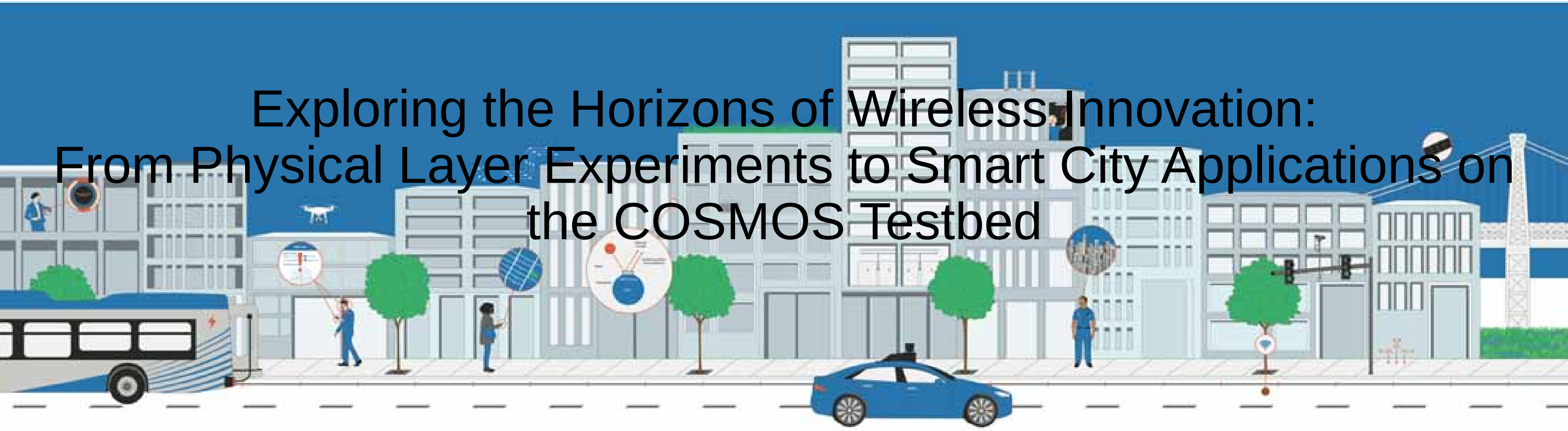
Exploring the Horizons of Wireless Innovation: From Physical Layer Experiments to Smart City Applications on the COSMOS Testbed



Ivan Seskar

WINLAB, Rutgers University

seskar@winlab.rutgers.edu

Acknowledgements

- **WINLAB, Rutgers University**: Dipankar Raychaudhuri, Jakub Kolodziejski, Michael Sherman, Prasanthi Maddala, Nilanjan Paul, Sumit Maheshwari, Shalini Choudhury, Newman Wilson, Janice Campanella
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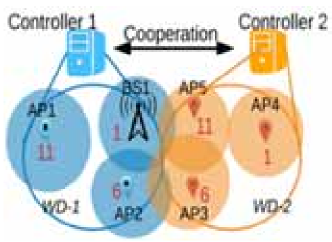
Rutgers, The State University of New Jersey / WINLAB

WINLAB 25,000 sq.ft. Tech Center Facility

WINLAB founded in 1989 as a collaborative industry-university research center with specialized focus on wireless networking

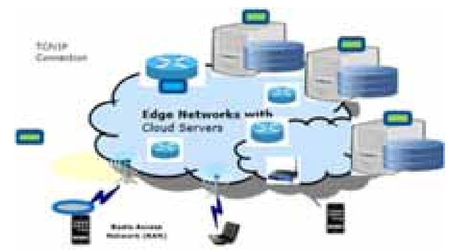
~25 faculty/staff, most from the ECE and CS departments at Rutgers
~40-50 grad students (80% PhD, 20% MS)

Center's research portfolio spans information theory, radio technology, wireless systems, mobile networks and computing

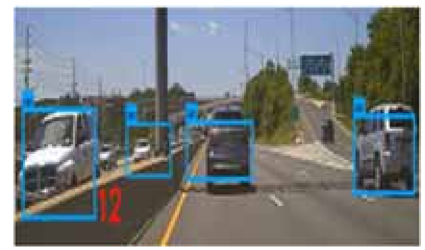


Dynamic Spectrum

Future Internet Arch.



Edge Cloud

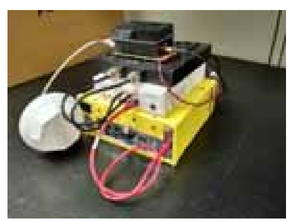


Connected Vehicle

Extensive experimental research infrastructure including COSMOS, ORBIT & GENI testbeds

Low Power IoT Device

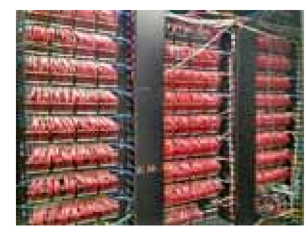
Massive MIMO



SDR

ORBIT Radio Grid Testbed

Computing Infrastructure



SDN

RUTGERS

WINLAB

Platforms for Advanced Wireless Research (PAWR)

- NSF public/private program ($50M + $50M)
- Managed by PAWR Project Office (NEU/US-Ignite)
- Build four “city scale” platforms in US
- Enable core wireless and mobile research
- Enable research related to services/applications that rely on wireless and mobile

POWDER
Salt Lake City

COSMOS
New York City

AERPAW
Research Triangle

ARA
Central Iowa

First round completed in early 2018:

- POWDER-RENEW (University of Utah, Rice University)
- COSMOS (Rutgers University, Columbia University, New York University)

Second round winner early 2020:

- AERPAW (North Carolina State University, Mississippi State University, RENCI)

Third round winner July 2021:

- ARA (Iowa State University)

Additional facilities and resources:

- Colosseum - The world's most powerful wireless network emulator
- OpenAirX-Labs (OAX) - An end-to-end open source 5G software lab

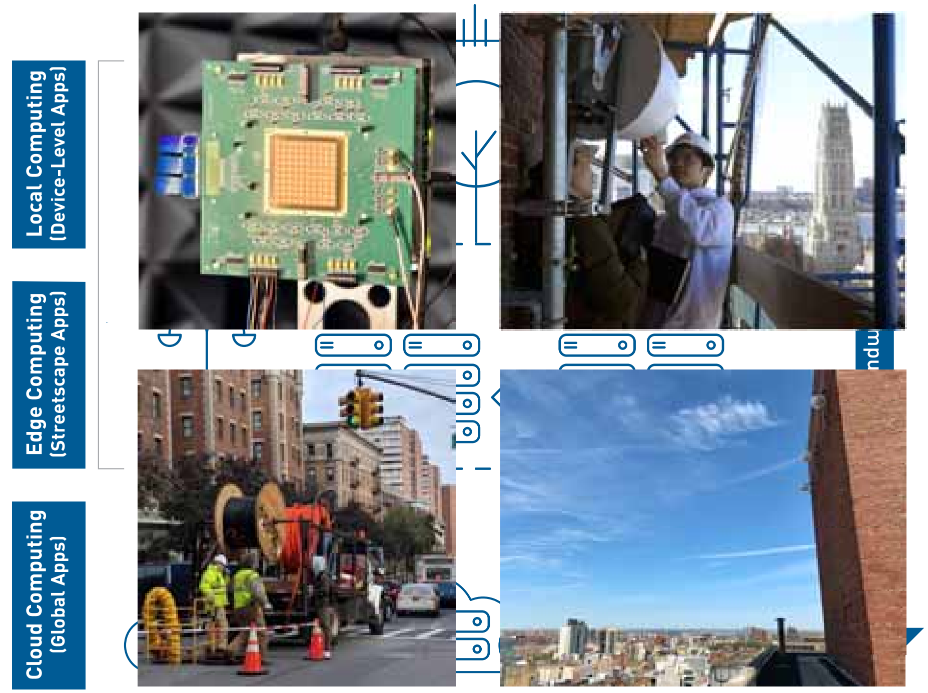
NSF

Platforms for Advanced Wireless Research

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



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)

COSMOS

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Objective: Take it Outside

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COSMOS: Deployment Area

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: Envisioned Deployment

- West Harlem with an area of ~1 sq. mile
  - ~15 city blocks and ~5 city avenues

- Large sites
  - Rooftop base stations
- Medium sites
  - Building side- or lightpole-mounted
- Small nodes
  - Including vehicular and hand-held

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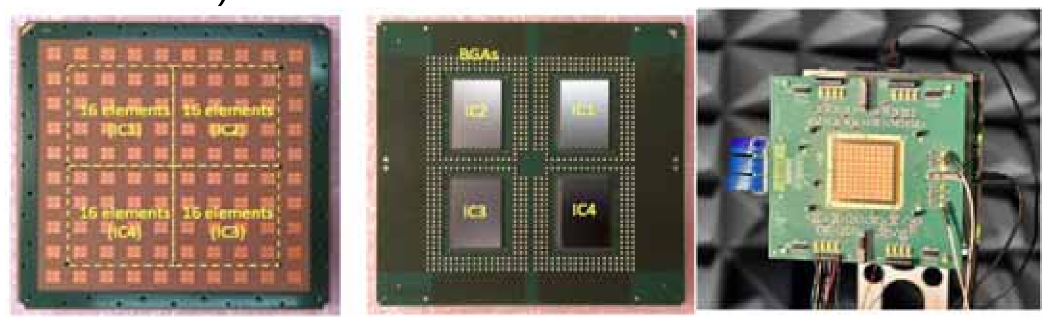
COSMOS Key Technologies

SDR

Design goal: 70 Mhz – 6 Ghz + 28 Ghz and 60 Ghz bands, ~500 Mhz BW, Gbps

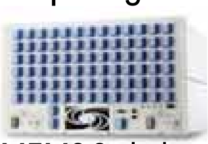
mmWave

IBM 28 GHz mmWave phased arrays (64 antennas with 1 or 8 beams)

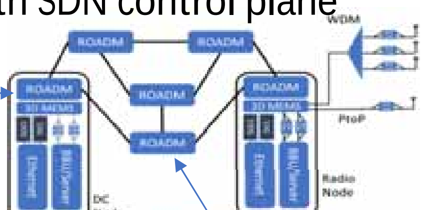


Optical Networking

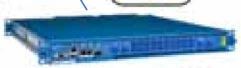
Fast and low latency optical x-haul network using 3D MEMS switch and WDM ROADM - wide range of topologies with SDN control plane



MEMS Switch



fast front-haul/mid-haul/back-haul connectivity between radio nodes and edge cloud

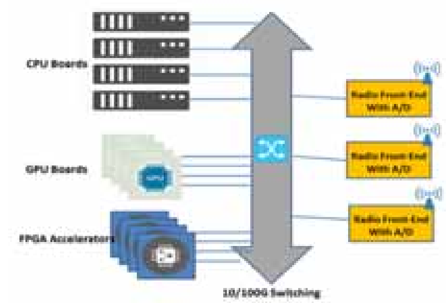


ROADM (whitebox)

SDN and (distributed) Cloud

Compute clusters with choice of CPU, GPU and FPGA proc.

SDN control plane used to control x-haul and (near) cloud server connectivity



Access to regular (far) cloud racks over L3

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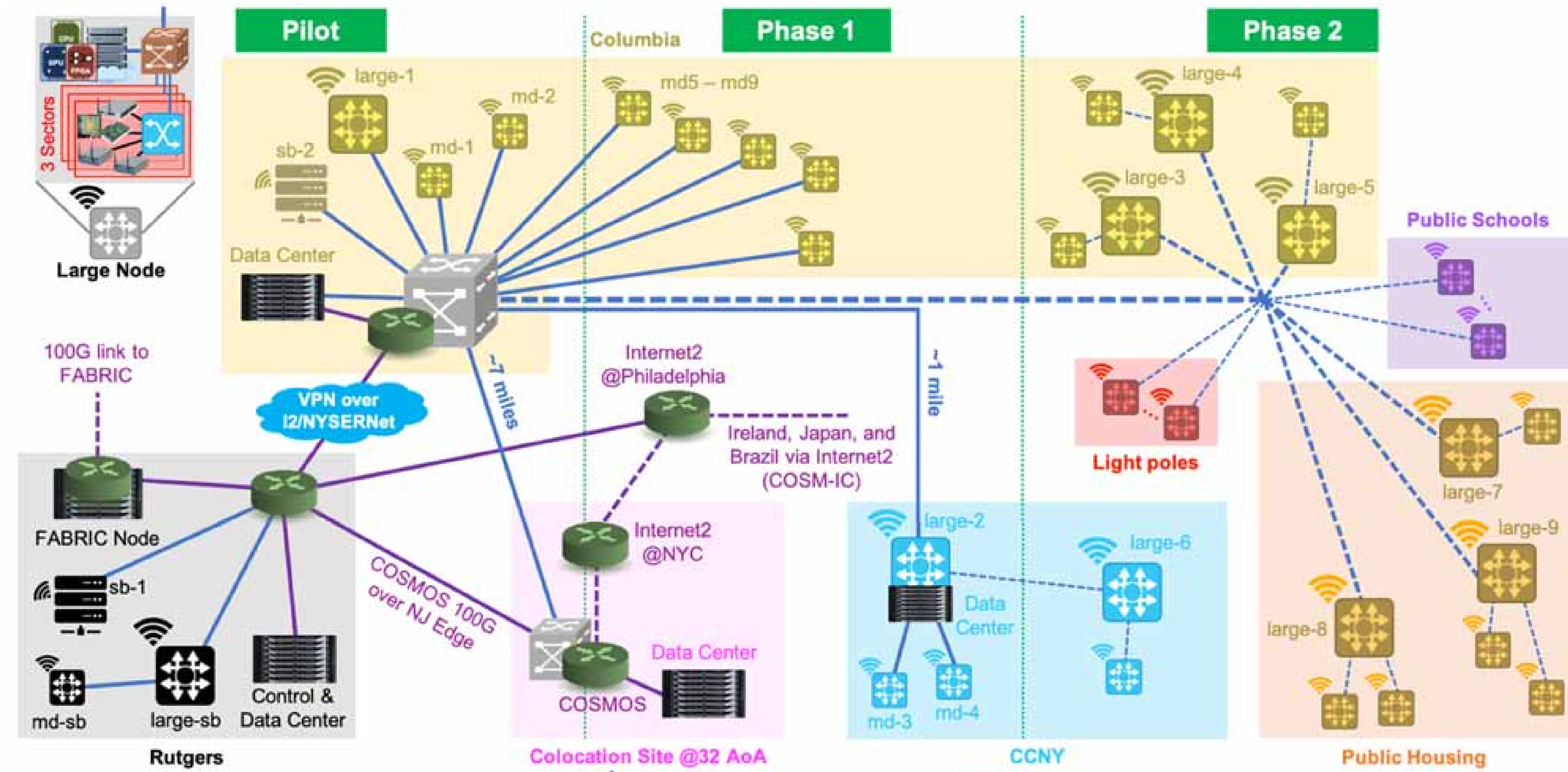
COSMOS: Envisioned Deployment



COSMOS: Envisioned Deployment

COSMOS Experimental Licenses

FCC Innovation Zone: "The New York City Innovation Zone encompasses area bounded by W 120th Street on the south, Amsterdam Avenue to the east, W 136th Street to the north and Hudson River on the west"

Frequency Band	Type of operation	Allocation	Maximum EIRP (dBm)
2500-2690 MHz	Fixed	Non-federal	20*
3700-4200 MHz	Mobile	Non-federal	20*
5850-5925 MHz	Mobile	Shared	20*
5925-7125 MHz	Fixed & Mobile	Non-federal	20*
27.5-28.35 GHz	Fixed	Non-federal	40*
38.6-40.0 GHz	Fixed	Non-federal	40*

(Additional) Program Experimental License: at Rutgers, Columbia and CCNY campuses

COSMOS

Platforms for Advanced Wireless Research

COSMOS: Project Timeline

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

- **Apr. 2018** — Project start
- **May 2019** — Pilot completion and the first COSMOS workshop/tutorial

- **Sept. 2019** — FCC Innovation Zone

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

- **Nov. 2020** — COSM-IC

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

- **Sept. 2022** — NSF CS3 ERC Awarded

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

- **Jan. 2023** — O-RAN OTIC

O-RAN ALLIANCE

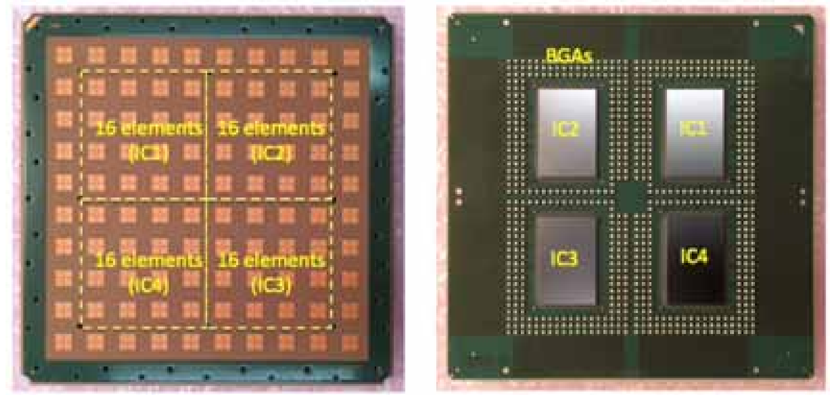
- **Q1 2023** — O-RAN nG Research Platform
- *Phase 1 completion Q3 2023**

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

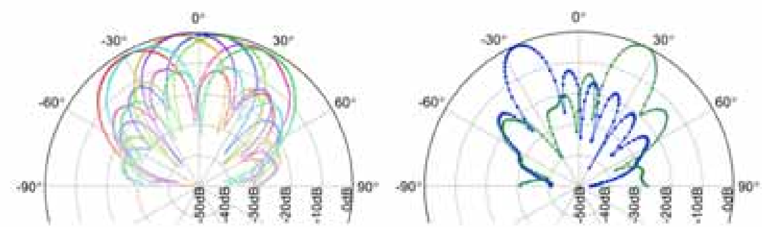
COSMOS | RUTGERS | COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK | NYU | NYC | <sh> | The City College of New York | The University of Arizona | IBM

IBM-Ericsson 28 GHz 64-element PAAM

- Multi-function module
  - 8 simultaneous16-element beams in TX or RX
  - 2 simultaneous 64-element beams in TX or RX
  - Dual-polarization with independent data streams
- Antenna gain uniformity & orthogonal and fast beam controls (no calibration required)

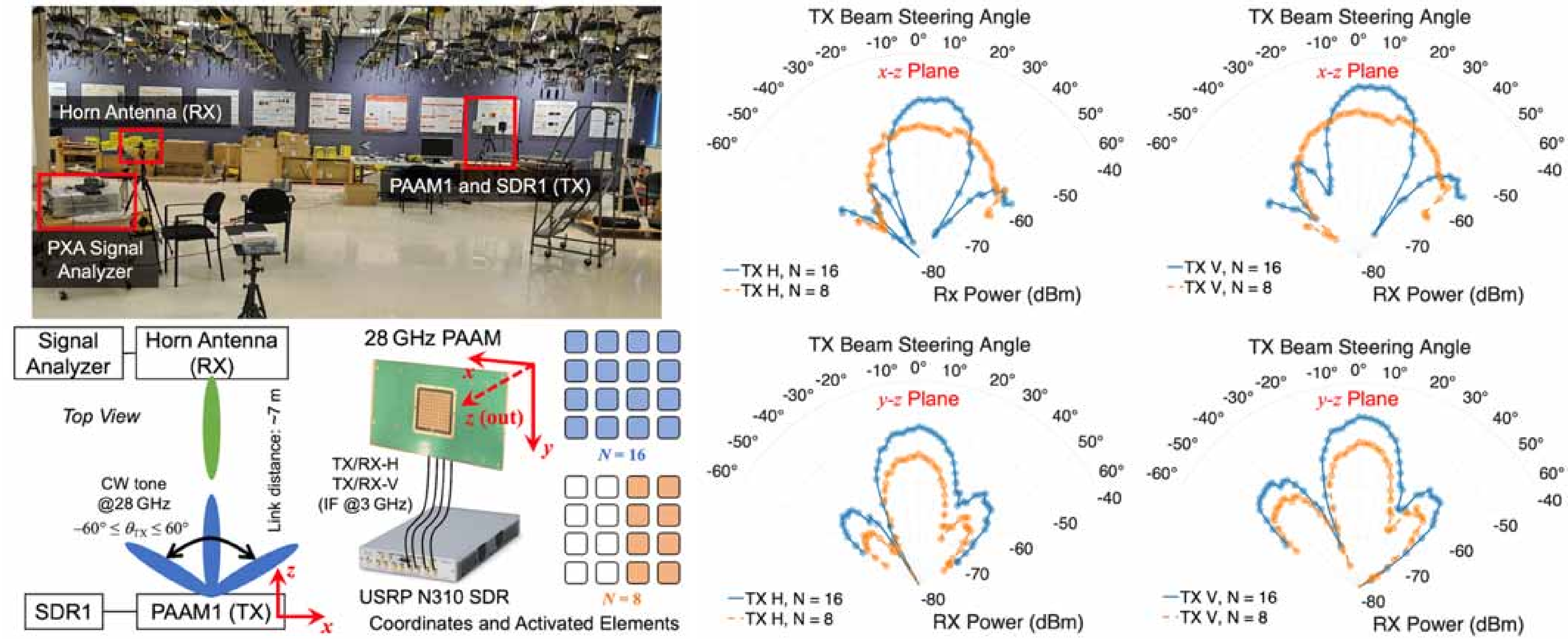


- TX/RX beamforming
  - Support >20,000 independent beamforming directions with 1° beam-steering resolution
  - Beam-steering up to ±60° in azimuth/elevation



- X. Gu, et al. "Development, implementation, and characterization of a 64-element dual-polarized phased-array antenna module for 28-GHz high-speed data communications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 67, no.7, pp. 2975-2984, 2019.
- X. Gu, et al. "A multilayer organic package with 64 dual-polarized antennas for 28GHz 5G communication," in *Proc. IEEE MTT-S International Microwave Symposium (IMS'17)*, 2017.
- B. Sadhu, et al. "A 28-GHz 32-element TRX phased-array IC with concurrent dual-polarized operation and orthogonal phase and gain control for 5G communications," *IEEE Journal of Solid-State Circuits*, vol. 52, pp.12, pp. 3373–3391, 2017. **Best Paper Award**
- B. Sadhu, et al. "A 28GHz 32-element phased-array transceiver IC with concurrent dual polarized beams and 1.4 degree beam-steering resolution for 5G communication," in *Proc. IEEE International Solid-State Circuits Conference (ISSCC'17)*, 2017. **Lewis Winner Award for Outstanding Paper (Best Paper Award)**

Experimentation with mmWave Characterization

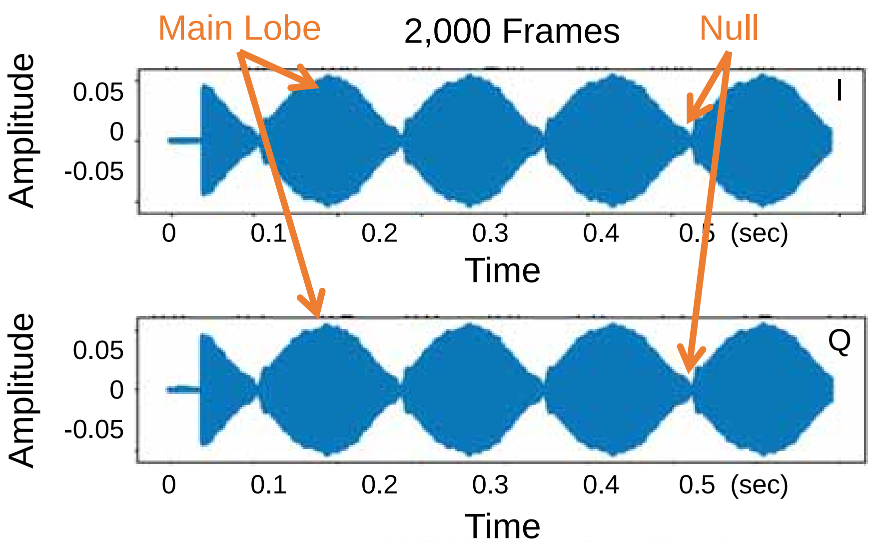


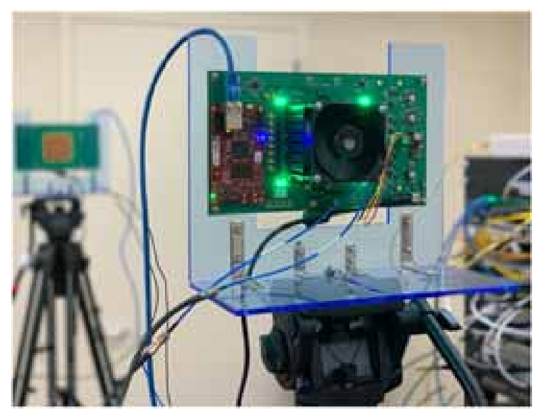
Example beam pattern measurements using the IBM 28 GHz PAAMs in Sandbox 1

- 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.

Experiment: Indoor 28 GHz Channel Sounding

- Hardware:
  - *2x* IBM 28 GHz PAAM boards and *2x* USRP N310 SDRs (sampling rate: 62.5 MHz) in COSMOS Sandbox 2
- Software:
  - IBM PAAM control API with fixed TX beam and RX beam sweeping within [–60°, 60°] in the azimuth plane
  - The *RENEWLab Sounder* framework with USRP support (https://github.com/renew-wireless/RENEWLab)





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Experimentation with mmWave Characterization

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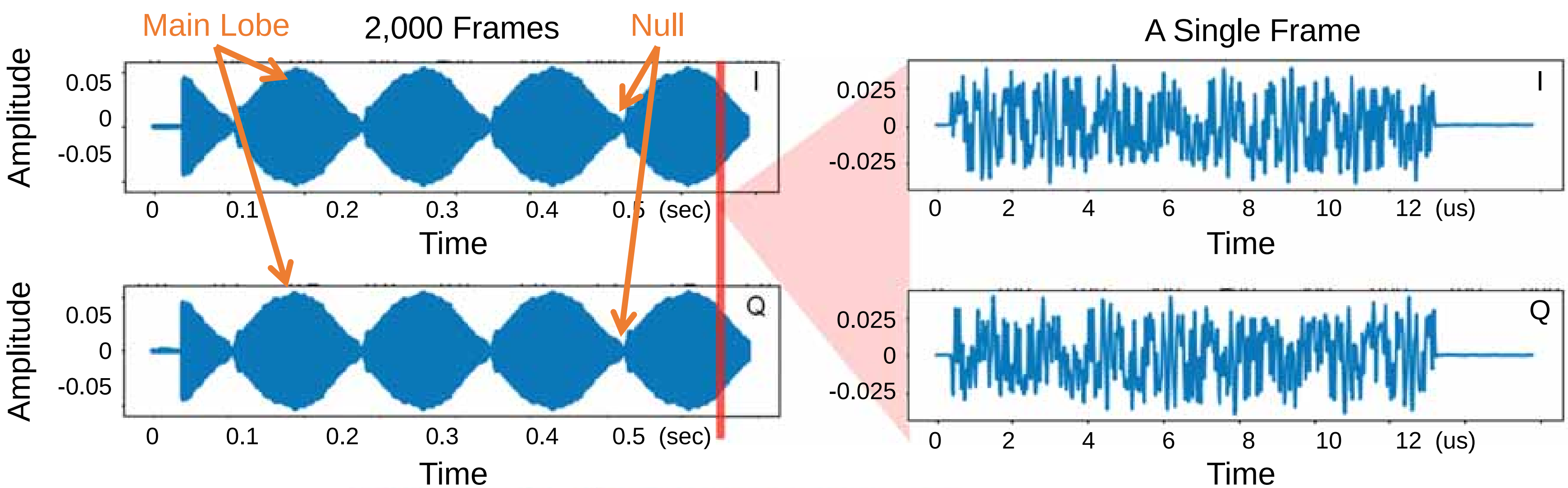
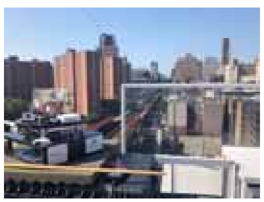


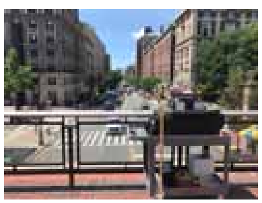
- Zhenzhou Qi, Zhihui Gao, Chung-Hsuan Tung, Tingjun Chen, "Programmable Millimeter-Wave MIMO Radios with Real-Time Baseband Processing", (to appear) in *Proc. ACM MobiCom'23 Workshop on Wireless Network Testbeds, Experimental evaluation & CHaracterization (WiNTECH'23)*,

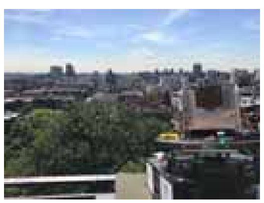
Experiment: Outdoor mmWave Channel Characterization

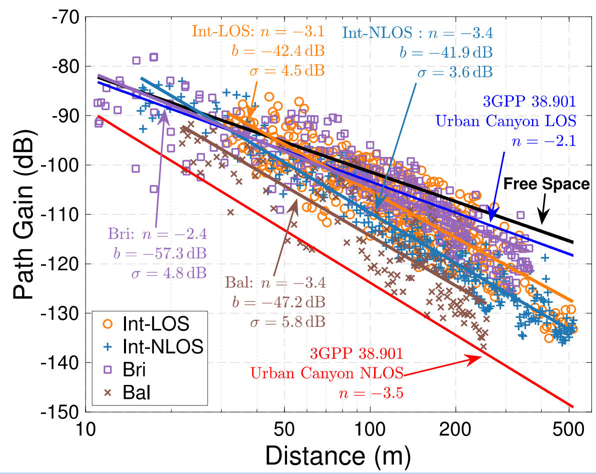
- 28 GHz channel measurements in the COSMOS testbed area in a dense urban canyon environment
  - Representative (potential) deployment sites of mmWave BSs (building rooftops, street lightpoles, etc.)
  - Extensive measurements on long sidewalks (up to 1,100 m) with fine-grained link step size (1.5/3 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

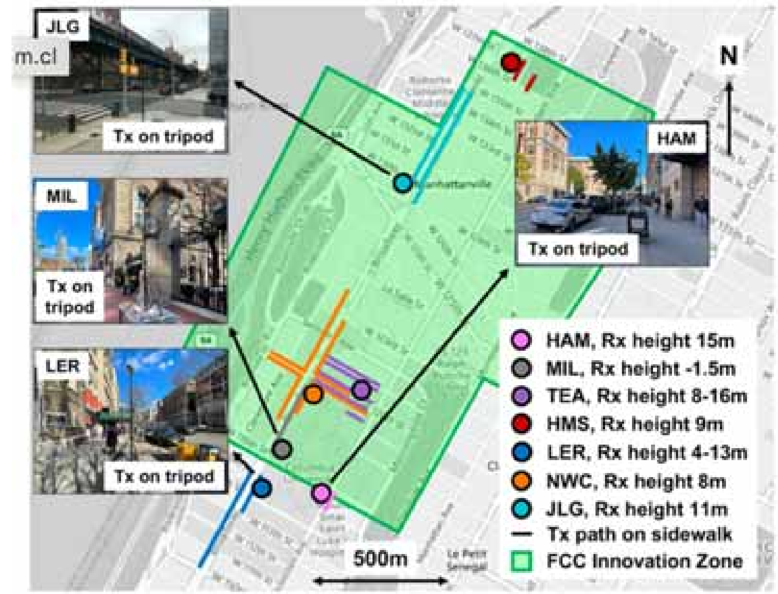


- D. Chizhik, J. Du, R. Valenzuela, “Universal path gain laws for common wireless communication environments”, *IEEE Transactions on Antennas and Propagation*, 2021
- J. Du, D. Chizhik, R. Valenzuela, R. Feick, M. Rodríguez, G. Castro, T. Chen, M. Kohli, and G. Zussman, “Directional measurements in urban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

Experiment: Outdoor to Indoor mmWave

- 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

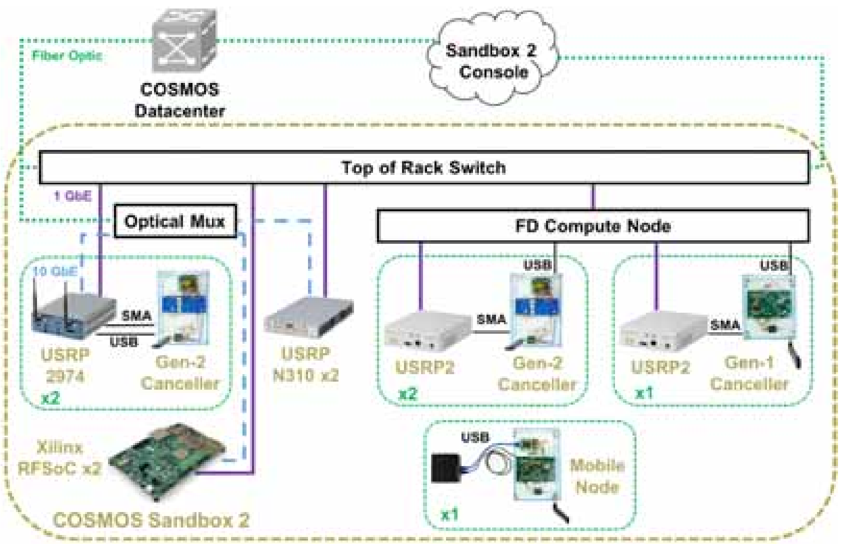


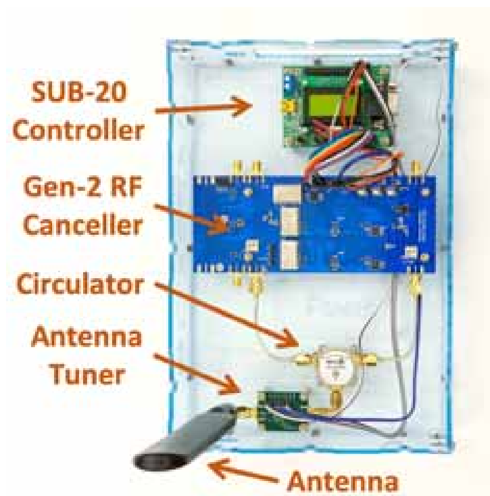
Outdoor-to-indoor measurements

- 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.

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

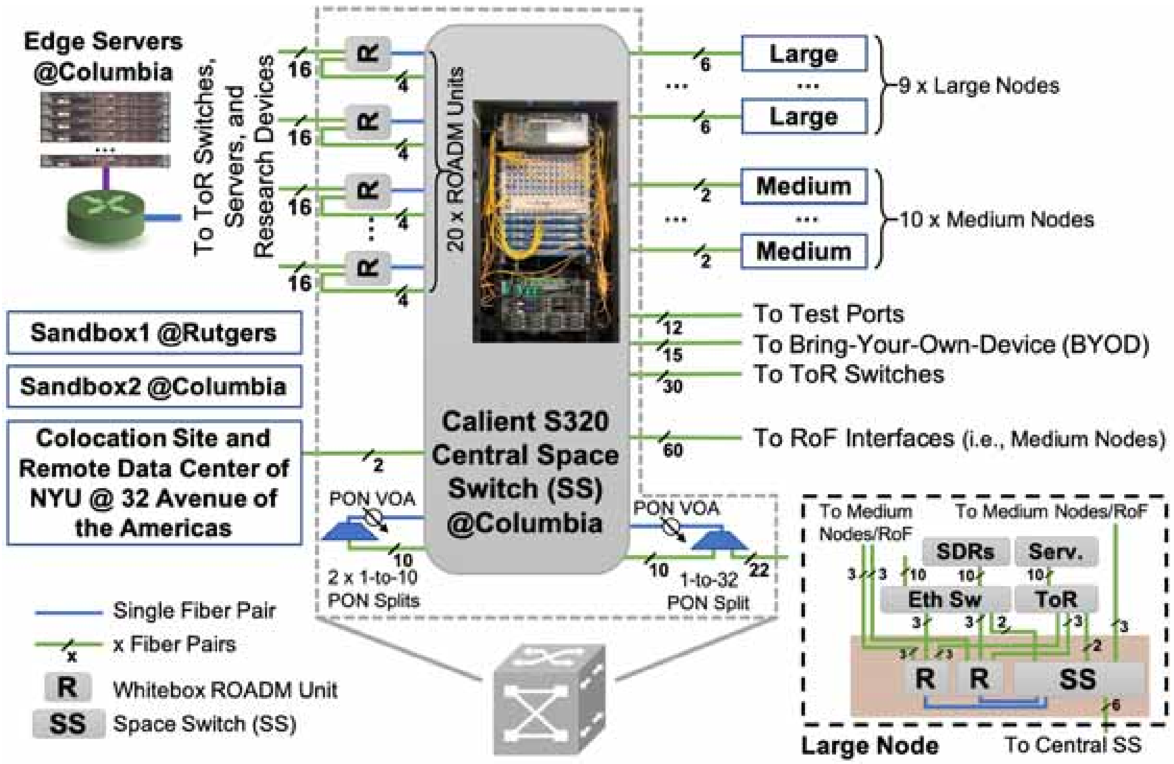


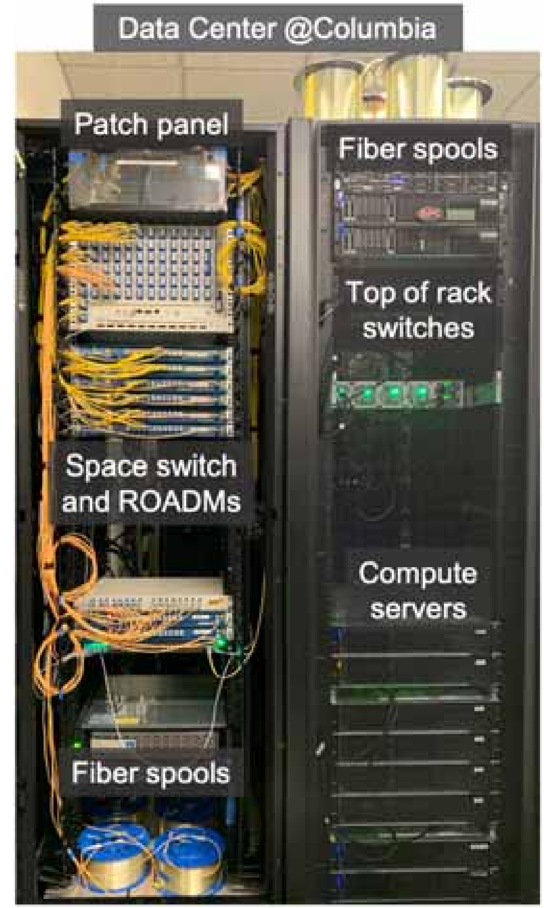


- M. Kohli, T. Chen, M. Baraani Dastjerdi, J. Welles, I. Seskar, H. Krishnaswamy, and G. Zussman, “Open-access full-duplex wireless in the ORBIT and COSMOS testbeds,” *Elsevier Computer Networks*, 2021.
- T. Chen, M. Baraani Dastjerdi, J. Zhou, H. Krishnaswamy, and G. Zussman, “Wideband full-duplex wireless 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.

Optical Networking

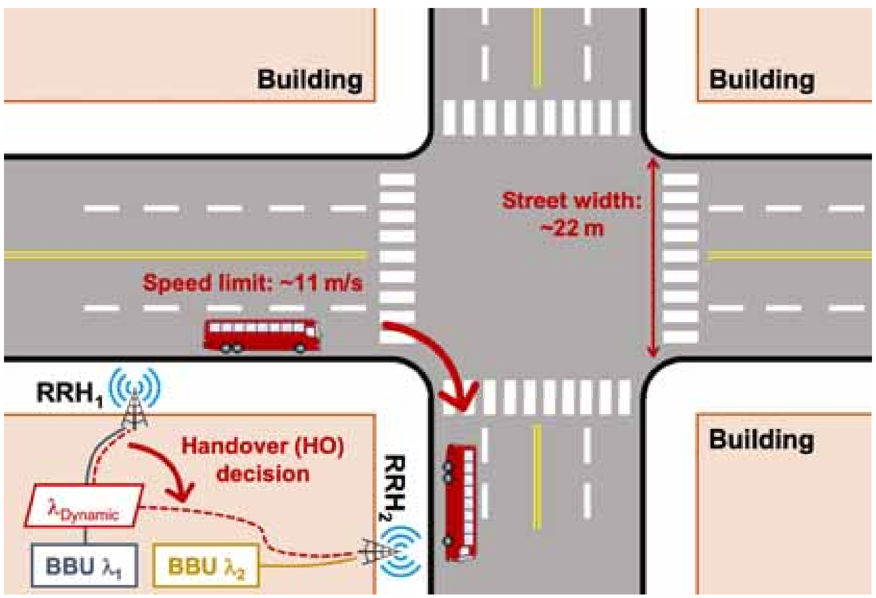


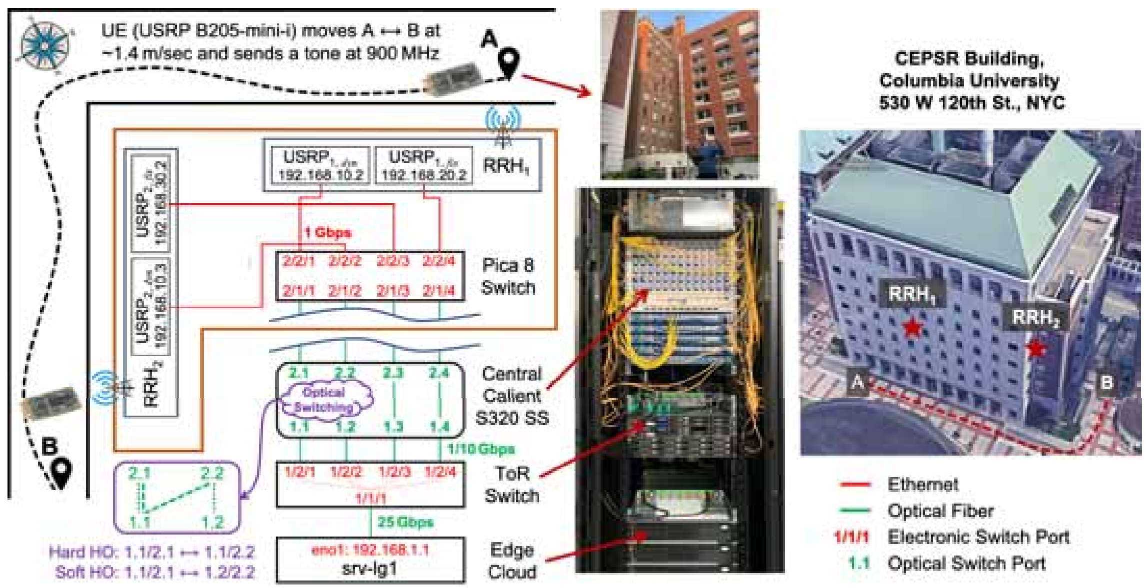


- T. Chen, J. Yu, A. Minakhmetov, C. Gutterman, M. Sherman, S. Zhu, S. Santaniello, A. biswas, I. Seskar, G. Zussman, and D. Kilper, “A software-defined programmable testbed for beyond-5G optical-wireless experimentation at city-scale,” *IEEE Network, Special Issue on Next-Generation Optical Access Networks to Support Super-Broadband Services and 5G/6G Mobile Networks*, vol. 36, no. 2, pp. 90-99, Mar./Apr. 2022.
- B. Lantz, J. Yu, A. Bhardwaj, A. Diaz-Montiel, A. Quraishy, S. Santaniello, T. Chen, R. Fujieda, A. Mukhopadhyay, G. Zussman, M. Ruffini, and D. Kilper, “SDN-controlled dynamic front-haul provisioning, emulated on hardware and virtual COSMOS optical x-haul testbeds,” in *Proc. OSA OFC’21, M2B.8*, 2021.
- 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.

Experiment: Optical+Wireless Handover

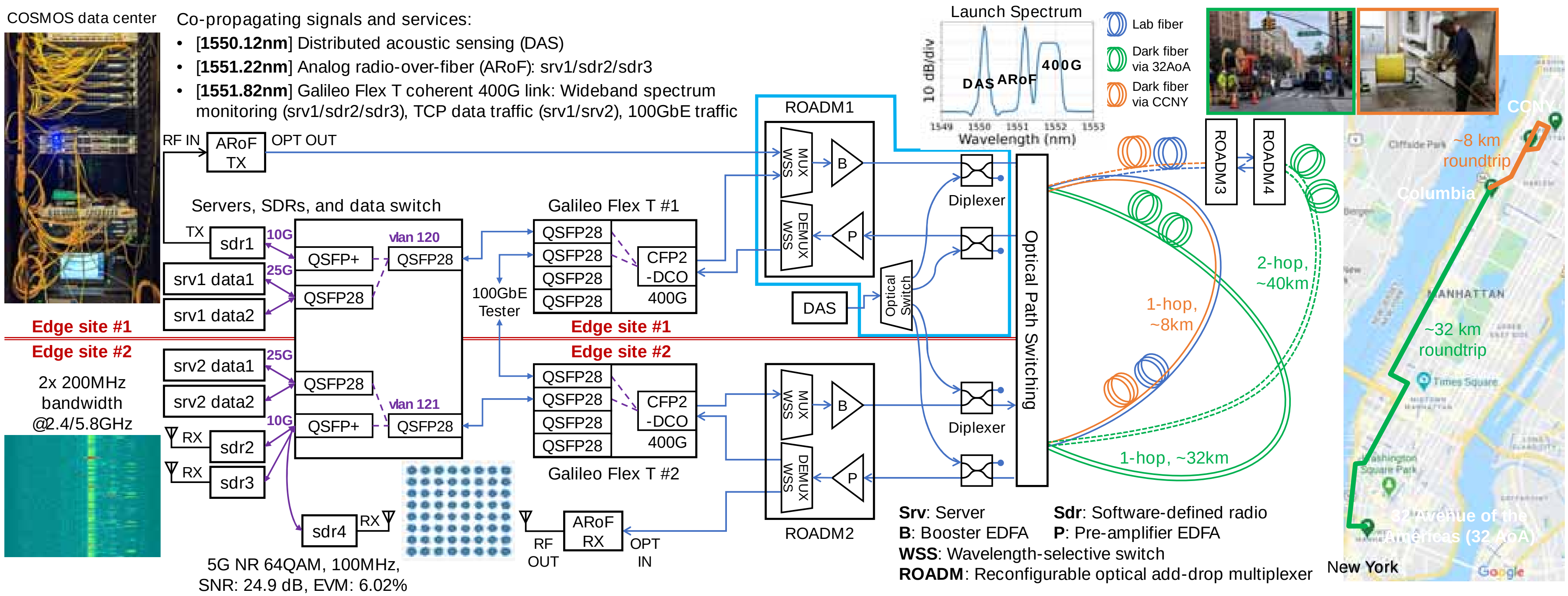
- SDN-based optical switching to support high bandwidth links with deterministic delay
- A vehicle taking a turn at an intersection receives services from two remote radio heads (RRHs) through dynamic optical switching and wavelength re-allocation.





- 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.

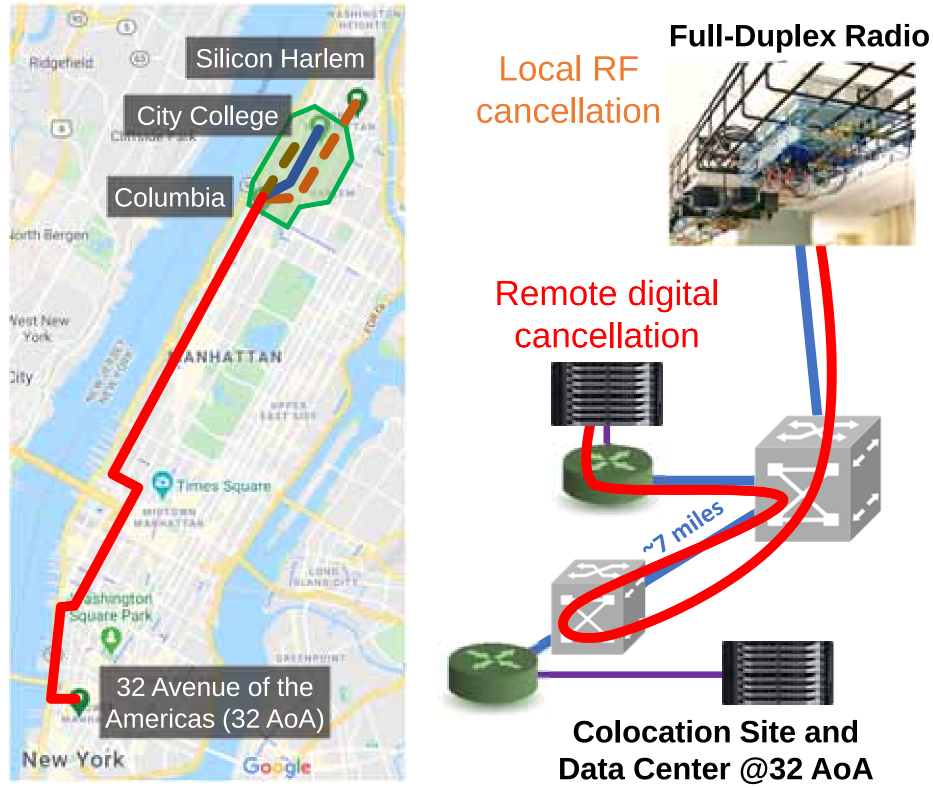
Experiment: Coexistence and Simultaneous Switching of Real-time Fiber Sensing and 400GbE



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)

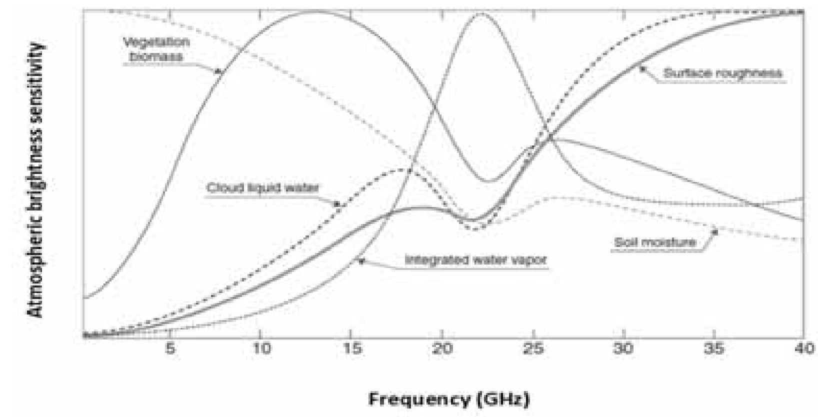


COSMOS dark fiber deployment and the supported Cloud-RAN applications

- 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.

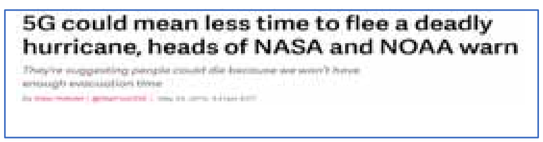
NSF SWIFT: Enabling Spectrum Coexistence of 5G mmWave and Passive Weather Sensing

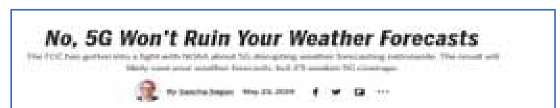
- Specific focus on 5G n258 mmWave band



- Weather prediction (WRF Data Assimilation)
  - Rely on passive satellite sensors/radiometers observations
  - AMSU-A sensors operate at 23.8 GHz on weather satellites
  - Operating bandwidth of 270 MHz, located at ~700 km distance from earth

- Big debate on acceptable 5G Leakage
  - -55 to -40 dBW (Weather Forecasters) vs -20 dBW (5G Community)


5G could mean less time to flee a deadly hurricane, heads of NASA and NOAA warn


No, 5G Won't Ruin Your Weather Forecasts

Pcmag.com: May 2019

- Passive Spectrum Coexistence
  - Can we model leakage from the n258 band on passive weather sensors at satellites and determine impact on actual weather prediction?
  - What does it mean for Transceiver Design and Resource Allocation?

RUTGERS

N. Mandayam, C. T. M. Wu, R. Wang, J. Brodie

WINLAB

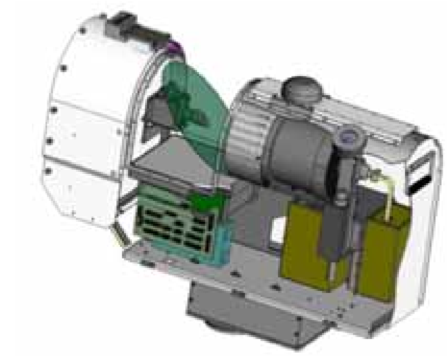
SII-NRDZ: Spectrum Sharing via Consumption Models and Telemetry - Prototyping and Field Testing in an Urban FCC Innovation Zone

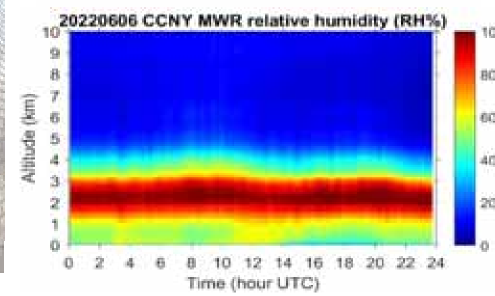
- The fundamental information model based on Spectrum Consumption Models (SCMs), recently standardized as IEEE 1900.5.2.
  - SCMs capture the transmission and reception spectrum use boundaries of wireless systems so their compatibility (i.e., non-interference) can be arbitrated by efficient and standardized computational methods
- Objectives:
  - Develop techniques for efficiently generating SCMs and using them in a large-scale ZMS
  - Develop spectrum sharing and interference management algorithms that use SCMs and measurement feedback to achieve high spectrum efficiency, low processing complexity and communication overhead, and scalability
  - Prototype a Zone Management System (ZMS)
  - Evaluate via real-world experimentation at COSMOS and NOAA-CESSRST

COSMOS | Columbia University in the City of New York | Rutgers | The City College of New York | Duke University | Princeton University | Syracuse University | NOAA-CESSRST

NRDZ: Considered Scenarios/Applications

- Protection of passive receivers in the NOAA-CESSRST center at 27–29 GHz (for part of the operating band of a radiometer used in weather monitoring)
  - Overlap with the mmWave frequency range used in COSMOS and 5G
- Protection of passive receivers in the NOAA-CESSRST center that operate at 1.7 GHz and 7.7–8.2 GHz (for reception from a polar orbiting satellite)
- Potentially – protection of 9.5GHz weather radar
- Protection mechanisms and sensing for 6-7 GHz operations
  - Indoor to outdoor effects in a dense urban environment



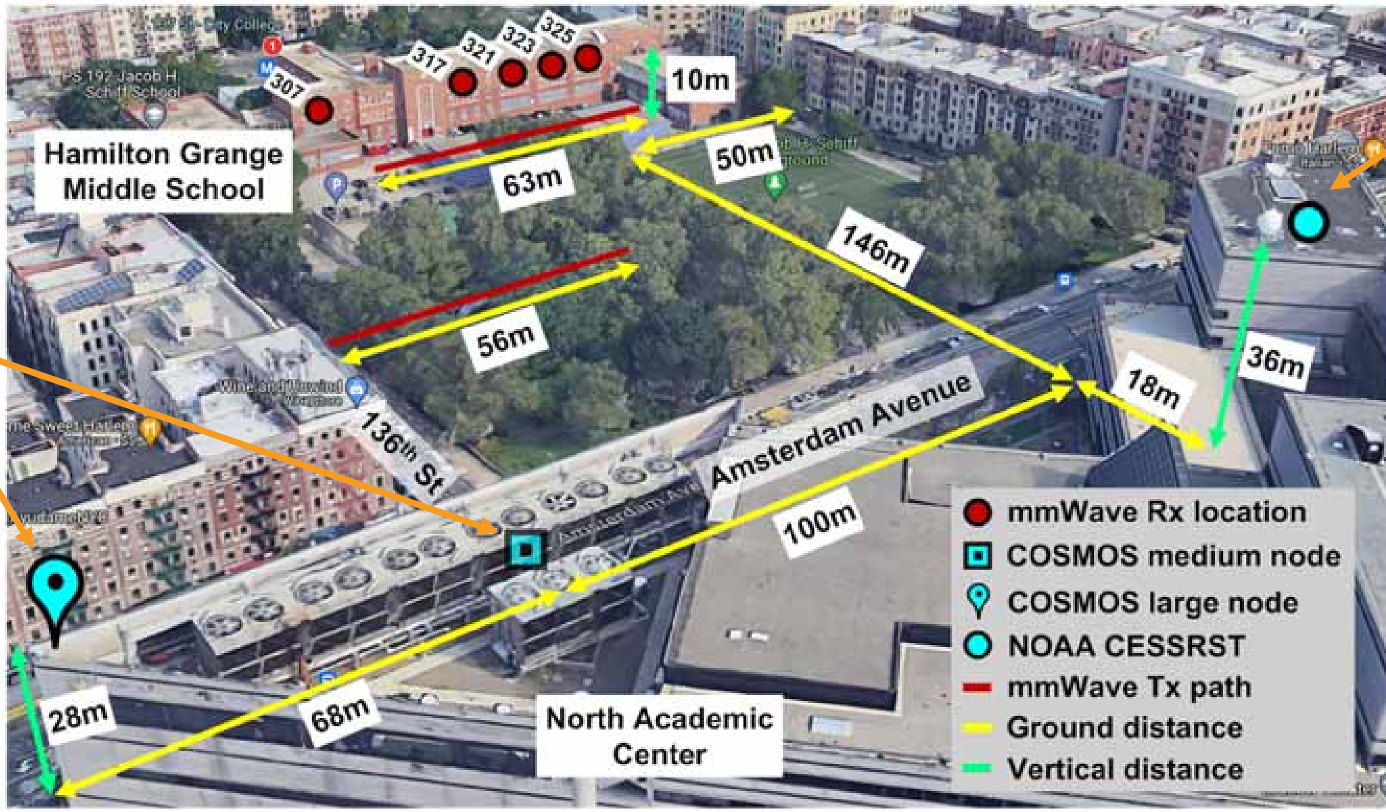


COSMOS · Columbia University in the City of New York · Rutgers · The City College of New York · Duke University · Princeton University · Syracuse University · NOAA-CESSRST

NSF COSMOS and NOAA CESSRST

NOAA-CESSRST

COSMOS

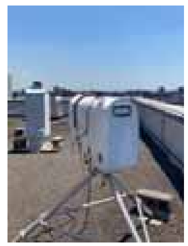


COSMOS | Columbia University in the City of New York | Rutgers | The City College of New York | Duke University | Princeton University | Syracuse University | NOAA-CESSRST

Overview (Cont.)

NOAA-CESSRST
NOAA Center for Earth System Sciences and Remote Sensing Technologies


Satellite Direct Broadcast Receiving System


Thermodynamic Radiometer


FCC NYC Innovation Zone


NSF PAWR COSMOS Testbed

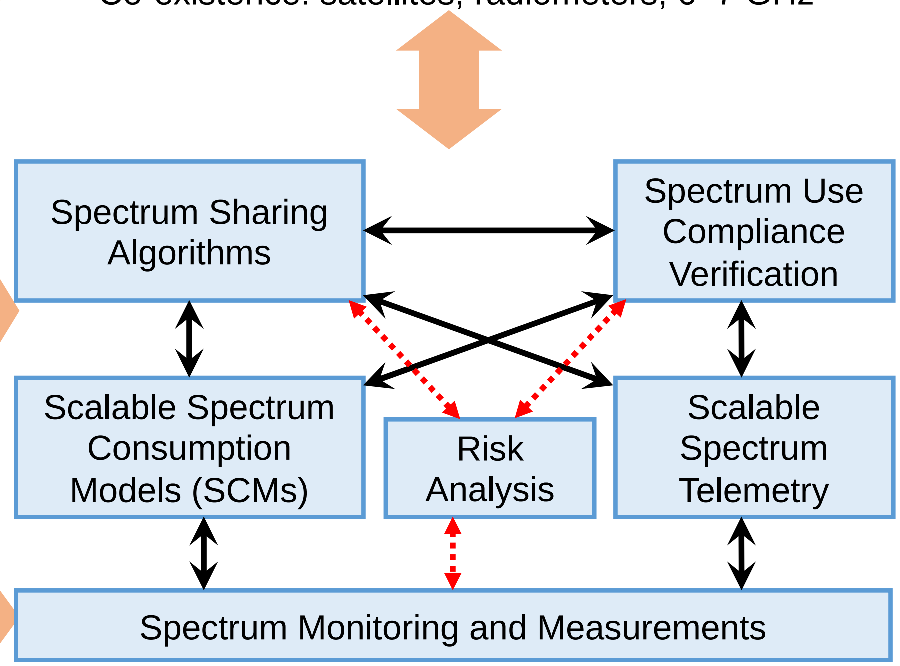
NRDZ Site

Trial & Testing

Collaboration Channel

Hardware & Software Support

Applications
Co-existence: satellites, radiometers, 6–7 GHz



Zone Management System (ZMS)

End-to-End Spectrum Sharing Solution

COSMOS | Columbia University in the City of New York | Rutgers | The City College of New York | Duke University | Princeton University | Syracuse University | NOAA-CESSRST

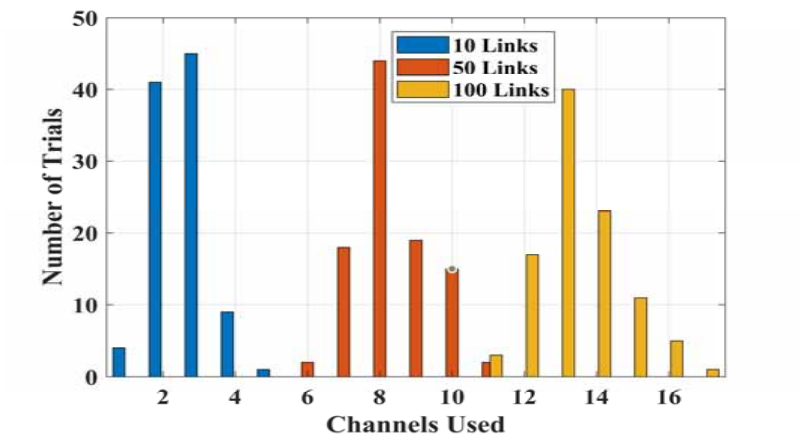
Spectrum Deconfliction (Centralized algorithm)

DOF: Central frequency (channel), Power (Power margin)

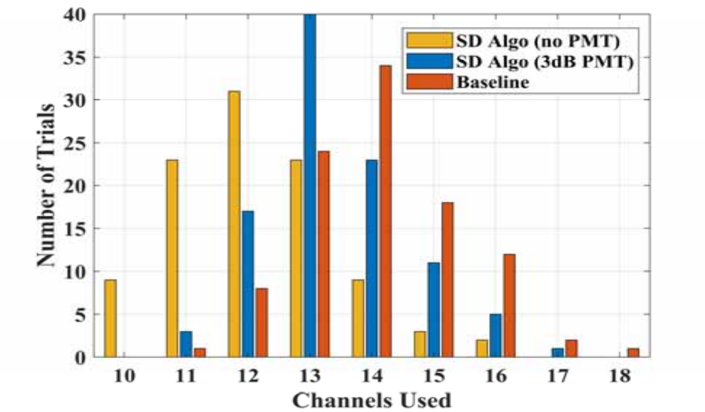
Simulation parameters

Parameter	Value
Operational Area	0.5 square mile
Min Tx-Tx separation	10 m
Tx-Rx separation	$Uniform(10m, 100m)$
Frequency shift (Δf)	1 MHz
Power margin threshold	3 dB
Number of trials	100
Python version	3.8
Machine configuration	Intel i7-4790 (3.60 GHz) Cores: 8, Memory: 15 GB

Aggregate interference is being taken into account !



Channels used by SD Algo (3dB PMT) to deconflict networks of different sizes



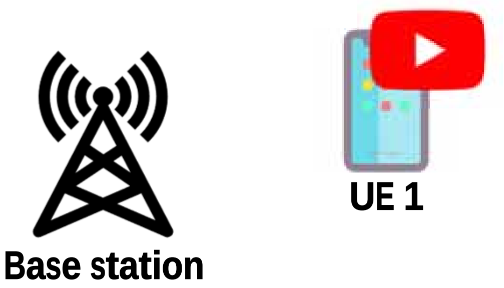
Channels used by SD Algo variants to deconflict networks of 100 links (100 trials)

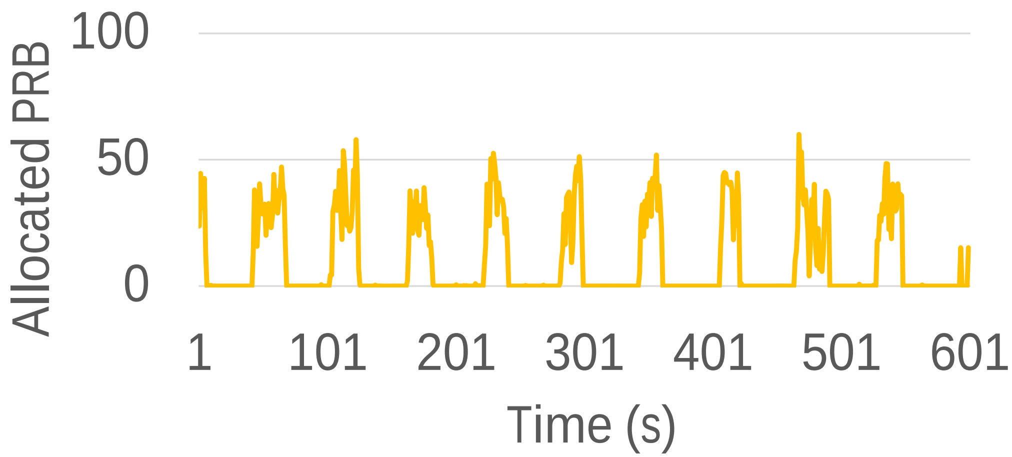
P. Netalkar, A. Zahabee, C. Caicedo Bastidas, I. Kadota, D. Stojadinovic, G. Zussman, I. Seskar, and D. Raychaudhuri, "Large-Scale Dynamic Spectrum Access with IEEE 1900.5.2 Spectrum Consumption Models". IEEE WCNC, Mar. 2023

NG-Scope: Fine-grained telemetry for NextG cellular
Analyzing traffic of each UE

<u>Allocated bandwidth (PRB)</u>:

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

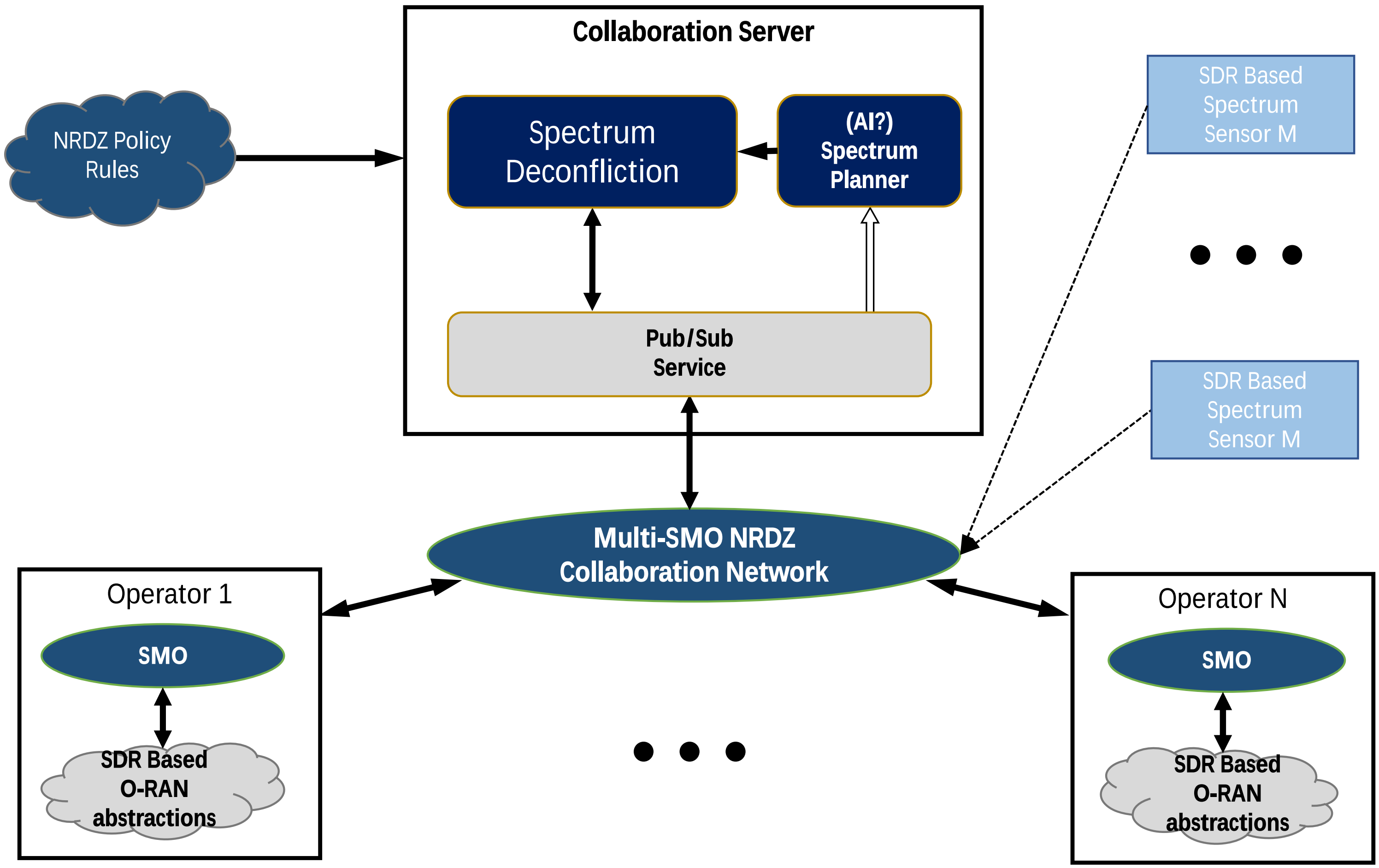




- If the signal layer detects strong cellular activities in certain bands, the PHY layer can be triggered to monitor those bands to obtain the spectrum utilization as a function of network statistics with at fine granularity using NG-SCOPE
- Will provide input to the Spectrum Sharing and Interference Management Algorithms

Y. Xie, K. Jamieson, "NG-Scope: Fine-Grained Telemetry for NextG Cellular Networks," Proceedings of the ACM on Measurement and Analysis of Computing Systems, 6(1), 2022

Proof of Concept: Private 5G (O-RAN Based) DSA Orchestrated NRDZ Deployment

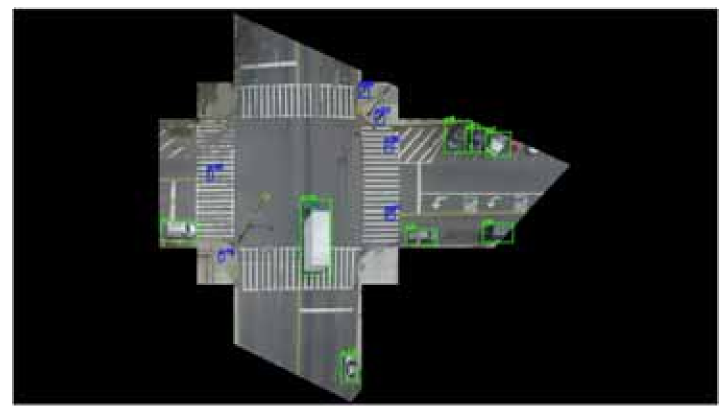


COSMOS

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.

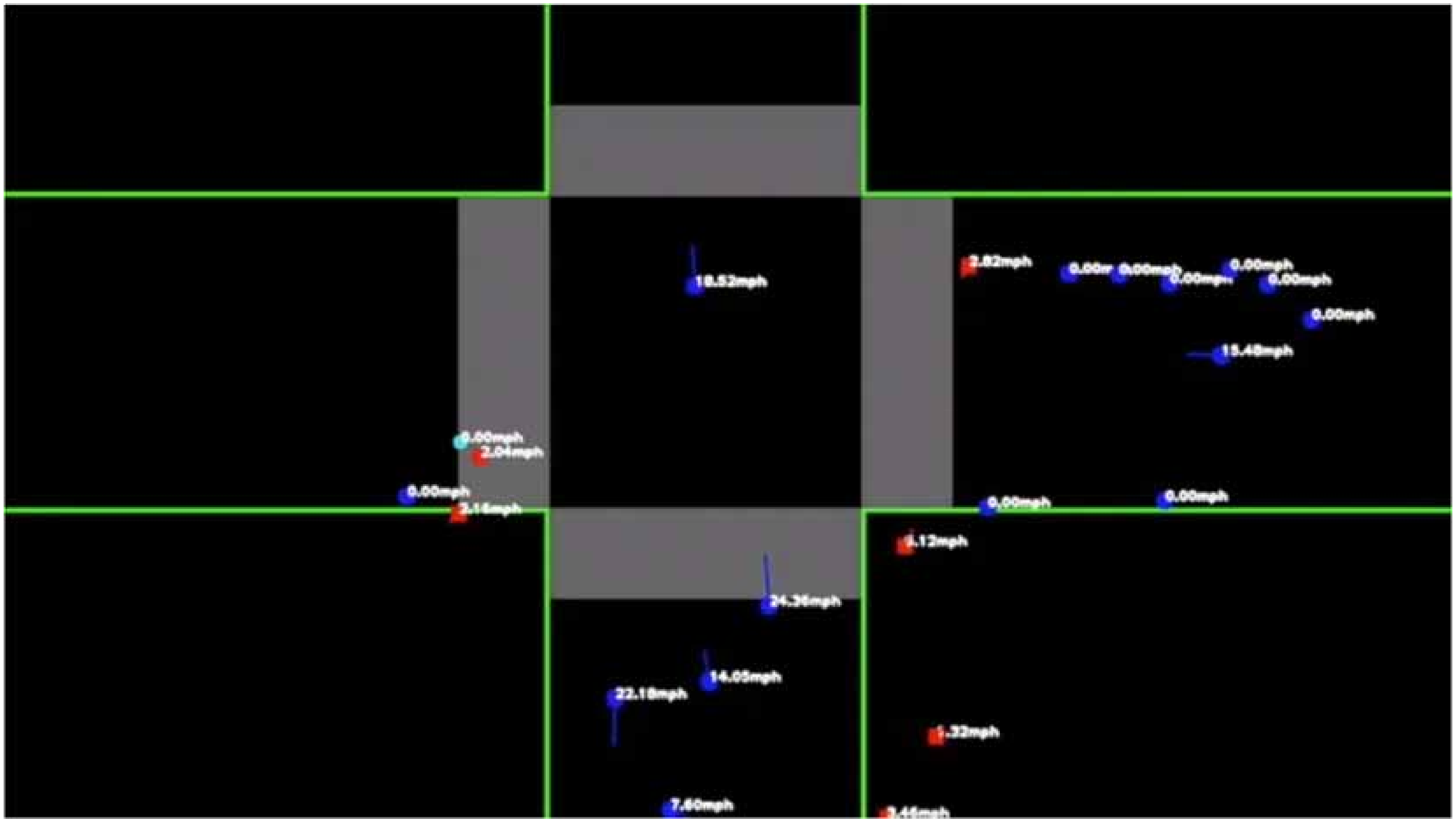
Experiment: Smart Intersection Radar Map

Broadcast to all:

From "Central" computing node to:

- all Vehicles
- all Pedestrians

...in real time.



COSMOS

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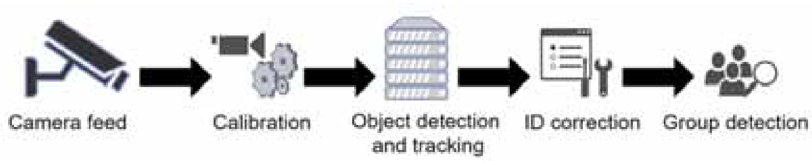
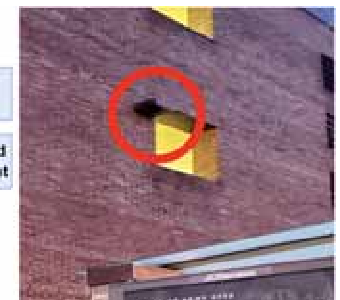
Experiment: Social Distancing Analysis

- Automated video-based Social Distancing Analyzer (Auto-SDA)



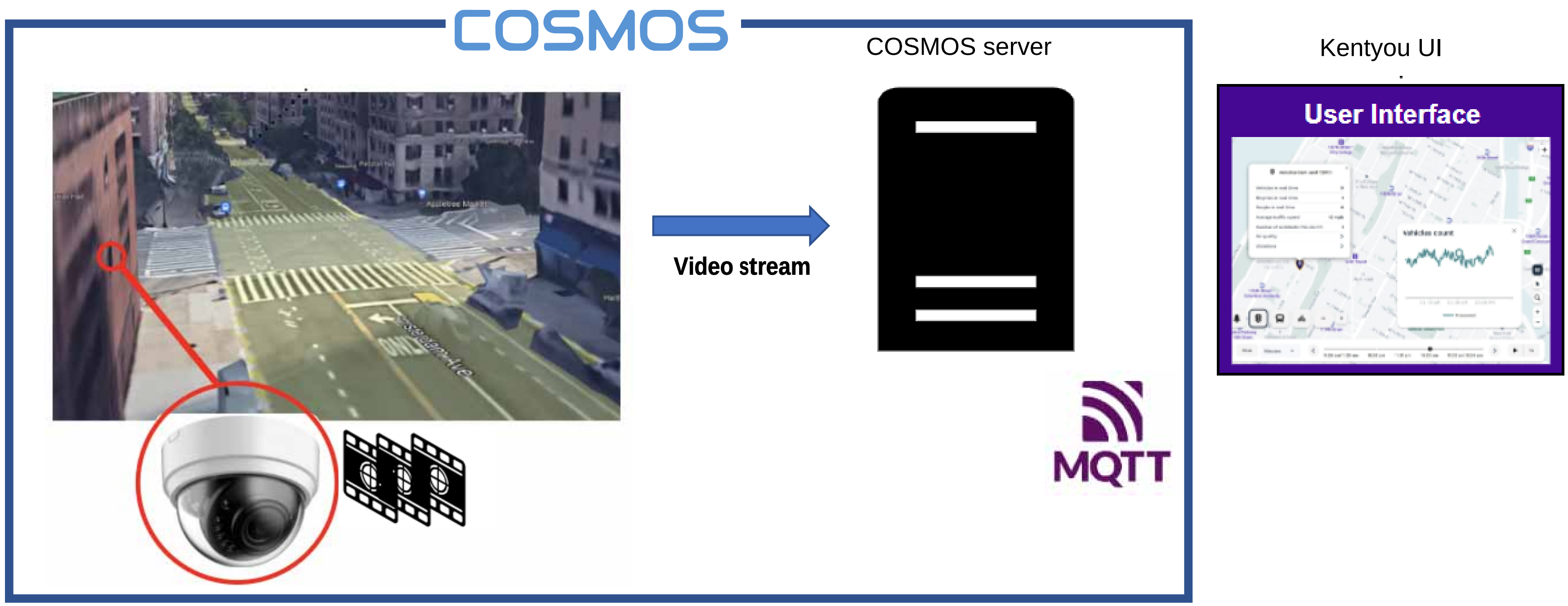
  - Calibration: Converts 2D on-image distances to 3D on-ground distances
  - Object detection and tracking: Locates the pedestrians and assigns an ID to each of them
  - ID correction: Removes the redundant IDs generated by the tracker
  - Group detection: Excludes the pedestrians affiliated with a single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


COSMOS camera on the 2nd floor

- 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.

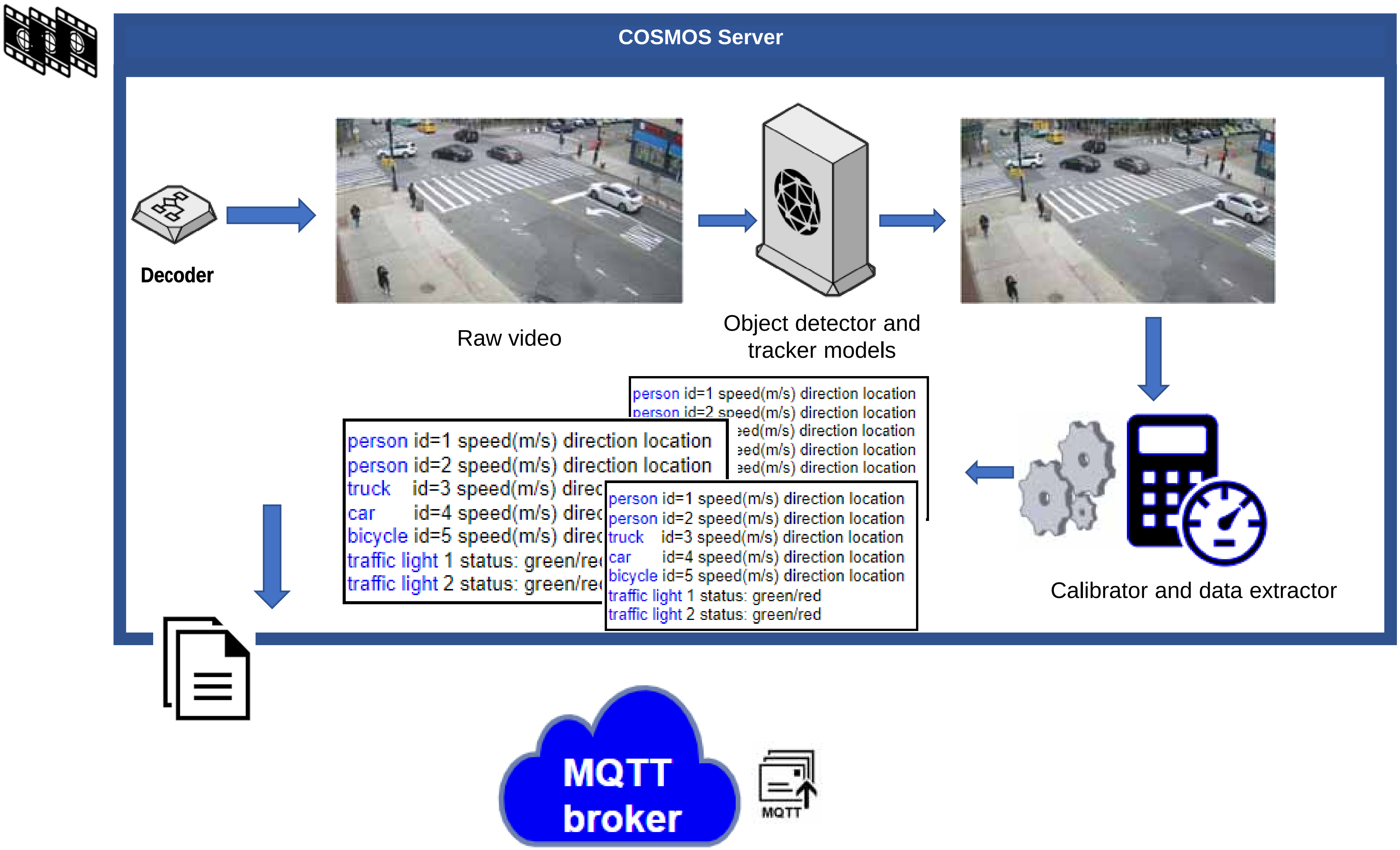
Experiment: Interfacing the COSMOS Sensors with External Systems

- First step towards a digital twin of the COSMOS environment (with Di, Du, Ghaderi, Kostic)
- In collaboration with Kentyou as part of an NGatlantic project, NSF COSM-IC, CPS , and ERC
- The COSMOS platform shares **real-time anonymized information** with an external system



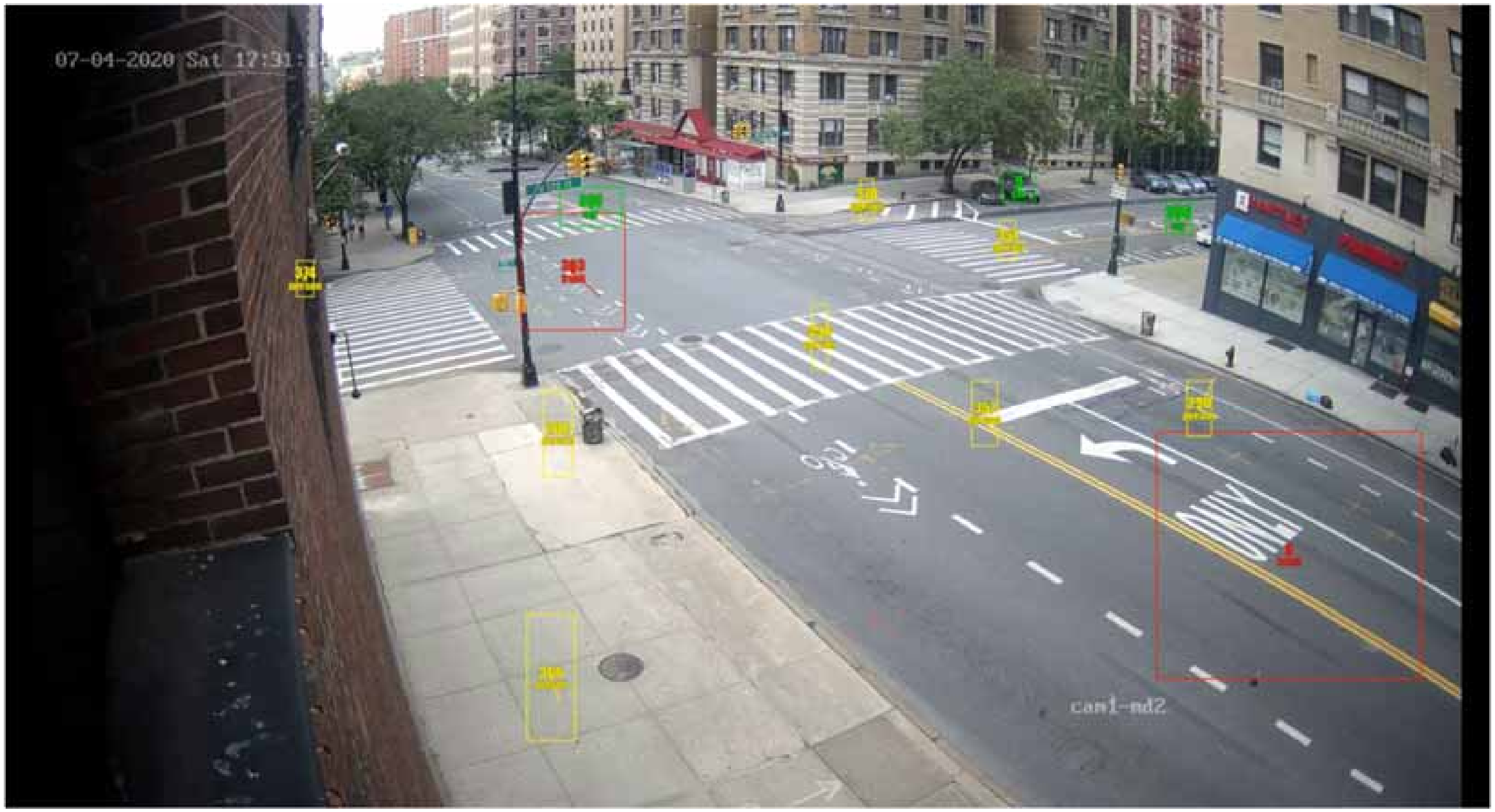
[1]https://wiki.cosmos-lab.org/wiki/Hardware/Cameras#Cameras

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.



COSMOS Server
Decoder
Raw video
Object detector and tracker models
Calibrator and data extractor
person id=1 speed(m/s) direction location
person id=2 speed(m/s) direction location
truck id=3 speed(m/s) direction location
car id=4 speed(m/s) direction location
bicycle id=5 speed(m/s) direction location
traffic light 1 status: green/red
traffic light 2 status: green/red
MQTT broker
MQTT

Visualization on Kentyou User Interface



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

Anomaly?

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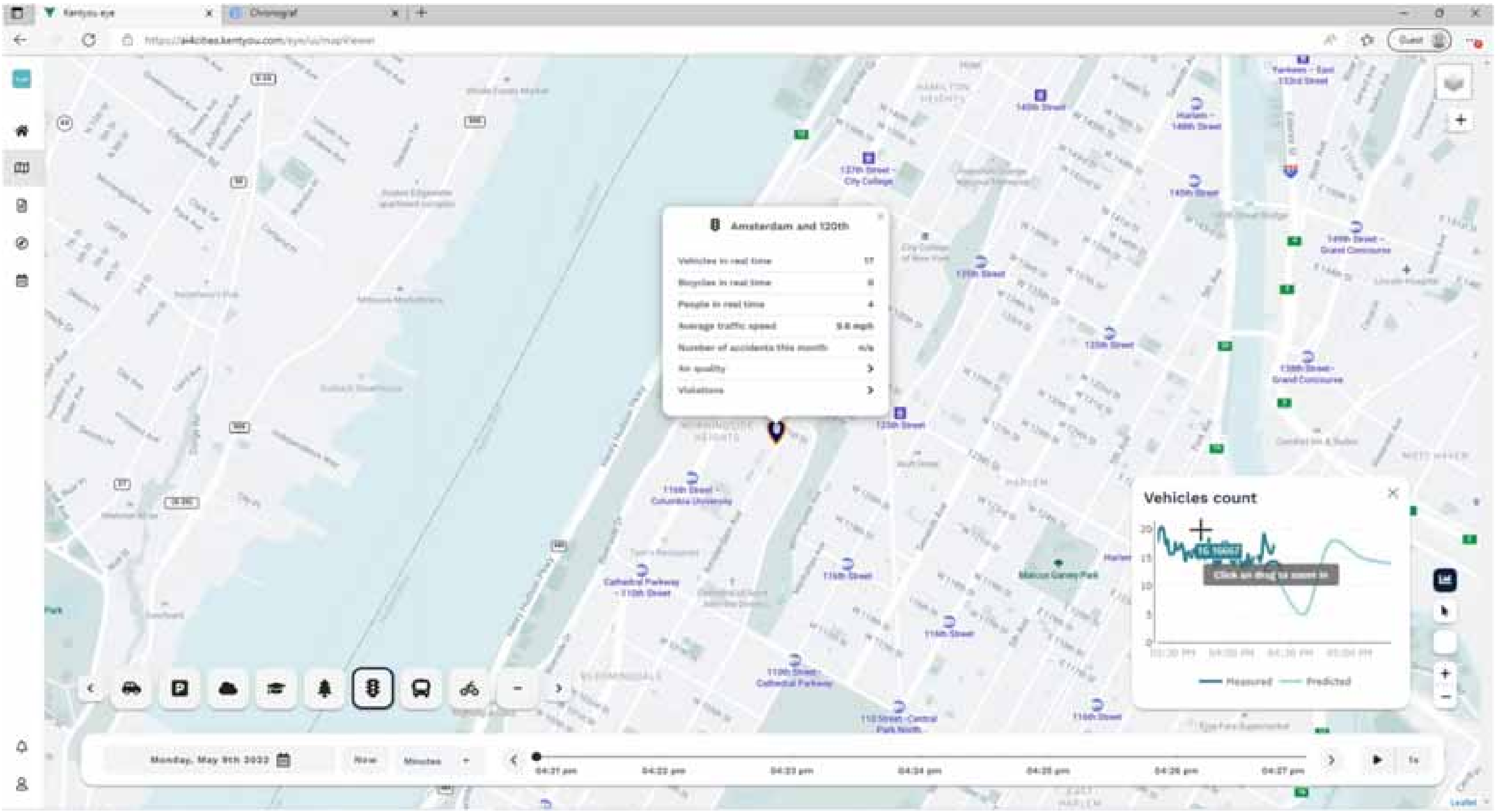
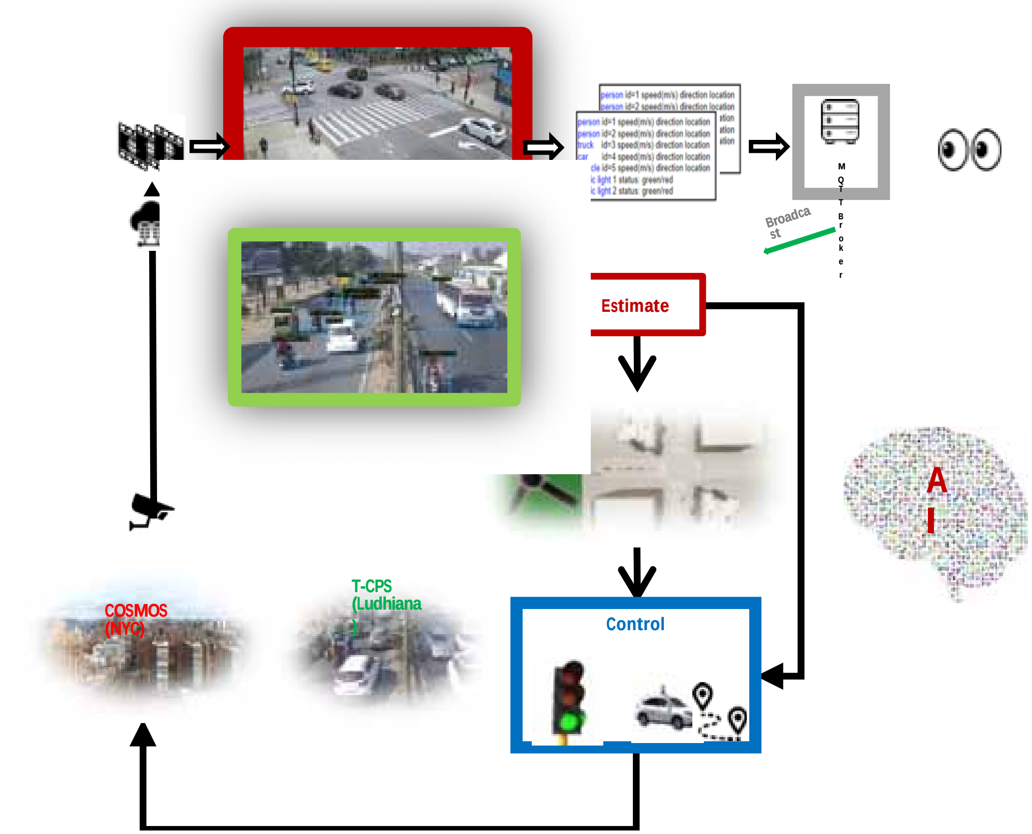
Historical and Statistical Information on Kentyou UI



CPS: Medium: Hybrid Twins for Urban Transportation: From Intersections to Citywide Management

Supplement: Networked Adaptive Traffic Signal Control in IoT-Enabled Smart Cities

Sharon Di, Qiang Du, Zoran Kostic, Gil Zussman (Columbia University)
Dhish Kumar Saxena, Amit Agarwal (IIT Roorkee), Ashish Ghosh (ISI, Kolkata)



Digital Twin for Traffic Intersections

Create a “realistic” 1 to 1 digital twin of an intersection:

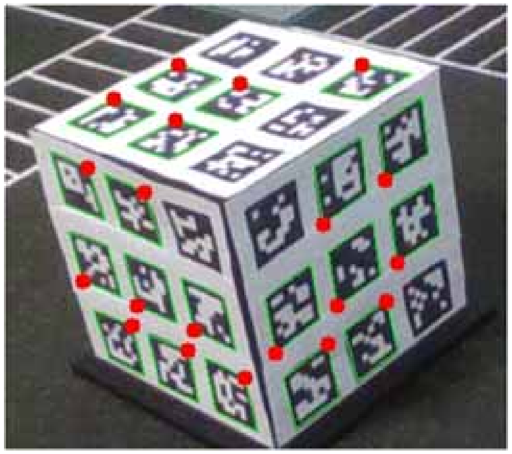
- Pedestrians with human-like erratic behavior based on real pedestrian data
- Cars with human-like erratic behavior based on real vehicle data
- Intersection arrival frequency for pedestrians and vehicles

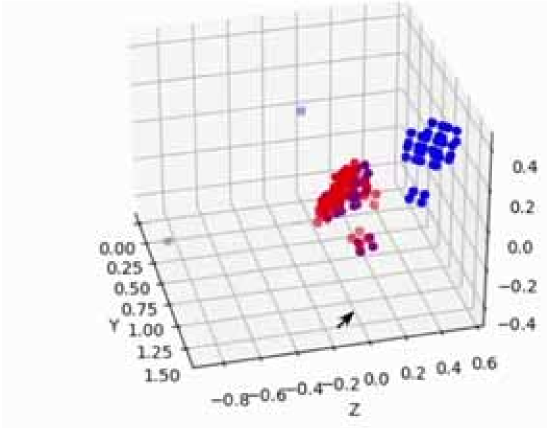
Target:

- Enable low prediction times (<100ms) for multiple possible trajectories in the next 10 seconds:Non-idealized estimates of time taken at the intersection for vehicles and pedestrians,
- Identifying pedestrians in danger of collision with vehicles
- Slowdowns caused by human randomness (not accounted by idealized simulations)
- Data generation for realistic traffic simulations to be used in self-driving car training and evaluation.

Merging Multiple Point Clouds

- Self-calibration based on reference points – needed for merging
- Aruco markers for 3D point projection based on Kabsch Algorithm
- Merge point clouds based on computed camera locations and view angles
- Additional calibration markers on road surface (view edge problem)
- Still looking for good real intersection markers…





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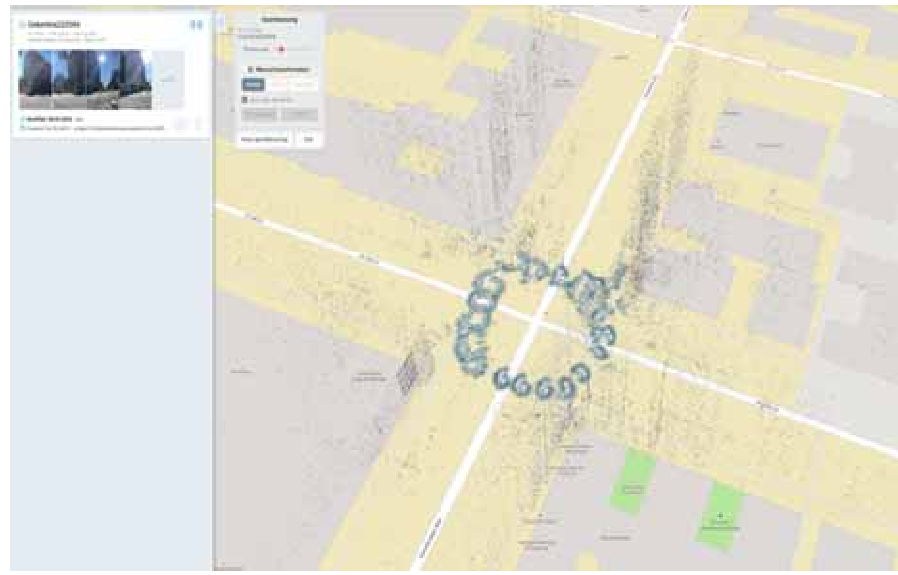
NGIAtlantic Experiment: Deployment and Evaluation of a 5G Open Spatial Computing Platform in a Dense Urban Environment

Digital twining processes as a replacement for physical access

Indoor Spaces: ORBIT Lab

- *Image acquisition*
- *Point Cloud generation*
- *Mesh generation*
- *Low poly mesh*



Outdoor Spaces - COSMOS Testbed deployment area: Corner of Amsterdam and 120th street

- *Augmented City API*

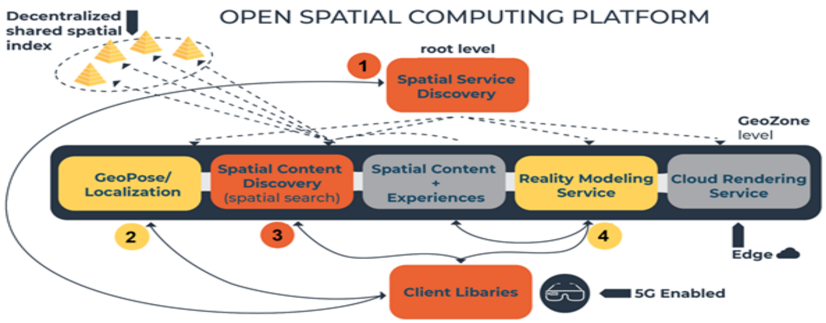
OPEN AR CLOUD EUROPE

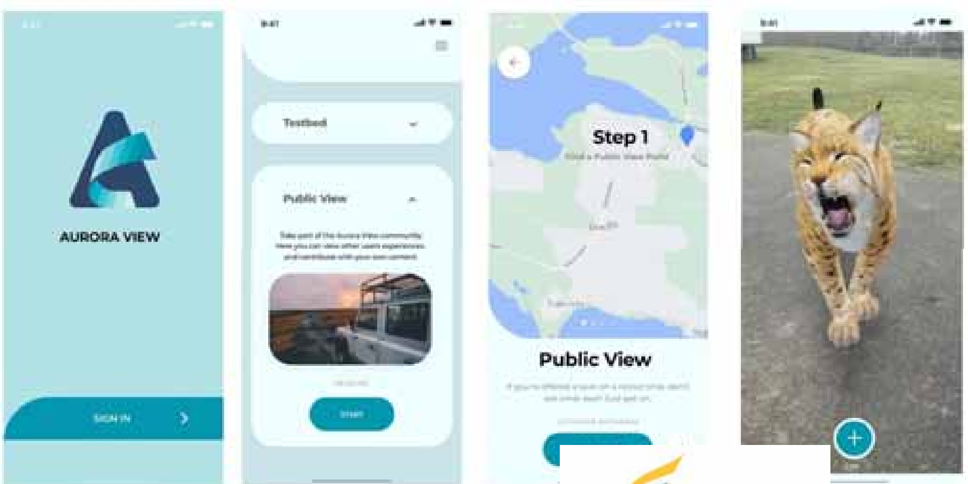
GEORGE MASON UNIVERSITY

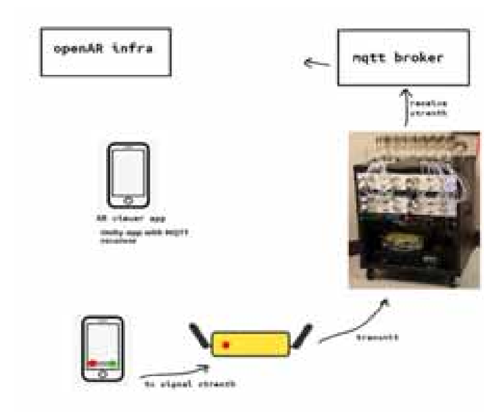
3D INTERACTIVE

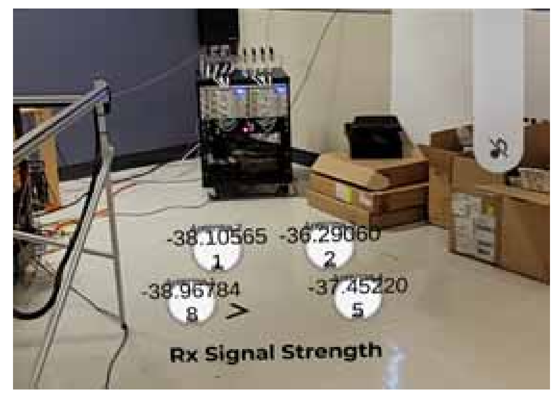
COSMOS

NGIAtlantic Experiment: Deployment and Evaluation of a 5G Open Spatial Computing Platform in a Dense Urban Environment (contd.)





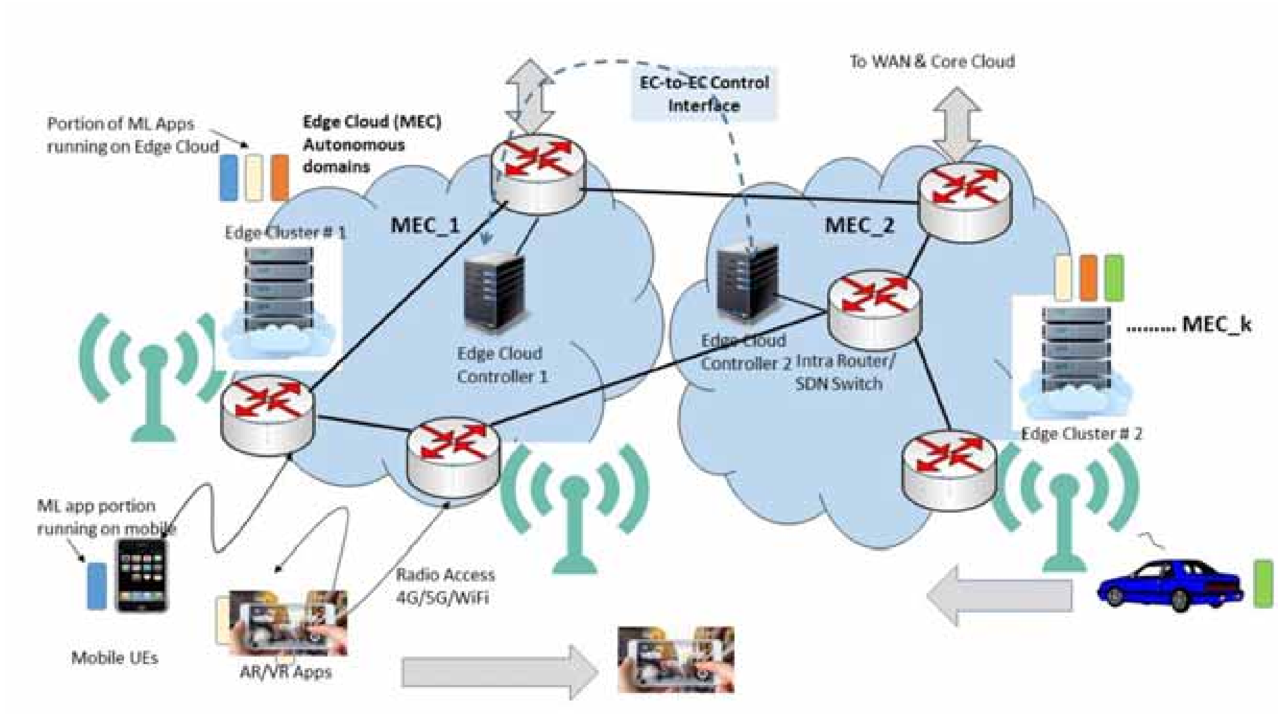




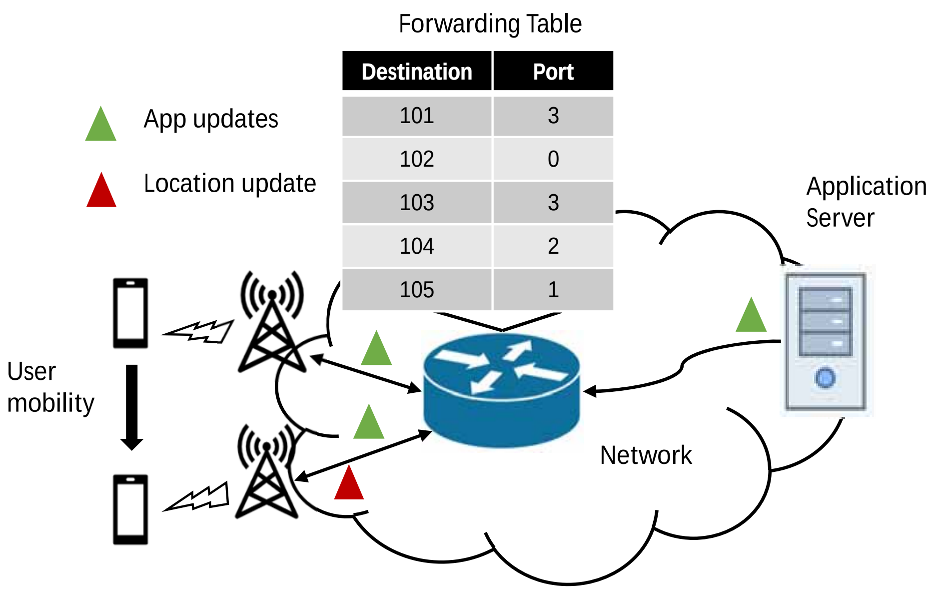
NSF RINGS Project: Real-Time Distributed ML

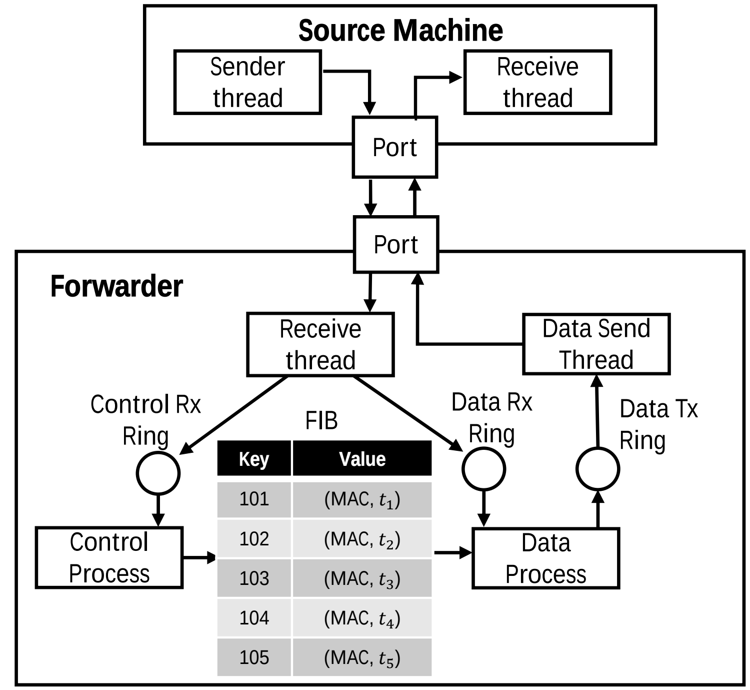
- Mobile users running AR applications served by distributed edge servers
- SDN mobile core network
- ~Gbps wireless access

System Model



Timely Mobile Routing: A COSMOS Experimental Study





Packet forwarding testbed

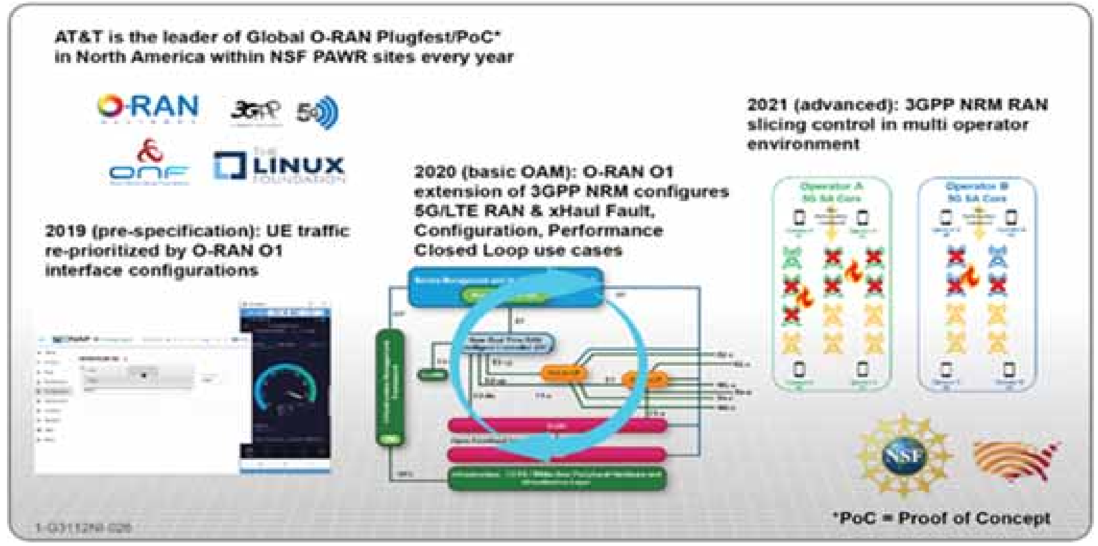
- **DPDK Experimental Eval:**
  - using high-speed packet processing framework DPDK.
  - Source and Forwarder machines on COSMOS testbed.
  - quantitatively analyze the *effects of concurrency constructs*
  - evaluate impact of *input queueing* caused by DPDK batch admission procedure.

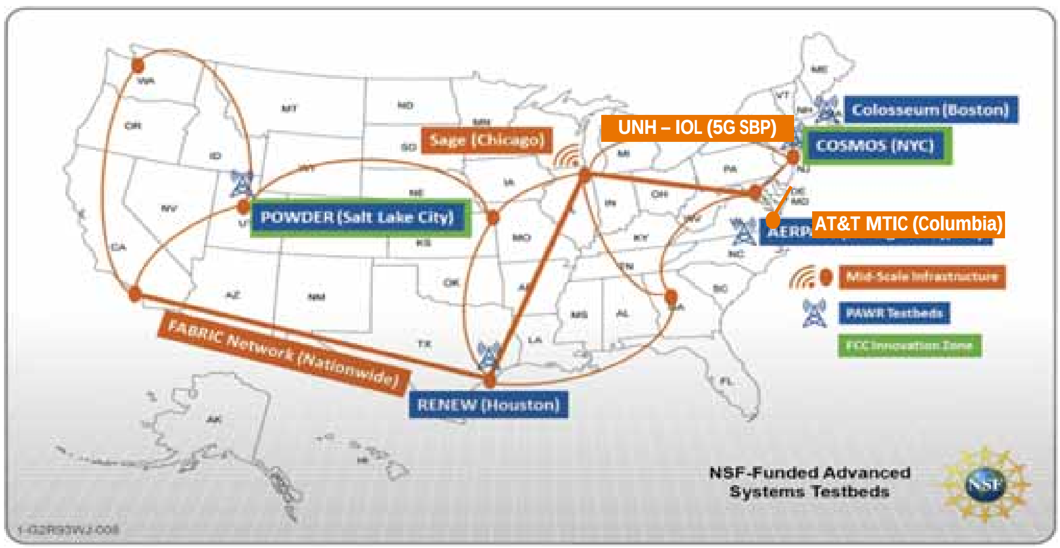
- Vishakha Ramani, Ivan Seskar, Roy D. Yates, “Timely Processing Of Updates From Multiple Sources. CoRR abs/2306.14677 (2023)

LaaS - Lab as a Service

The Platform for Advanced Wireless Research program is enabling experimental exploration of new wireless devices, communication techniques, networks, systems, and services that will revolutionize the nation's wireless ecosystem while sustaining US leadership and economic competitiveness for decades to come.

PAWR is funded by NSF and a wireless Industry Consortium of 30 companies and associations. AT&T established the Open Wireless Lab (OWL) within Rutgers/WINLAB (now NSF PAWR COSMOS) in 2017. (https://wiki.onap.org/display/DW/Open+Wireless+Lab)





Curtesy: AT&T

O-RAN Proofs of Concept & Plugfests "PoC-fests"

O-RAN PoC-fests support the ecosystem players in testing and integration of their solutions, ensuring the openness and interoperability of O-RAN solutions from different providers.

US based MNOs (AT&T, Dish, Verizon) co-lead the O-RAN/OSC joint PoC-fests at COSMOS every year since the inception of O-RAN

6th global O-RAN PoC/Plugfest- 2Q 2023
5th global O-RAN PoC/Plugfest – 4Q 2022
4th global O-RAN PoC/Plugfest – 2Q 2022
3rd global O-RAN PoC/Plugfest – 4Q 2021
2nd global O-RAN PoC/Plugfest – 3Q 2020
1st global O-RAN PoC/Plugfest – 4Q 2019

COSMOS ONAP/ORAN Open Wireless Lab (2019)

Permanent setup for ONAP/ORAN experimentation:

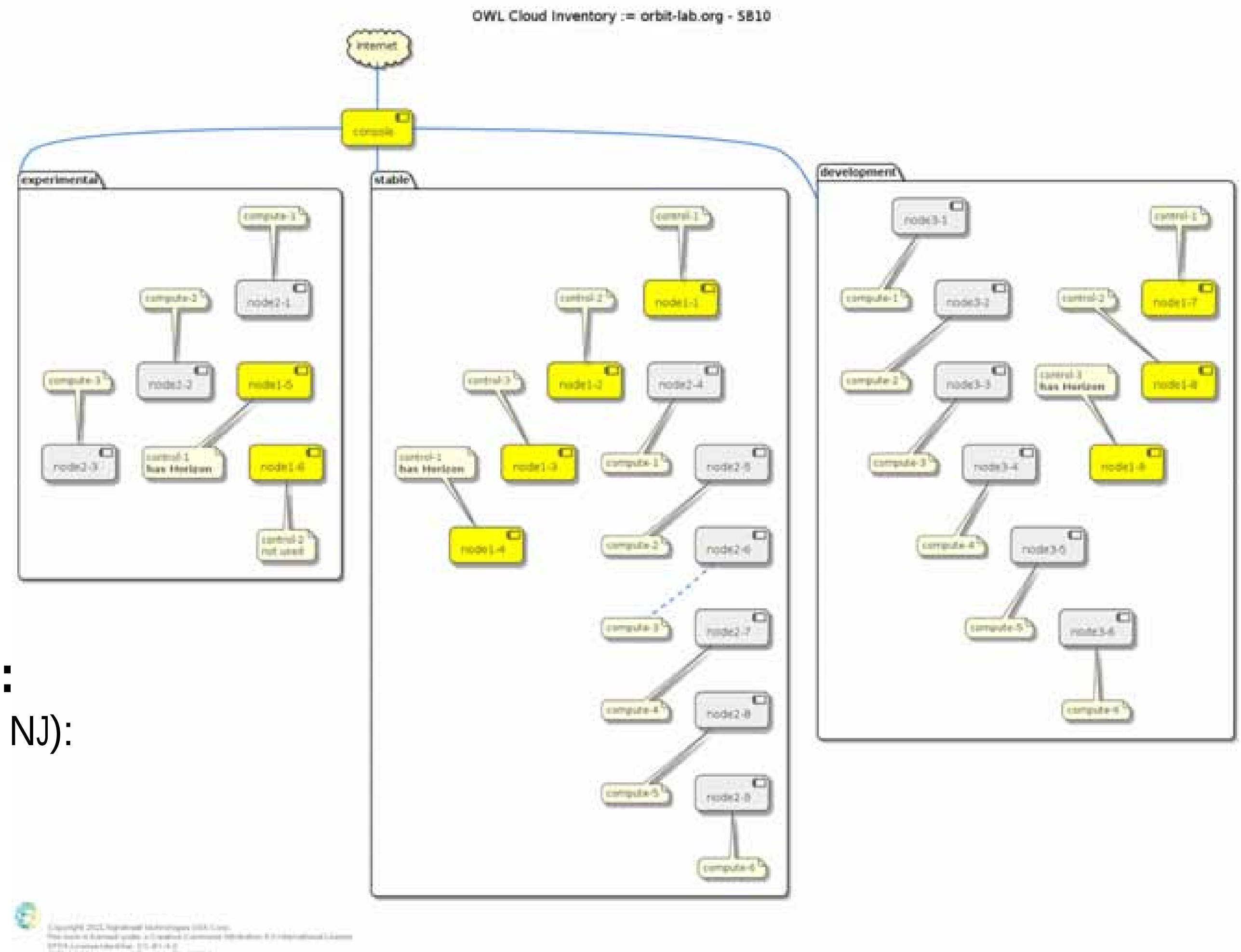
- 6 control nodes
- 21 compute nodes
- Number of other (vendor) components

Three (OpenStack/ONAP/O-RAN) configurations

- Stable
- Development
- Experimental

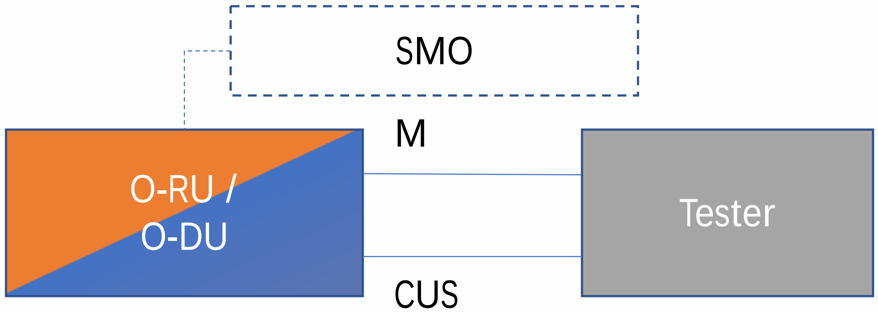
Additional (on-demand) resources:

- Main ORBIT testbed (North Brunswick, NJ):
  - Indoor grid (400 nodes)
  - 2 larger sandboxes (8 nodes)
  - 8 smaller sandboxes (2 nodes)

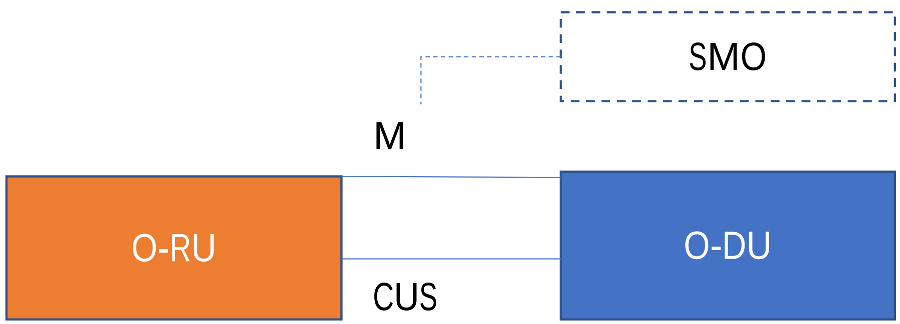


O-RAN Plugfest: Testing, Badging and Certification

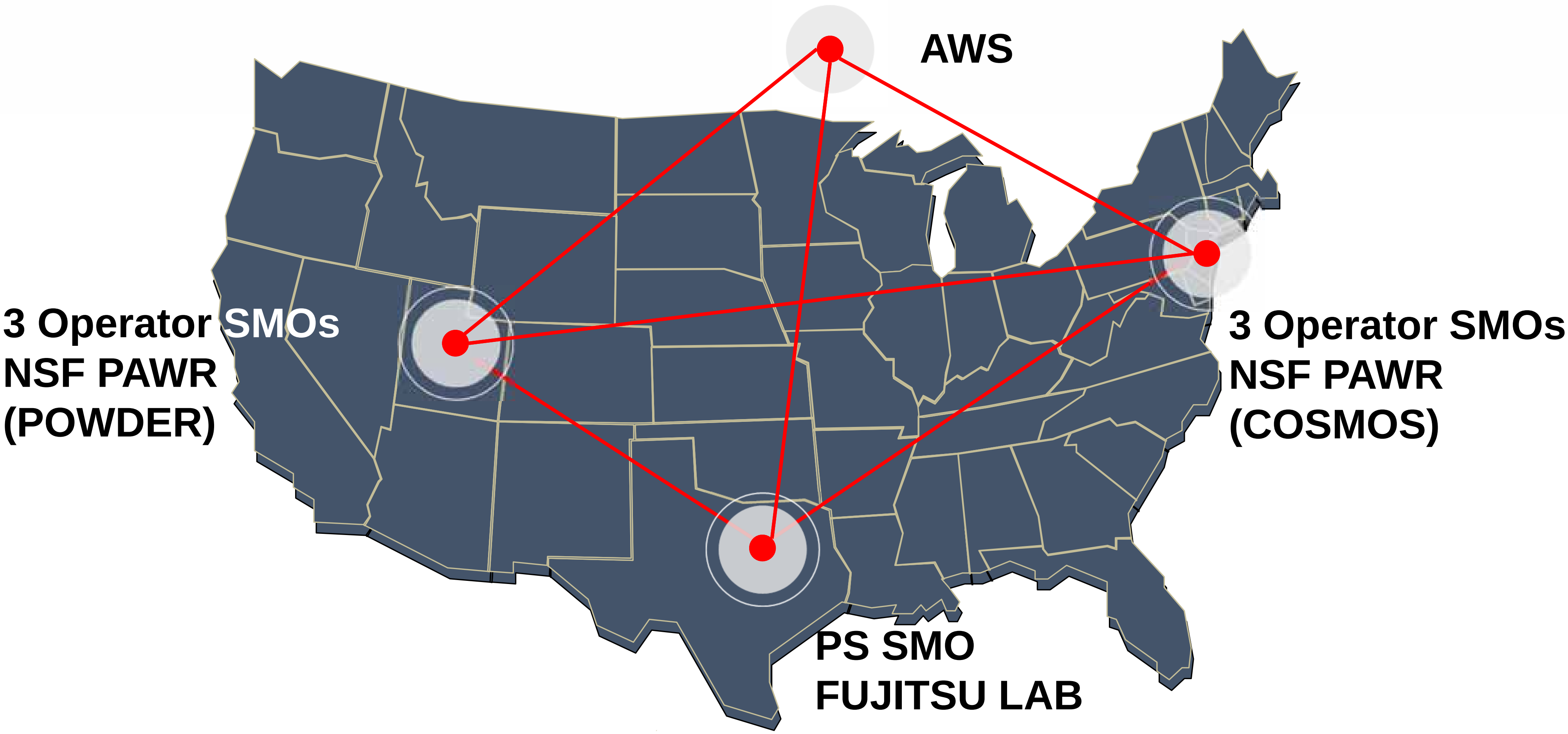
Conformance

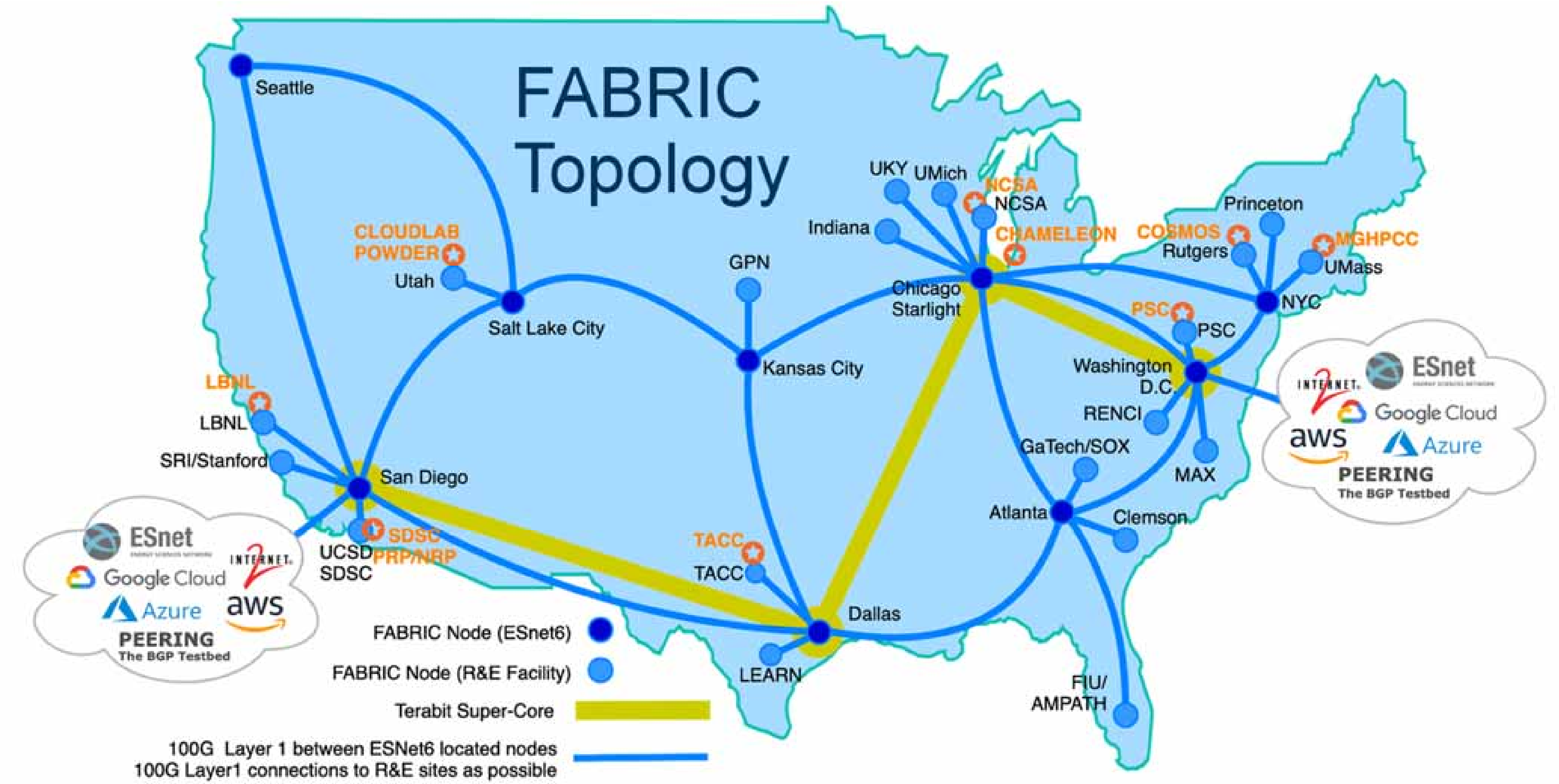


Multi-vendor interoperability



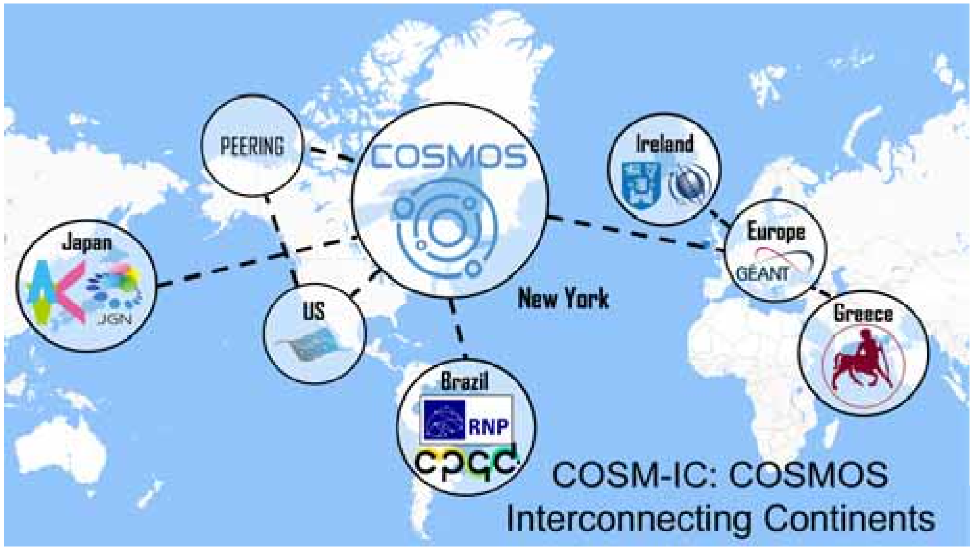
PF3 PoC #3: SMO Deployments





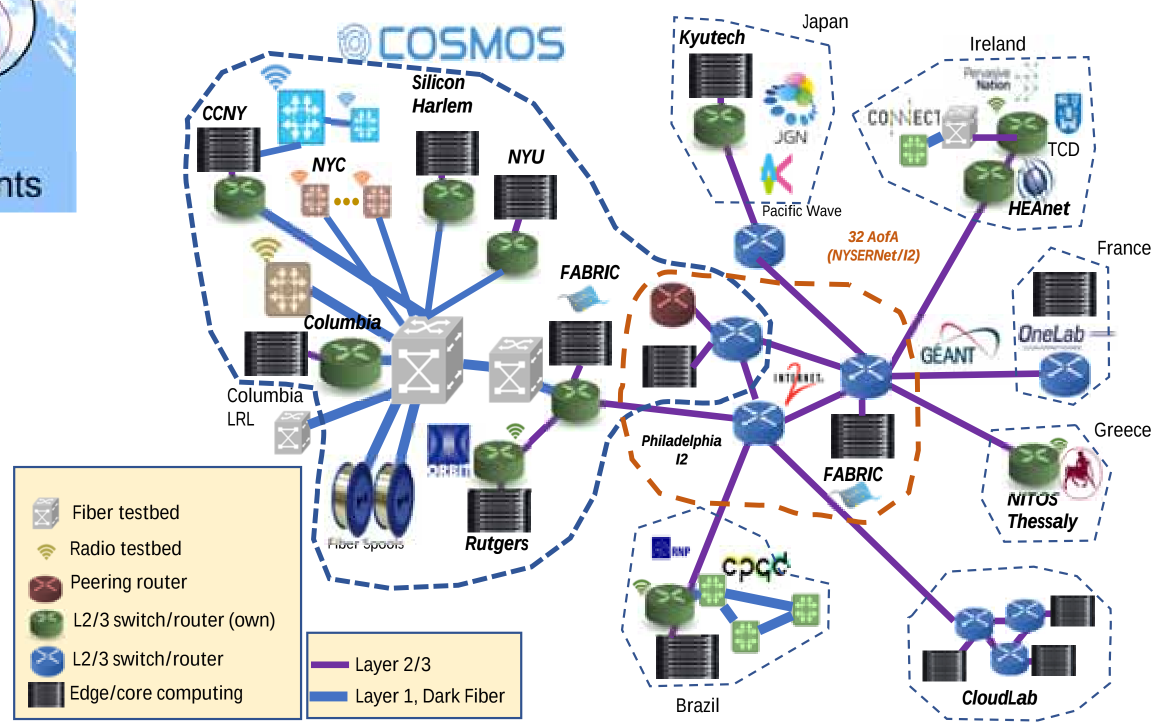
FABRIC Testbed

Implementation of connectivity between several wireless/optical/IoT testbeds to support global experimentation



Research Plan:

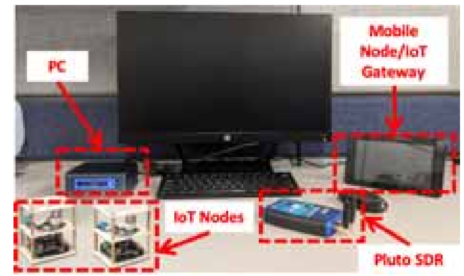
- Cross Layer SDX Experimentation
- Mininet Optical with Data-Driven Platform Models
- Federating with and via PEERING
- EIR (Edge Aware Interdomain Routing) Experimentation
- Education and Outreach



COSMOS/EFRI Research Experience and Mentoring for Teachers (RET/REM)

- Building on Summers 2018–2022 programs for teachers
- the COSMOS education toolkit - A small pre-configured COSMOS node offering 100+ K–12 educational labs in Math/Science/CS using SDRs
- Toolkit is remote/virtual since 2022

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.

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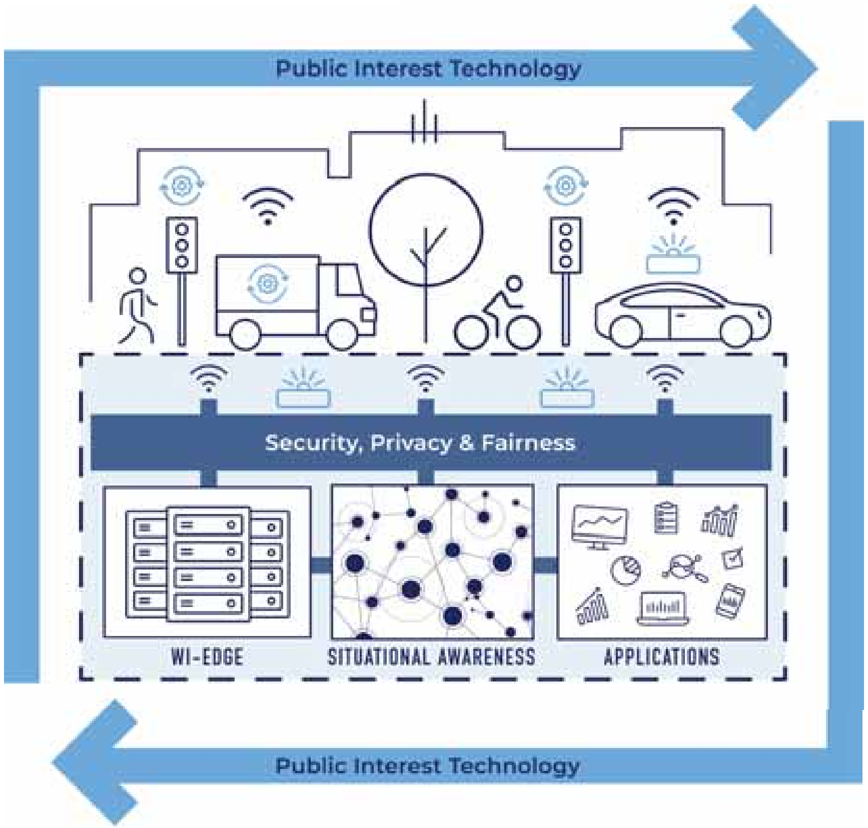


- **Vision:** High-precision, real-time understanding and coordination of streetscapes, to foster **livable**, **safe** and **inclusive** communities.
- **Balance** of public **data collection** with community-defined **benefits.**

Application Thematic Areas

Road Safety and
Traffic Efficiency

Public Safety

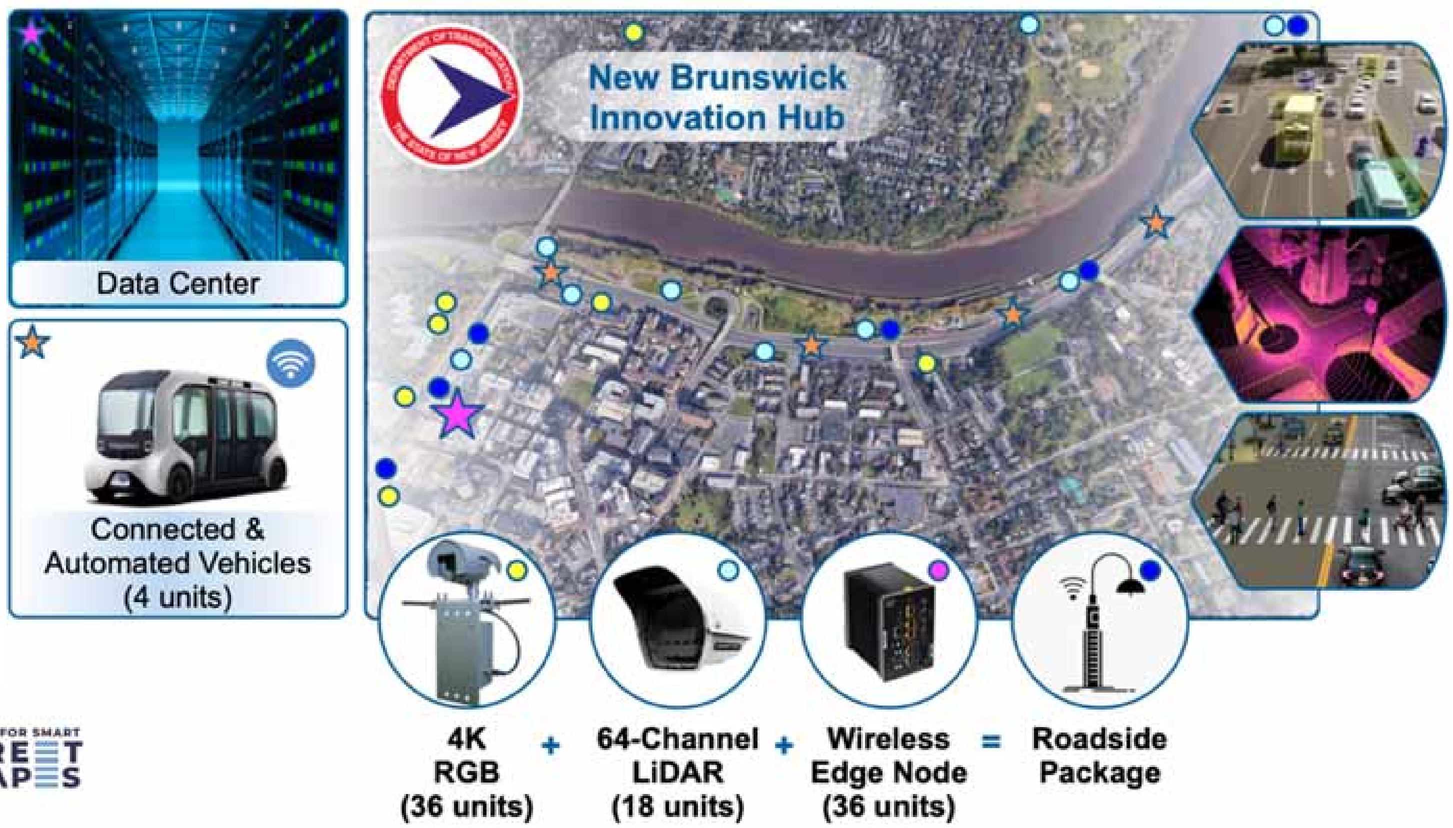
Assistive
Technologies

Future of
Outdoor Work

Hyper-Local
Environments

CENTER FOR SMART
STREETSCAPES

CS3 OVERVIEW - DataCity SMTG Testbed in New Brunswick, NJ



Research in Real-World Urban Testbeds

- Testbeds leverage recent research investment
- Partnerships
  - 36 Industry Partners
  - 11 Educational/Workforce Development Partners
  - 9 Innovation Partners
  - 16 Governmental Partners
  - …. And rapidly growing.
- Community Engagement & Inclusion is central to the ERC.

CENTER FOR SMART STREETSCAPES

Summary

- COSMOS Testbed
  - Focus on ultra-high bandwidth, ultra-low latency, and edge cloud
  - Open platform integrating SDRs, mmWave, and optical x-haul
  - Main outdoor experimentation area: 1 sq. mile densely populated area in West Harlem
  - Multiple urban/suburban campuses with roof access
- ONAP/O-RAN/OTIC Facilities:
  - Large (7000 sq. foot) indoor laboratory
- Industry and local community outreach

Related links:

- COSMOS: https://www.cosmos-lab.org/ Twitter: **#pawrcosmos**
- ORBIT: https://www.orbit-lab.org/
- CS3: https://cs3-erc.org/
- Open Wireless Lab: https://wiki.onap.org/display/DW/Open+Wireless+Lab
- WINLAB: https://www.winlab.rutgers.edu
- PAWR: https://advancedwireless.org/

COSMOS