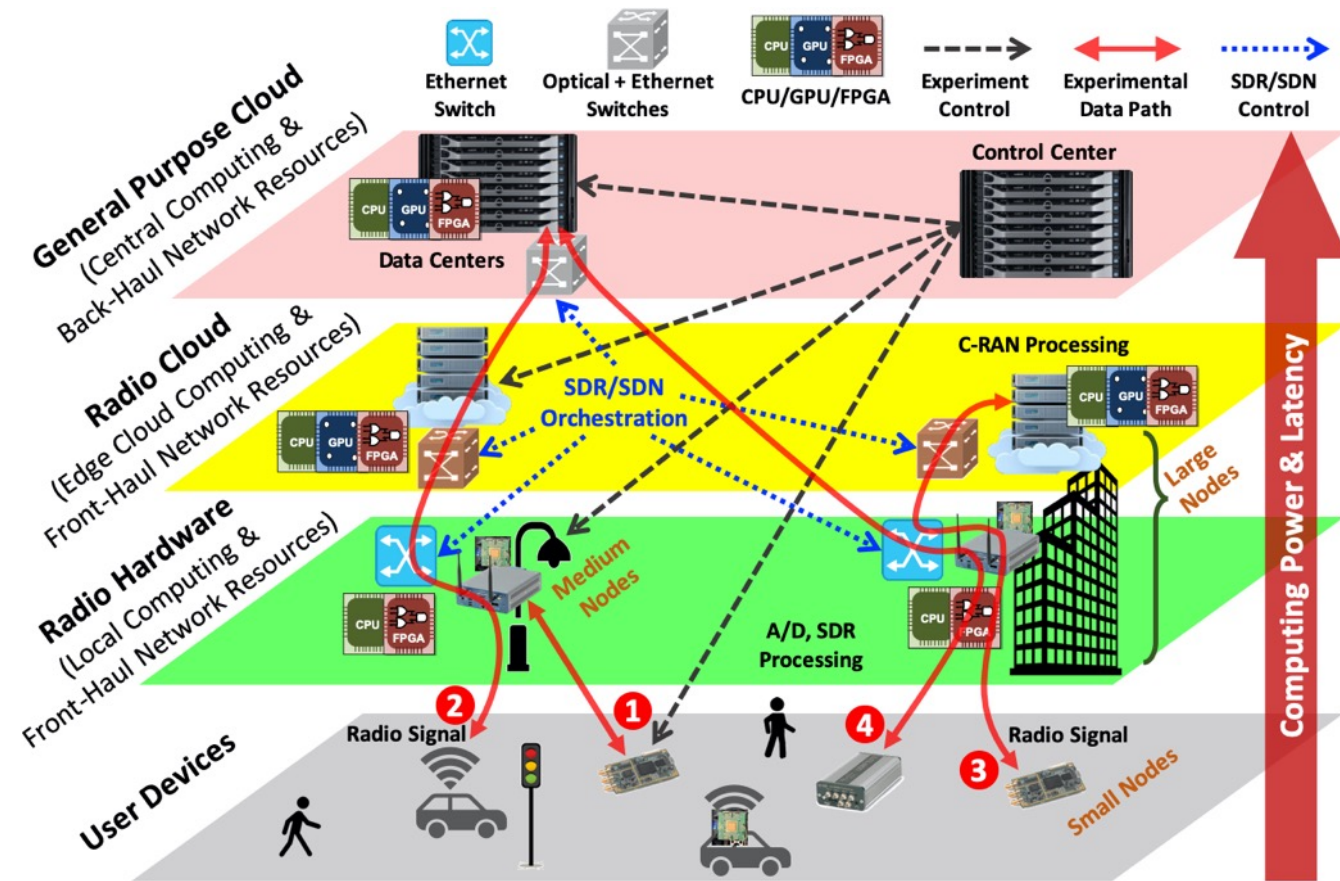


Pilot (May 2019): Medium Nodes



COSMOS: Design and Architecture

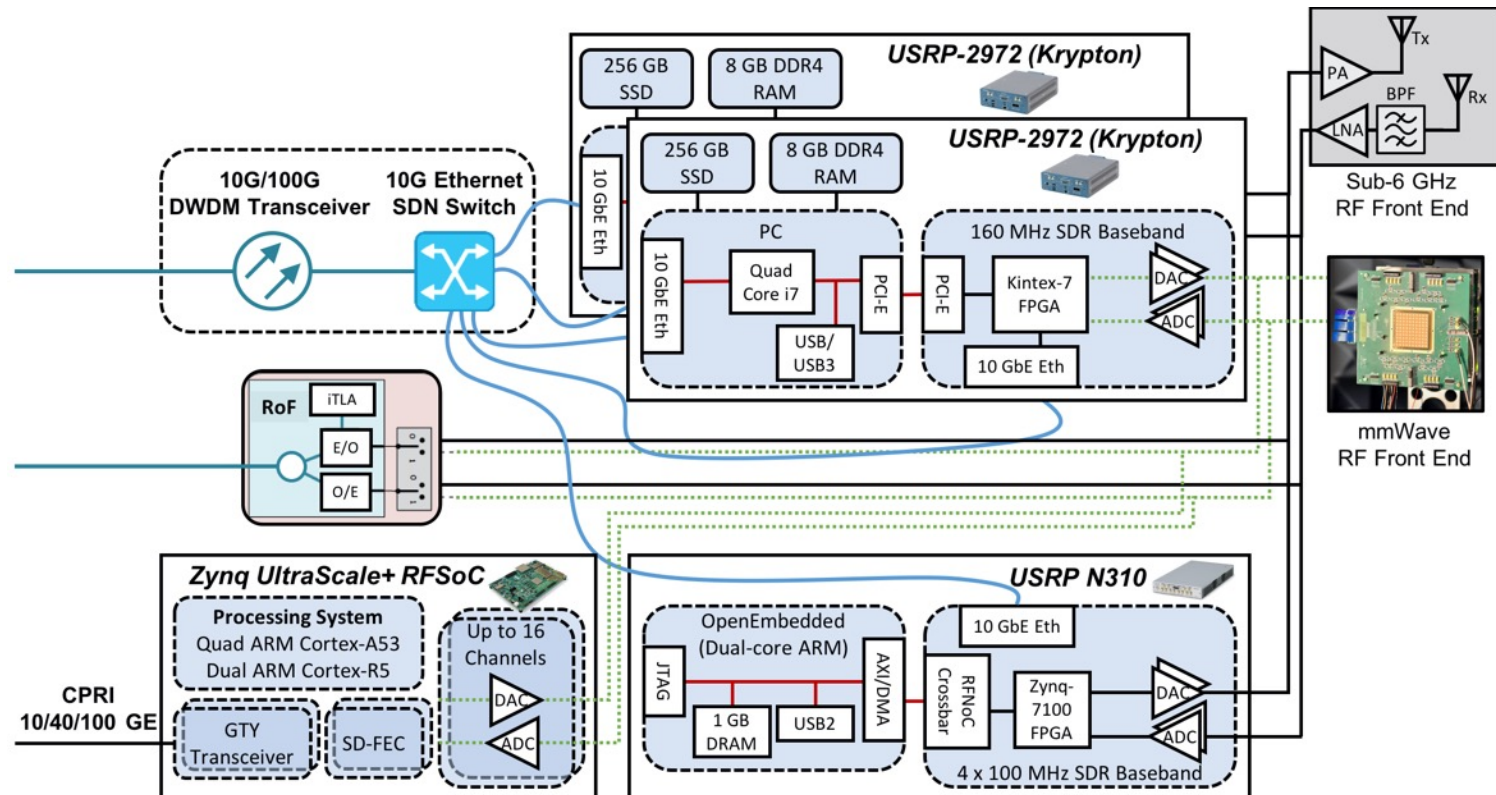
- Key design challenge: Gbps+ performance and full programmability at the radio level
 - Fully programmable multi-layered computing architecture for flexible experimentation
- Key technologies:
 - Software-define radios (SDRs)
 - Millimeter-wave (mmWave) radios
 - Optical x-haul networks
 - Software-defined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



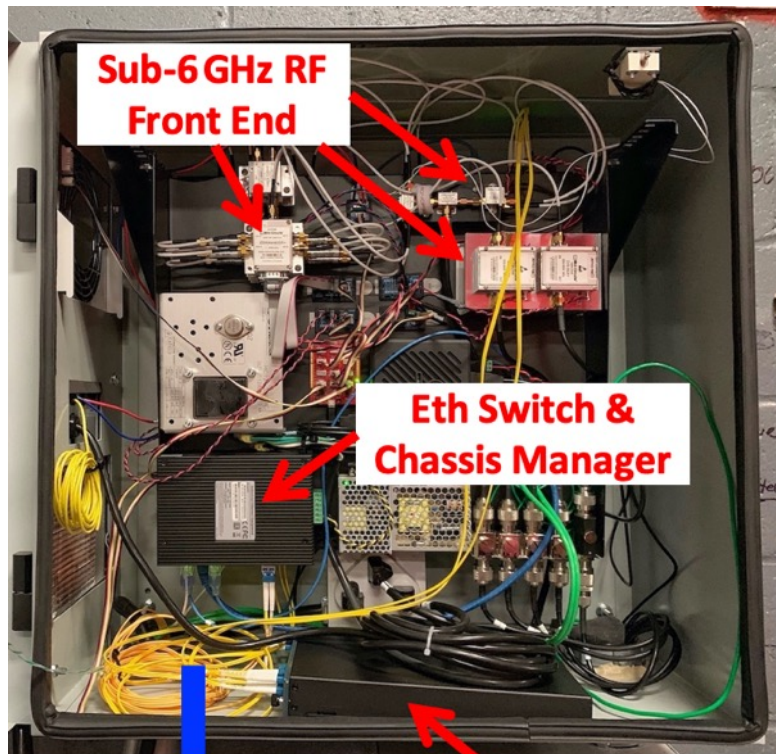
COSMOS's multi-layered computing architecture

Key Technology: Software-Define Radios

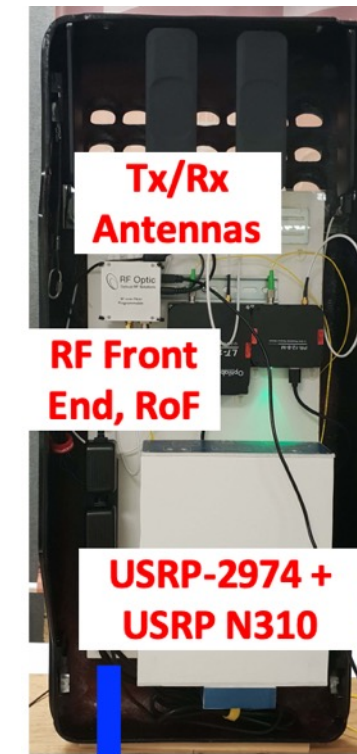
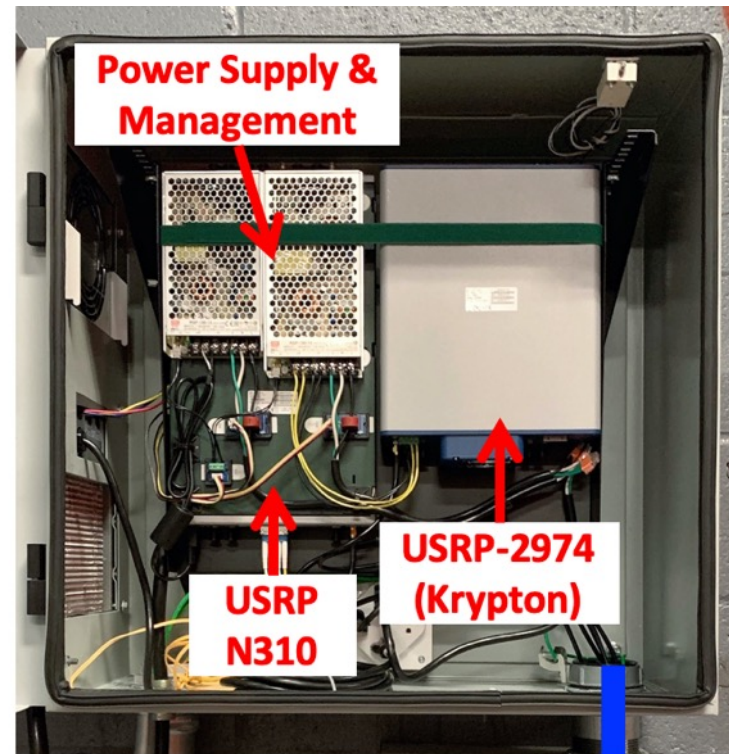
- Software-defined radio (SDR) nodes at various performance levels and form factors:
 - (i) 0.4–6 GHz bands, (ii) 28/60 GHz bands (with up to ~500 MHz bw), Gbps
- Signal processing can be spread between radio node & edge cloud RAN



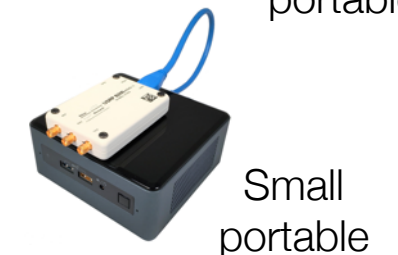
Key Technology: Software-Define Radios



A large node sector or a medium node



Medium-light node (lightpole-mounted)



Small mobile node

Key Technology: mmWave

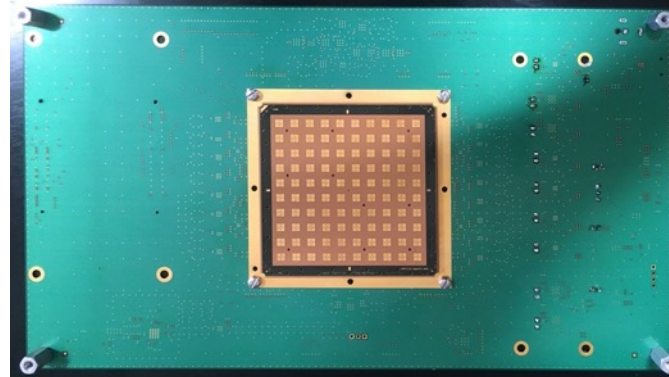
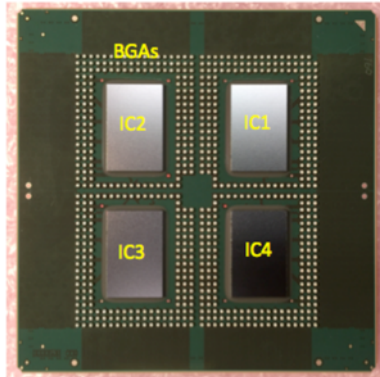
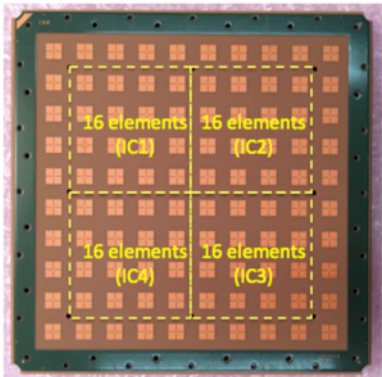
- IBM 28 GHz programmable phased array antenna modules (PAAMs)
 - Integration of the β -version in Sandbox 2
 - Up to ~500 MHz BW using the Zynq UltraScale+ RFSoc platform
 - Experiment with adaptive beamforming and MIMO
- Facebook Terragraph 60 GHz radios



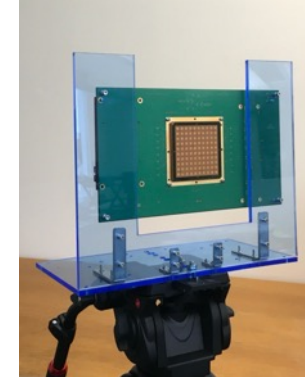
USRP-2974 (Krypton)



Zynq RFSoc



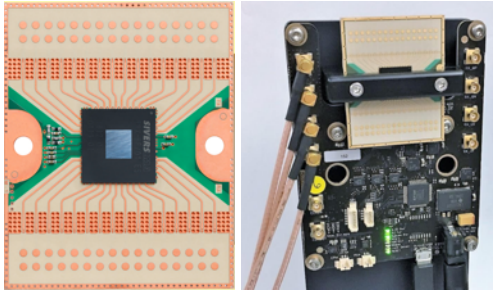
IBM 28 GHz phased array antenna module
(in collaboration with Ericsson)



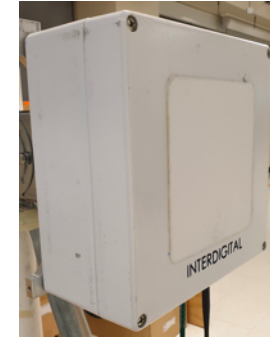
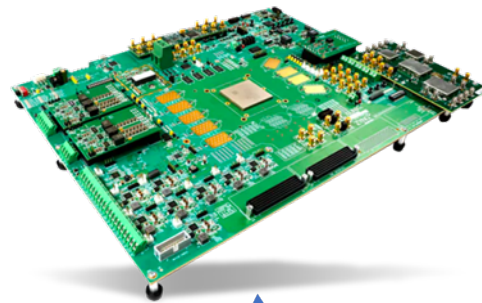
Facebook Terragraph
60 GHz radios

Key Technology: mmWave

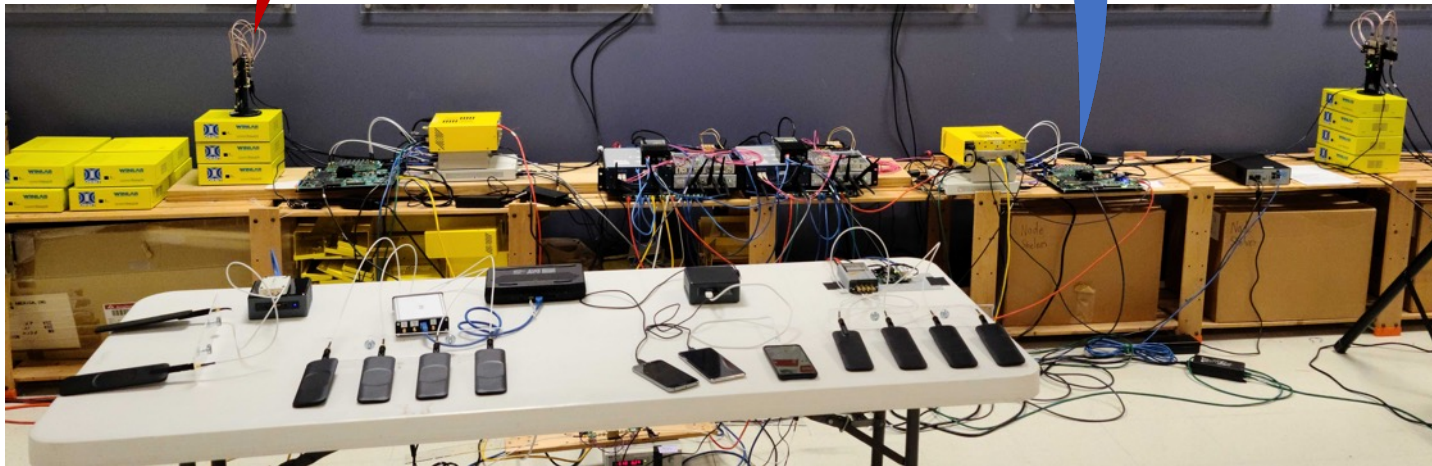
Sivers IMA 60 GHz Radios



Zynq UltraScale+ RFSoc



InterDigital EdgeLink (60 GHz)

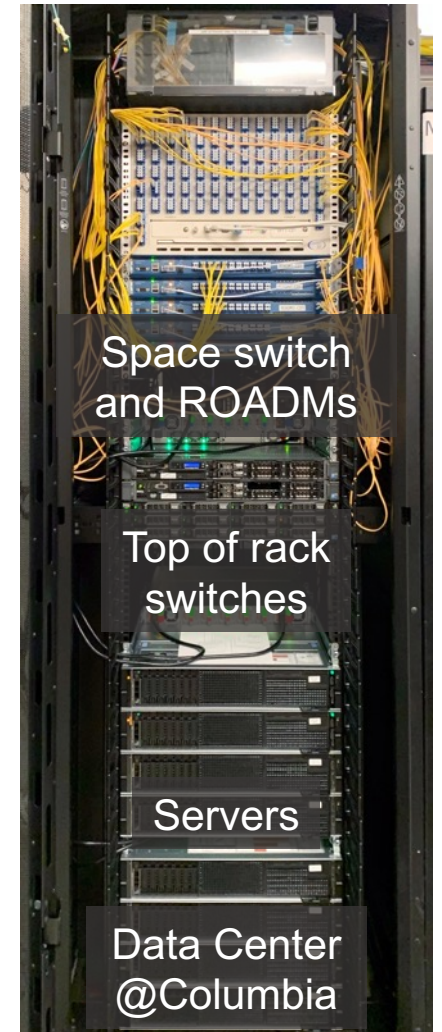
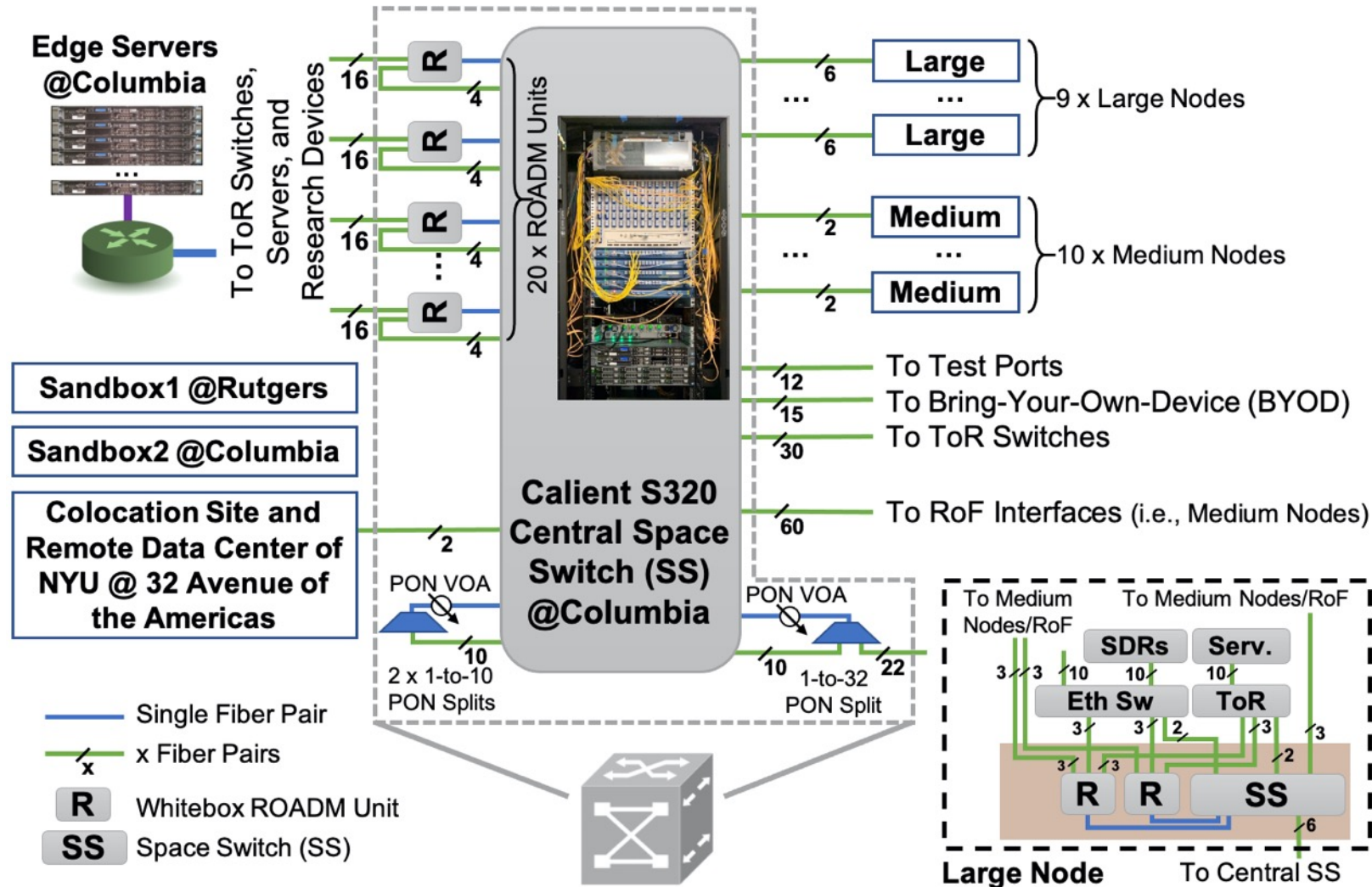


Sivers IMA Radios (60 GHz) with RFSoc



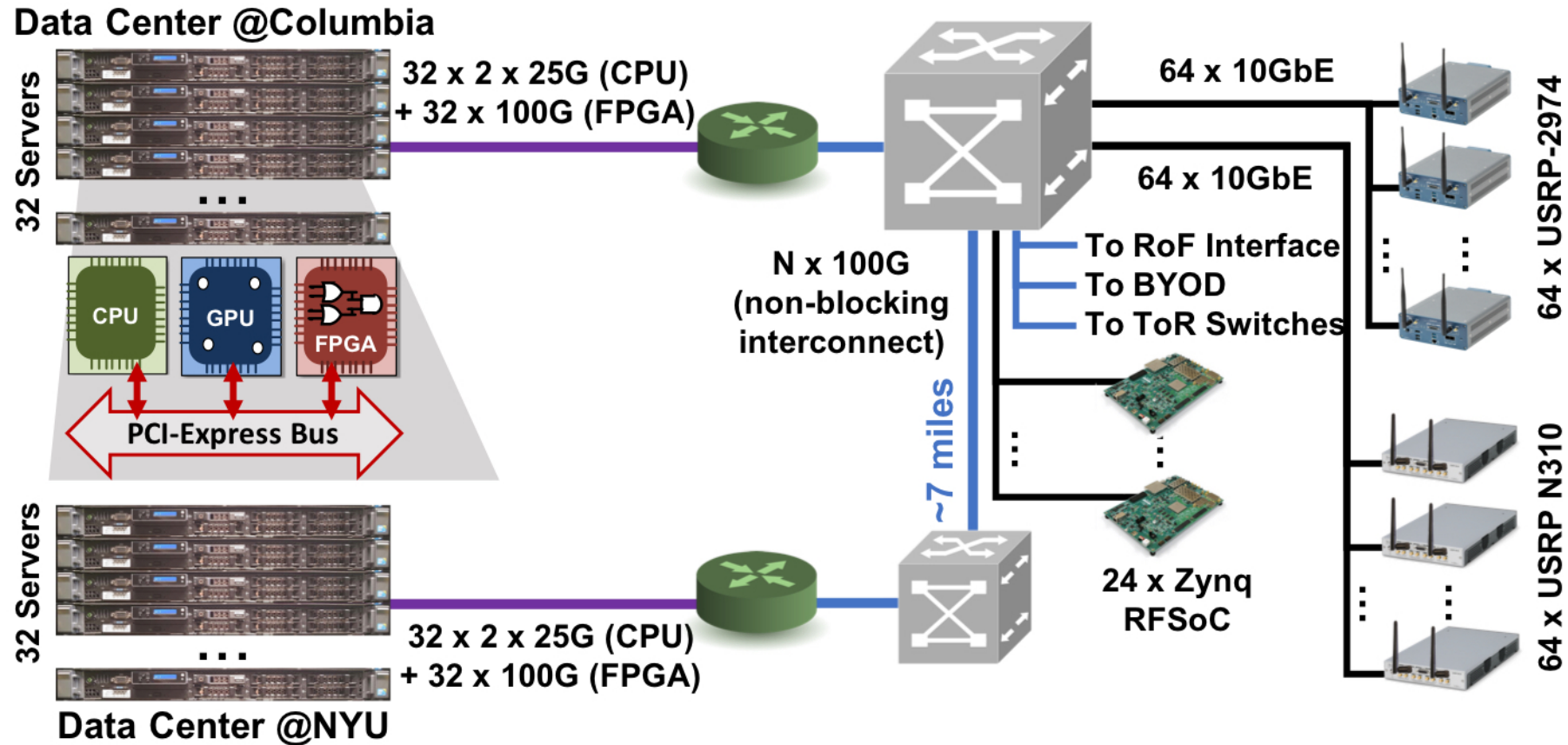
InterDigital 5G NR Platform (28 GHz)

Key Technology: Optical Networking

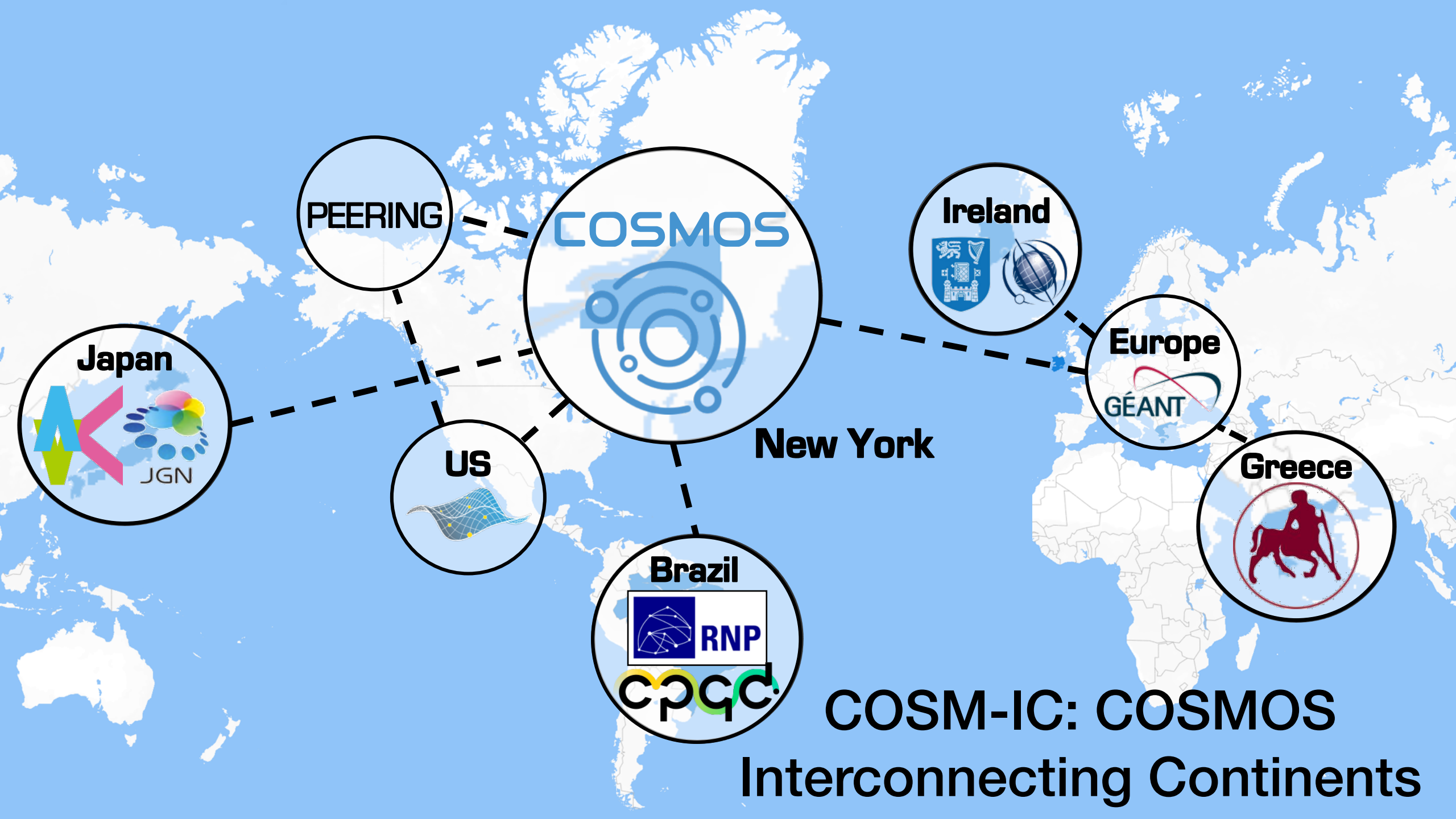


- J. Yu, C. Gutterman, A. Minakhmetov, M. Sherman, T. Chen, S. Zhu, G. Zussman, I. Seskar, and D. Kilper, "Dual use SDN controller for management and experimentation in a field deployed testbed," in *Proc. OSA OFC'20, T3J.3*, 2020.
- J. Yu, T. Chen, C. Gutterman, S. Zhu, G. Zussman, I. Seskar, and D. Kilper, "COSMOS: Optical architecture and prototyping," in *Proc. OSA OFC'19, M3G.3 (invited)*, 2019.

Key Technology: Cloud Architecture



- COSMOS serves as an Open Test and Integration Center during the O-RAN North America plugfest and proof-of-concept demonstration

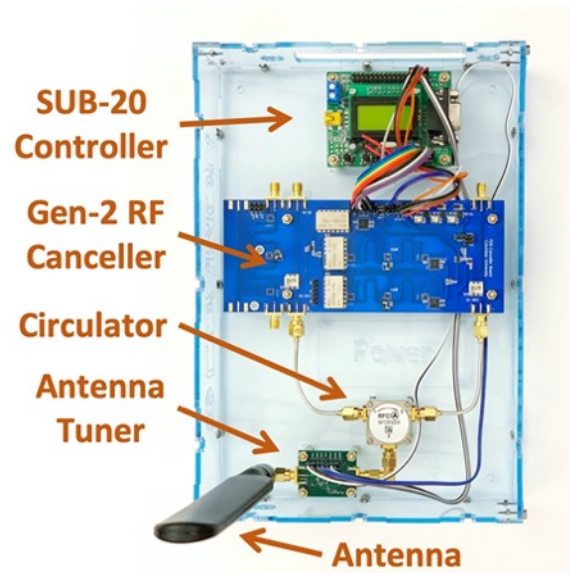


COSM-IC: COSMOS
Interconnecting Continents

Pilot Experiment: Full-Duplex Wireless

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

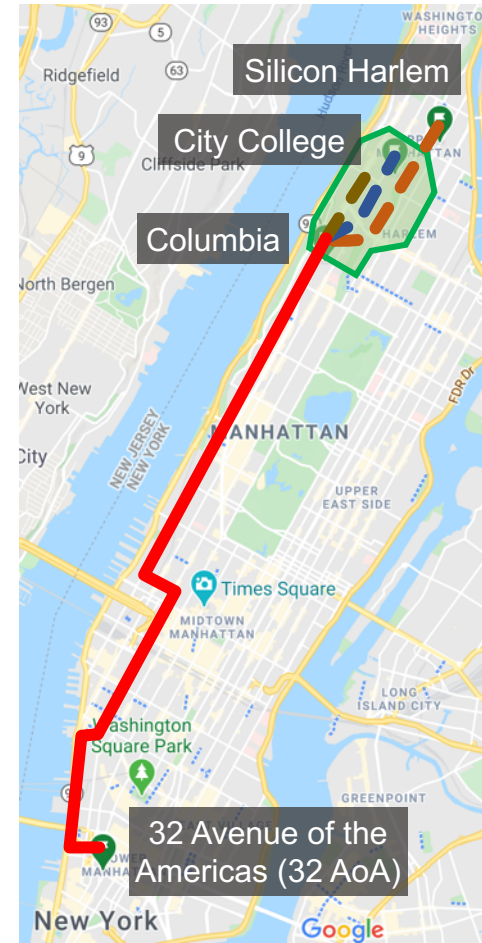
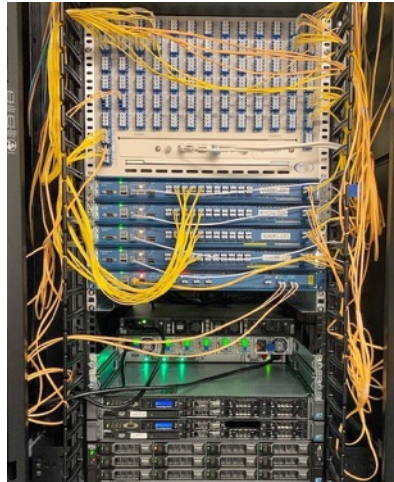
Real-time visualization of data packets, signal spectrum, and digital self-interference cancellation



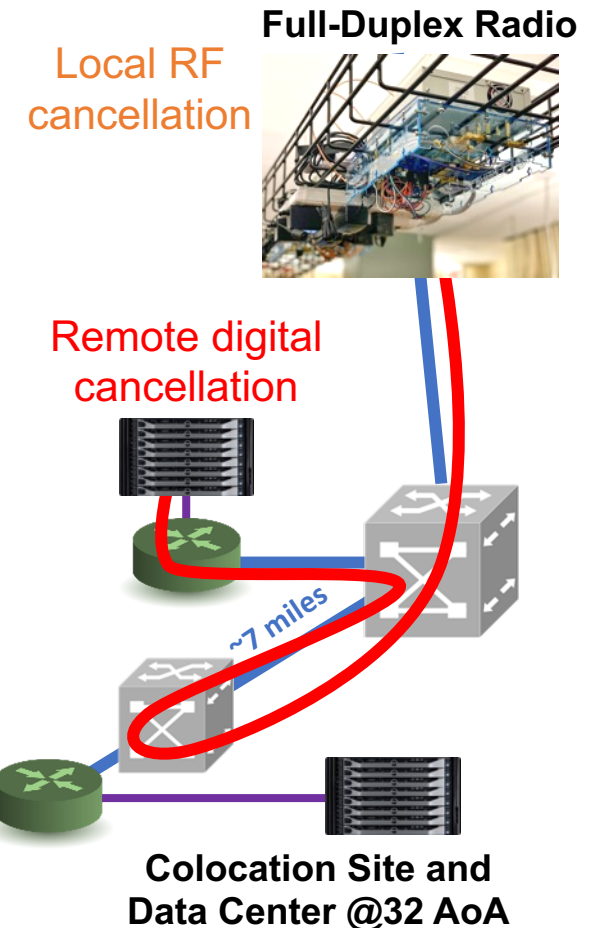
- M. Kohli, T. Chen, M. Baraani Dastjerdi, J. Welles, I. Seskar, H. Krishnaswamy, and G. Zussman, "Open-access full-duplex wireless in the ORBIT and COSMOS testbeds," in *Proc. ACM MobiCom'20 Workshop on Wireless Network Testbeds, Experimental evaluation & CHaracterization (WiNTECH)*, 2020.
- T. Chen, 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)

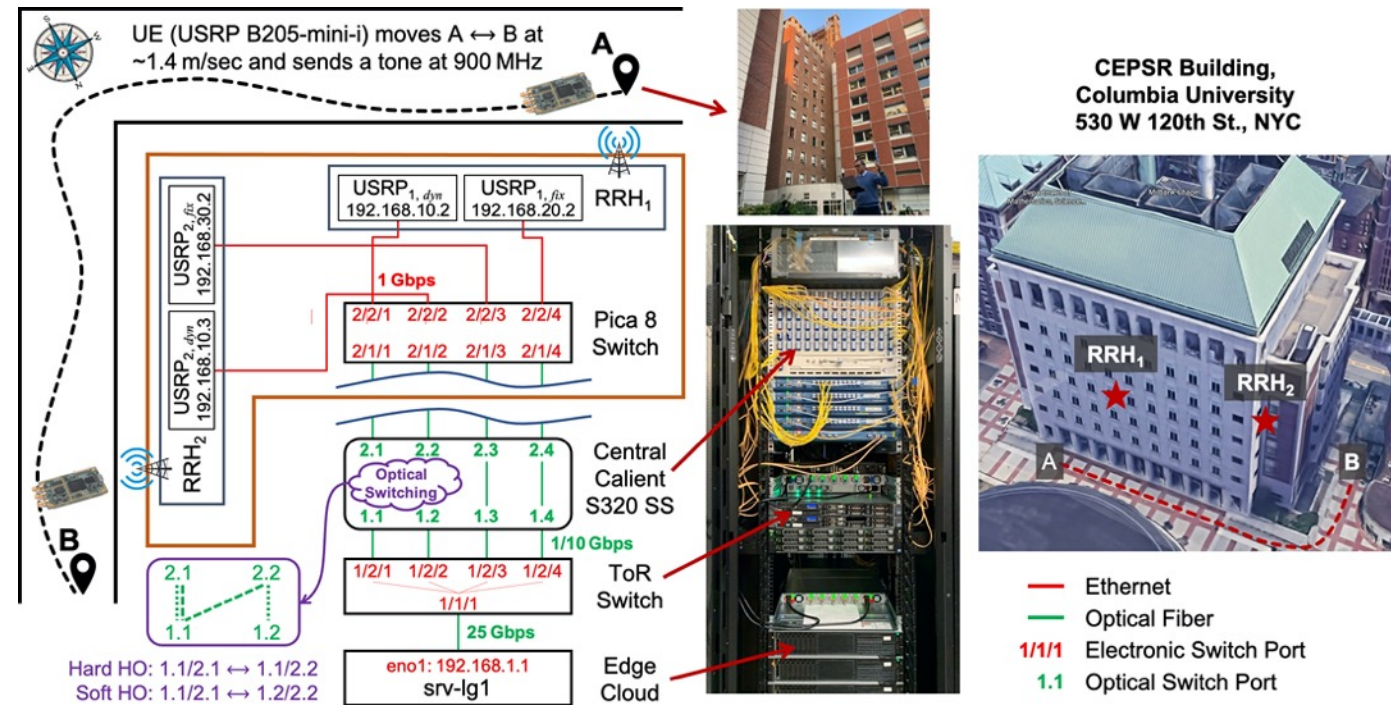
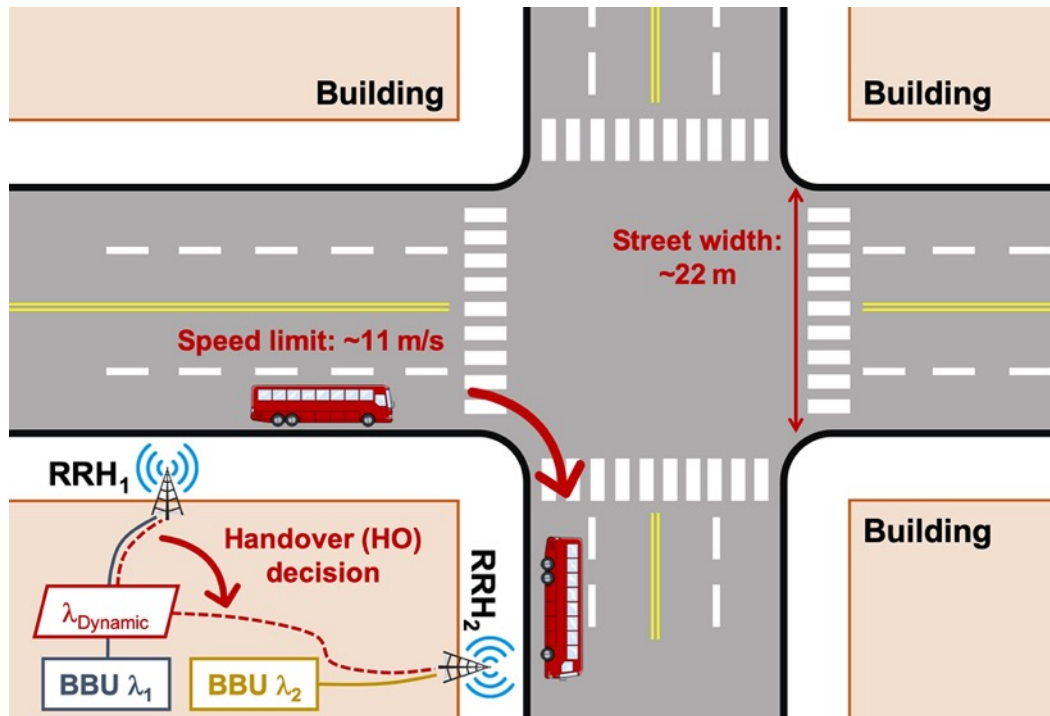


COSMOS dark fiber deployment and the supported Cloud-RAN applications



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: Smart Intersection

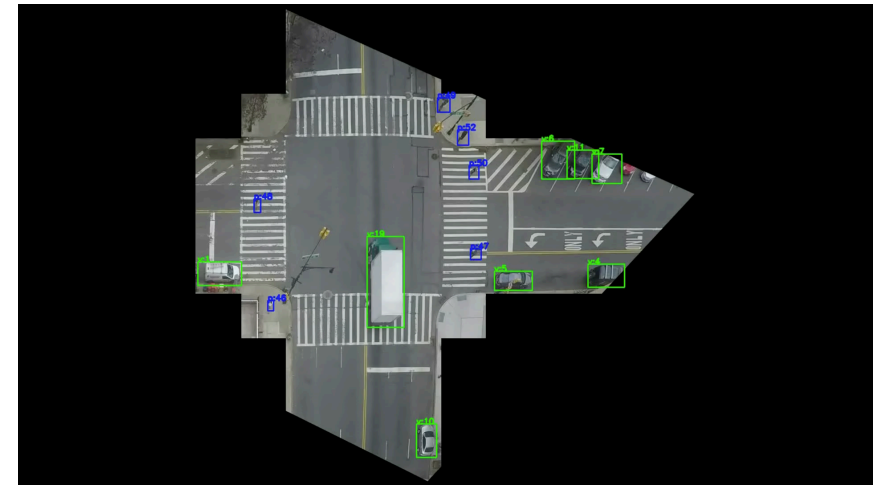
- Smart intersection as a core smart city asset
 - Low latency, high bandwidth wireless links, sensor data acquisition
 - Edge cloud computing and machine intelligence for interaction with pedestrians
- **Real-time** (latency) – something useful for traffic interaction/management
 - Vehicle speed: 10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



COSMOS pilot site



Bird's eye videos fed into the COSMOS edge node for vehicles/pedestrians detection and classification



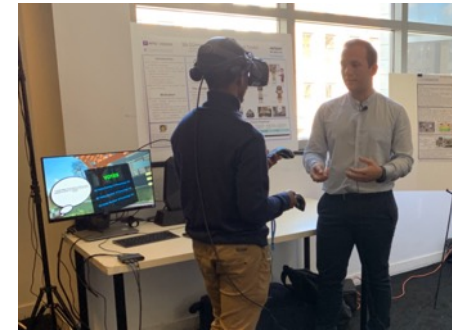
- S. Yang, E. Bailey, Z. Yang, J. Ostrometzky, G. Zussman, I. Seskar, and Z. Kotic, "COSMOS smart intersection: Edge compute and communications for bird's eye object tracking," in *Proc. 4th International Workshop on Smart Edge Computing and Networking (SmartEdge'20)*, 2020.

Education and Outreach

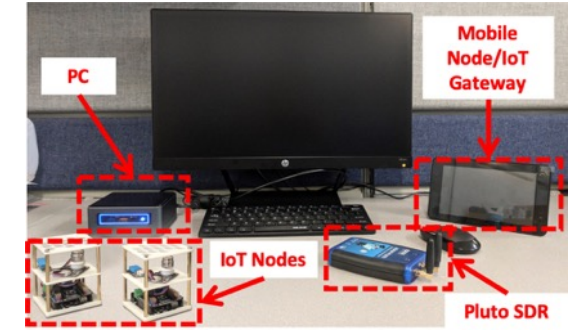


AT&T verizon✓

- COSMOS education toolkit: A small pre-configured COSMOS node (developed in Summers 2018–2020 RET programs) 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.
- "5G in 3D: Immersive COSMOS Education Toolkit Wins Verizon EdTech Challenge", <https://www.engineering.columbia.edu/news/verizon-edtech-challenge>

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 and mmWave SDRs with different form factors
 - A unique programmable optical 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 application domains: AR/VR, autonomous vehicles, smart intersections...
- COSMOS as an education and outreach toolkit

Acknowledgements



- Janice Campanella, Prasanthi Maddala, Nilanjan Paul, Newman Wilson (WINLAB, Rutgers)
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- Clayton Banks, Bruce Lincoln (Silicon Harlem)
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- Myung Lee, Rosemarie Wesson (CCNY)
- Arun Paidimarri, Bodhisatwa Sadhu, Alberto Valdes-Garcia (IBM Research)
- Nikos Makris (U. Thessaly)
- Artur Minakhmetov (Télécom Paris)
- ... and many other contributors in Rutgers, Columbia, NYU, NYC, Silicon Harlem, U. Arizona, CCNY, and IBM Research.

Upcoming Events

- COSMOS Tutorial at ACM MobiCom'20 (online)
 - Sept. 25, 9am–1pm (EDT), <https://www.cosmos-lab.org/mobicom2020/>
- Open-access full-duplex wireless in the COSMOS testbed
 - Paper at *ACM WiNTECH'20* (Sept. 25). Demo in the *ACM MobiCom'20 Demo Session* (Sept. 23)
- NSF PI's of active research awards can receive up to \$50K supplemental funding to conduct experimental research on the testbed (for more details see NSF DCL-20-046).
- The [NGlatlantic.eu](https://www.nglatlantic.eu) 2nd Open Call (deadline on Sept. 30, 2020): To incentivize EU–US Next Generation Internet (NGI) teams to carry out experiments using EU and/or US based experimental platforms via grants to the European counterparts.
- 2nd COSMOS Research Community Workshop and Tutorial (online)
 - Oct. 14–15, <https://www.cosmos-lab.org/2ndworkshop>, **register here!** →





Thank you!

<https://www.cosmos-lab.org/>

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