Programmable and Open-access Millimeter-wave Radios in the PAWR COSMOS Testbed

Tingjun Chen[1], Prasanthi Maddala[2], Panagiotis Skrimponis[3], Jakub Kolodziejski[2], Xiaoxiong Gu[4], Arun Paidimarri[4], Sundeep Rangan[3], Gil Zussman[5], and Ivan Seskar[2]

[1]Electrical and Computer Engineering, Duke University, [2]WINLAB, Rutgers University
[3]Electrical and Computer Engineering, NYU, [4]IBM Research, [5]Electrical Engineering, Columbia University

ACM WiNTECH 2021

Apr. 1, 2022

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)
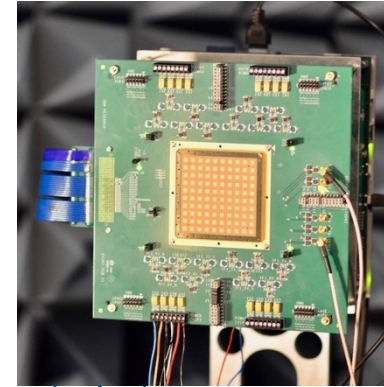
Edge Computing (Streetscape Apps)

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

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

Wireless Testbeds

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

POWDER-RENEW **COSMOS** **AERPAW** **ARA**

Salt Lake City New York City Research Triangle Central Iowa

- Colosseum: A massive RF channel emulator from DARPA SC2

- Other testbeds: 5TONIC, ADRENALINE, Arena, Bristol Is Open, CORNET, FED4FIRE+, FIT, …

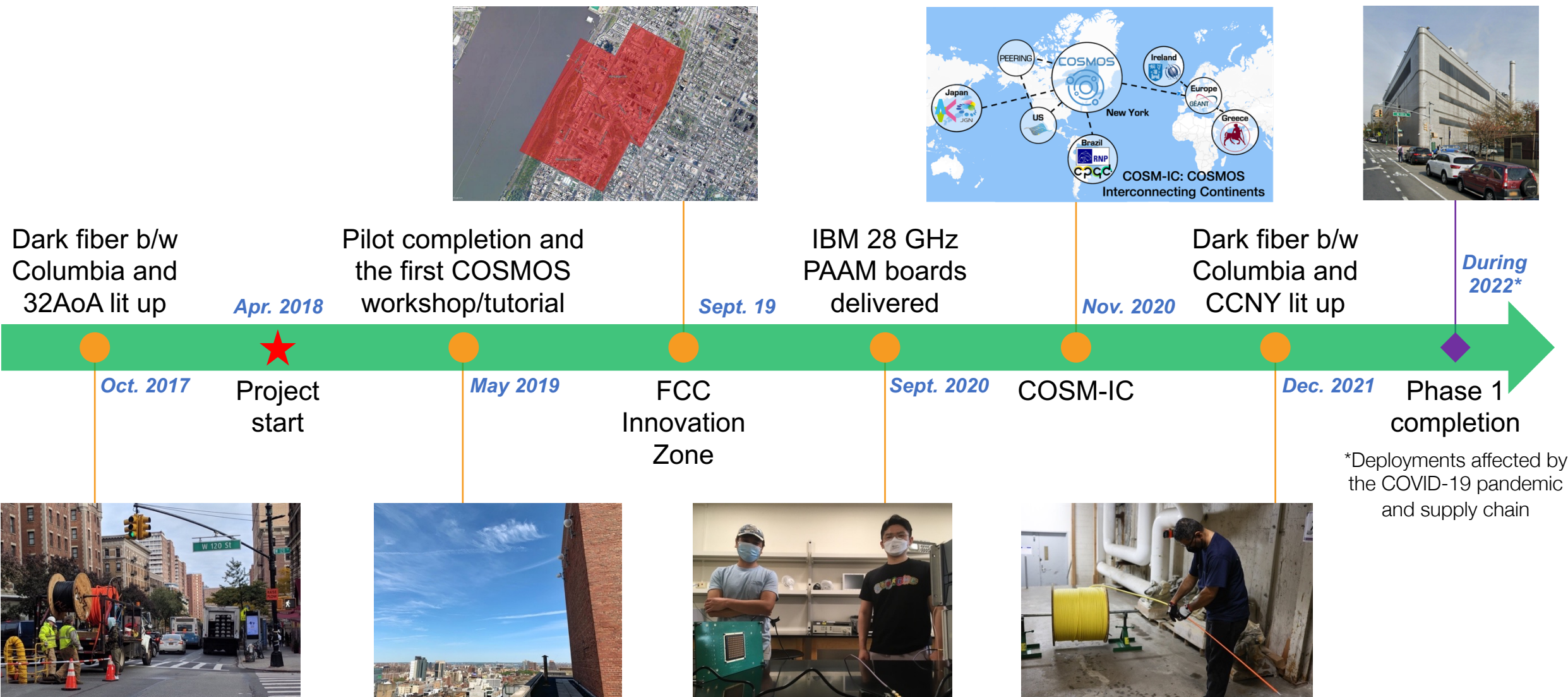# Objective: Take it Outside
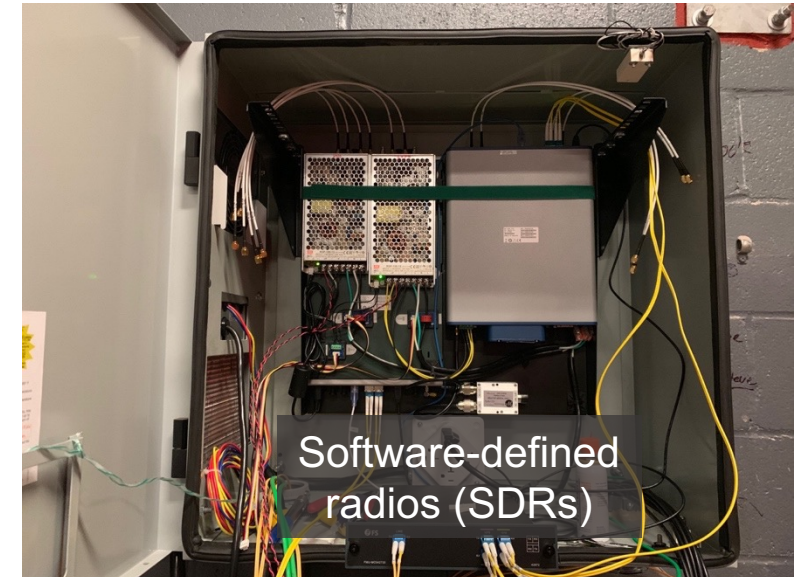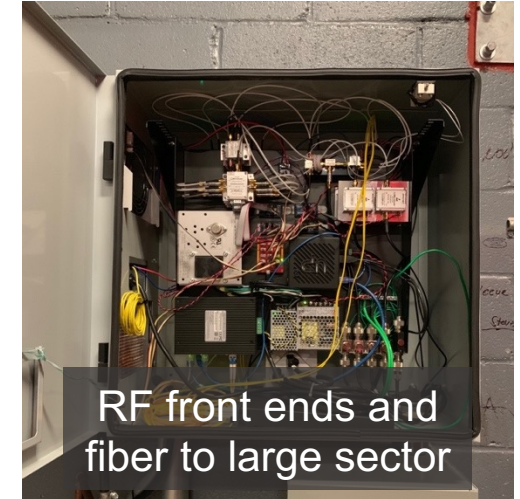
Objective: Take it Outside

COSMOS Wireless Testbed

Videos

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

- 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.
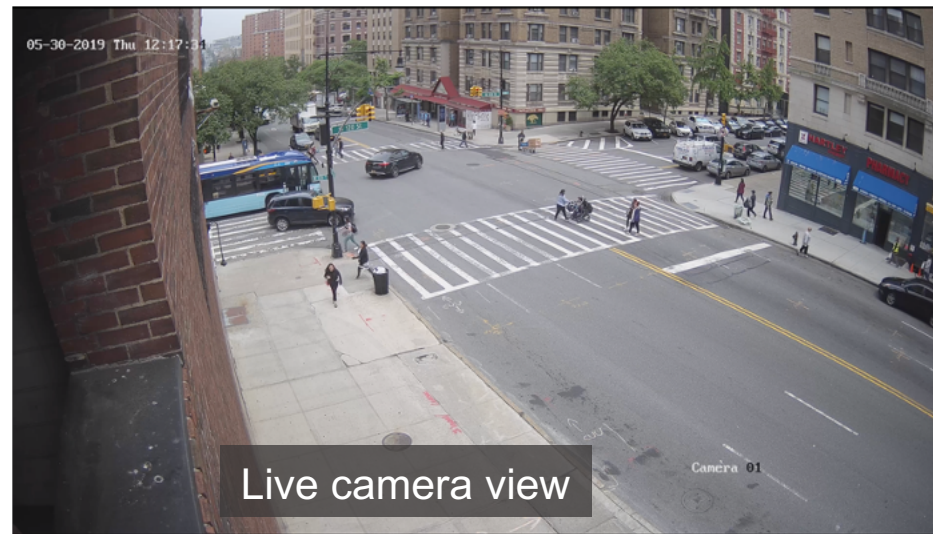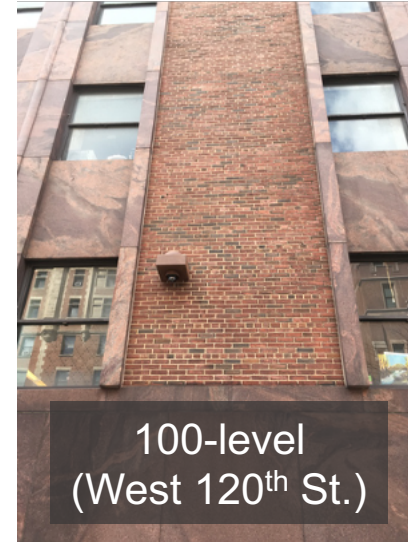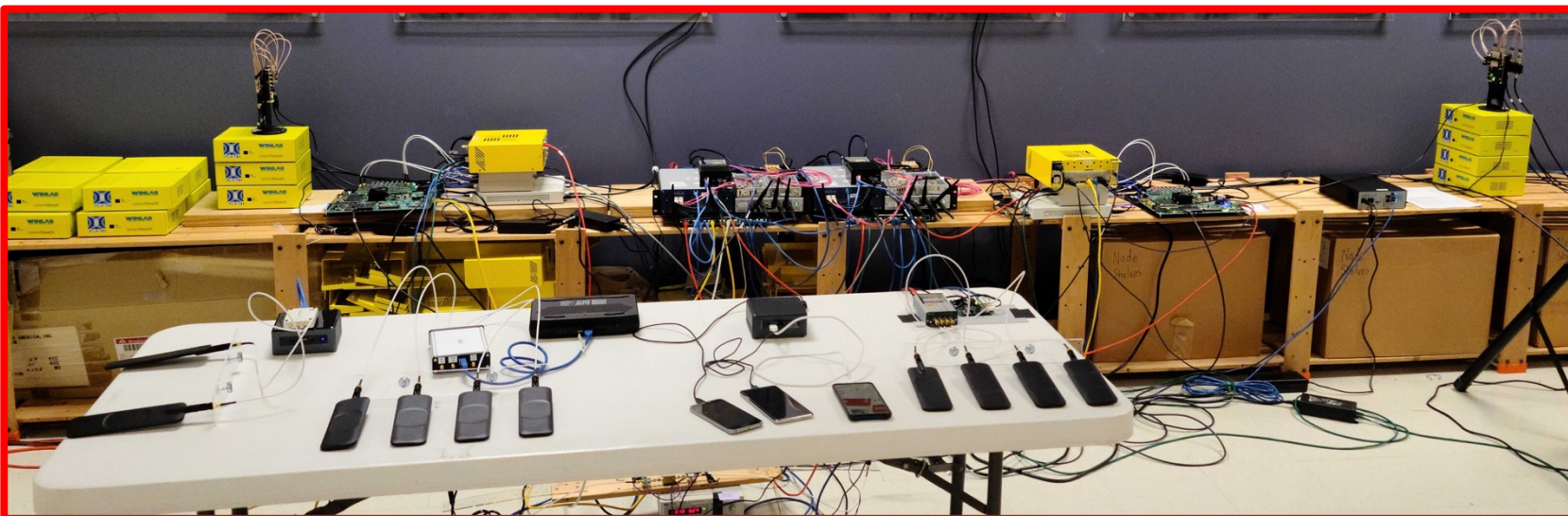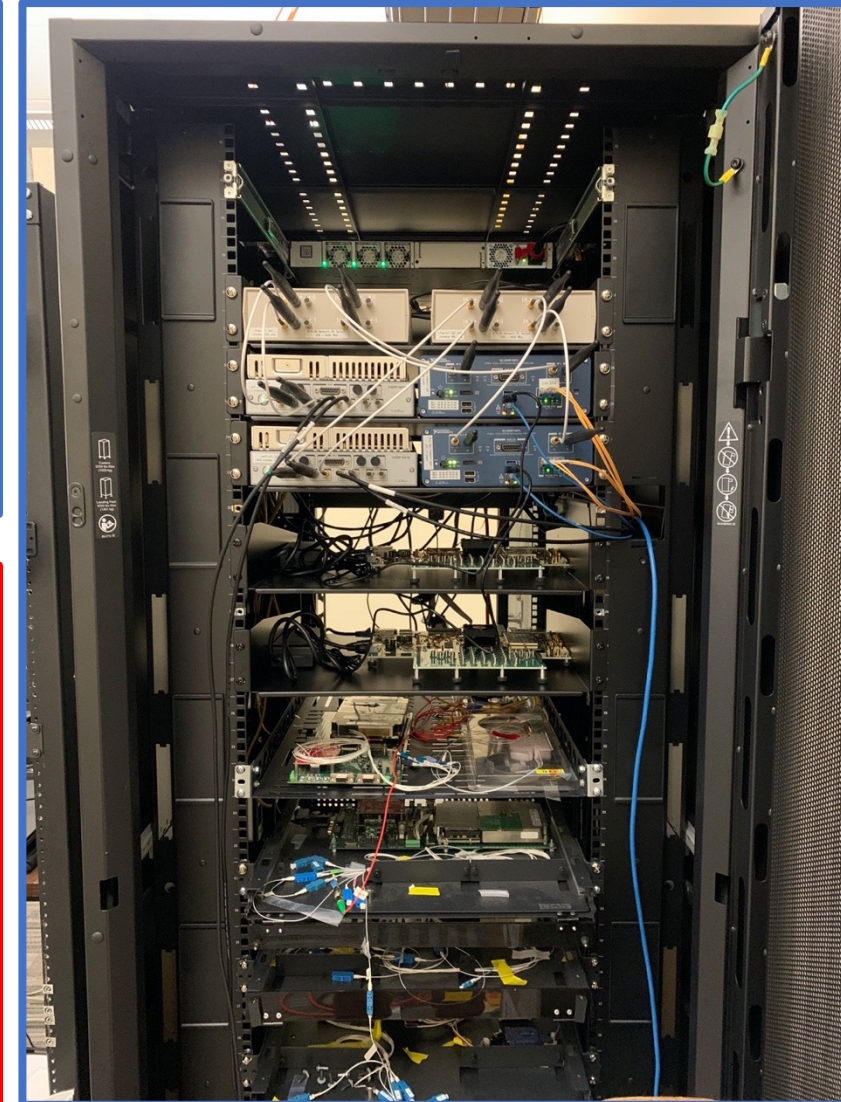
COSMOS: Project Timeline

Dark fiber b/w Columbia and 32AoA lit up

Apr. 2018

Pilot completion and the first COSMOS workshop/tutorial

Sept. 19

IBM 28 GHz PAAM boards delivered

Nov. 2020

Dark fiber b/w Columbia and CCNY lit up

During 2022*

Oct. 2017

Project start

May 2019

FCC Innovation Zone

Sept. 2020

COSM-IC

Dec. 2021

Phase 1 completion

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

Columbia Large Node (lg1)

RF front ends and fiber to large sector

Large sectors

s2 s1

s3

Software-defined radios (SDRs)

Medium Nodes (md1 and md2)

200-level (Amsterdam Ave.)

100-level (West 120th St.)

Medium antenna with GPS

Medium node coverages

Live camera view

Rutgers and Columbia Sandboxes (sb1 and sb2)

InterDigital 28 GHz MHU

Rack with USRP SDRs, Xilinx RFSoC, and RF Switches

IBM 28 GHz PAAM Board

InterDigital 60 GHz EdgeLink

Sivers IMA 60 GHz Transceiver (mounted on the X–Y table)

1.3 m x 1.3 m X–Y Table
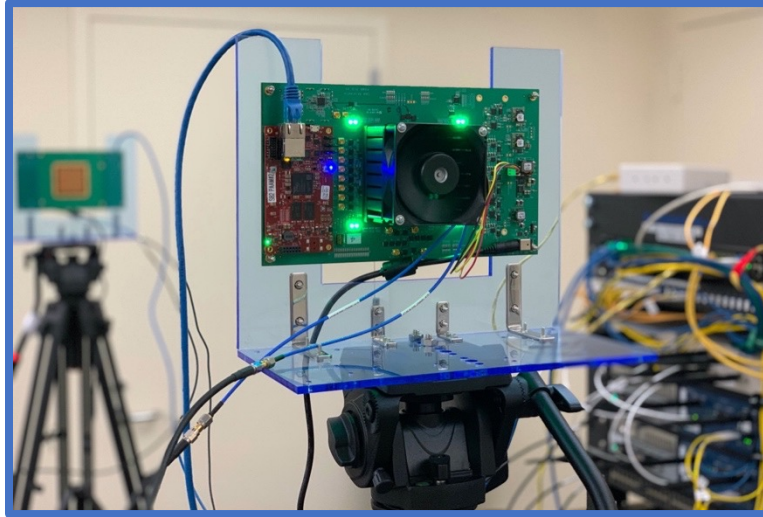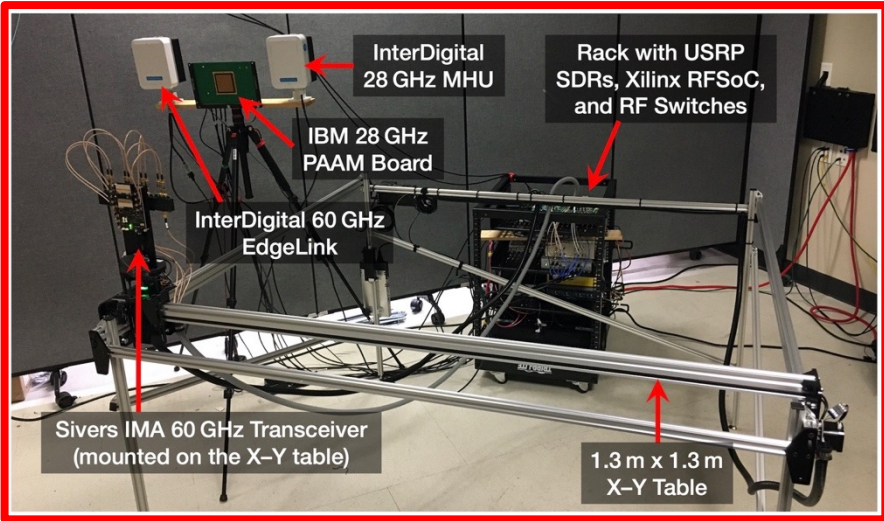
Sandbox1 (sb1) @Rutgers

Sandbox2 (sb2) @Columbia

CCNY Large and Medium Nodes (lg2 and md3)
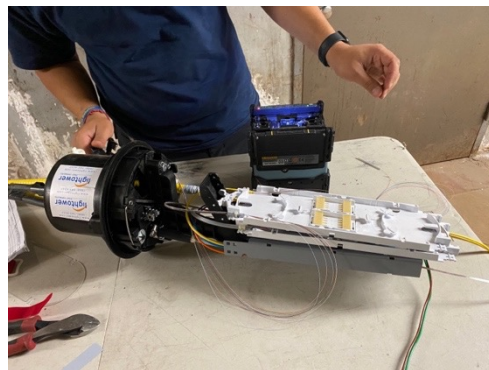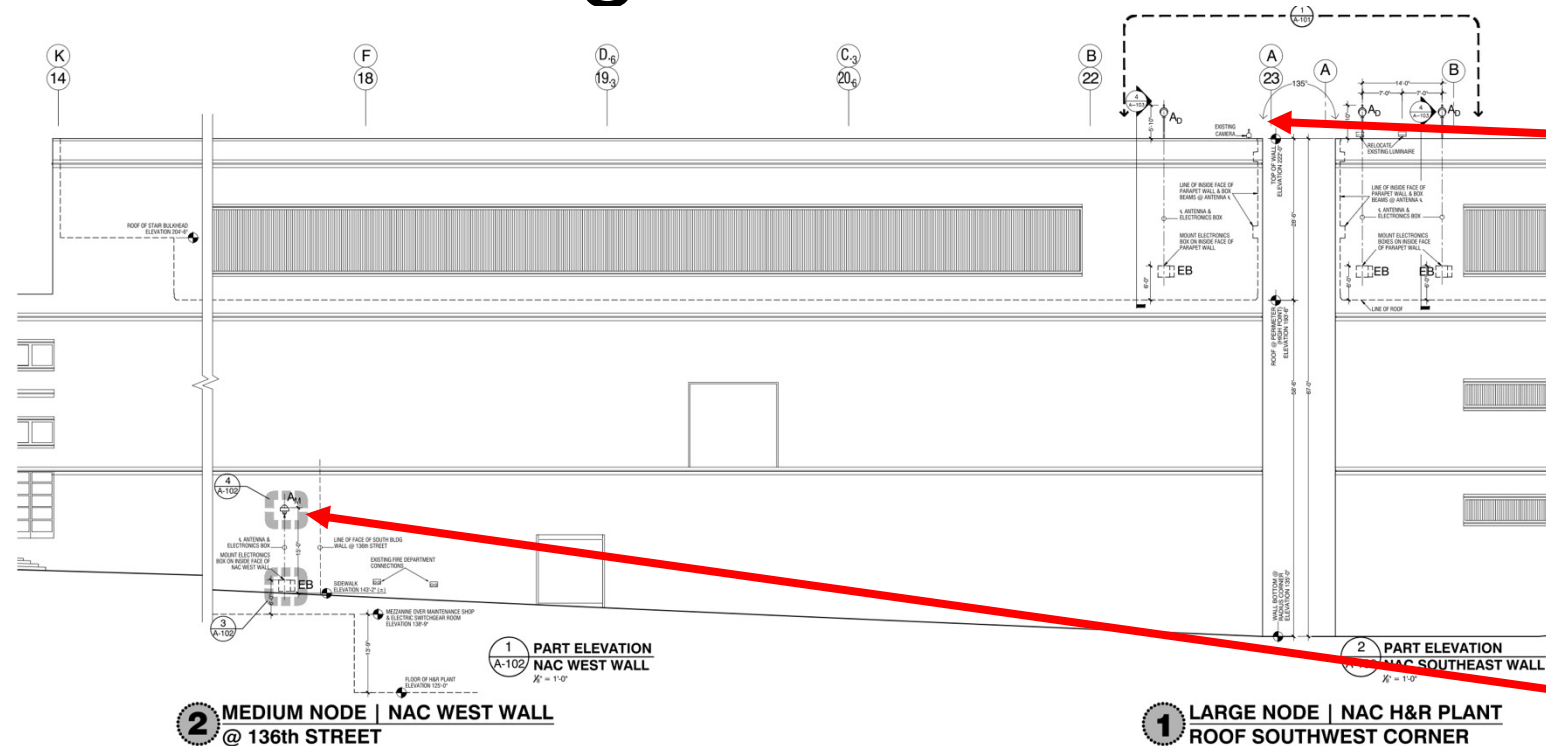
COSMOS: Design and Architecture

- **Key design challenge**: Gbps+ performance and full programmability from the radio level to the central/edge cloud
  - Fully programmable multi-layered computing architecture for flexible experimentation

- **Key technologies**:
  - Software-define radios (SDRs)
  - **Millimeter-wave (mmWave) radios**
  - Optical x-haul networks
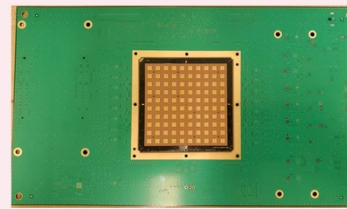 - Software-defined networking and cloud
  - Control and management software
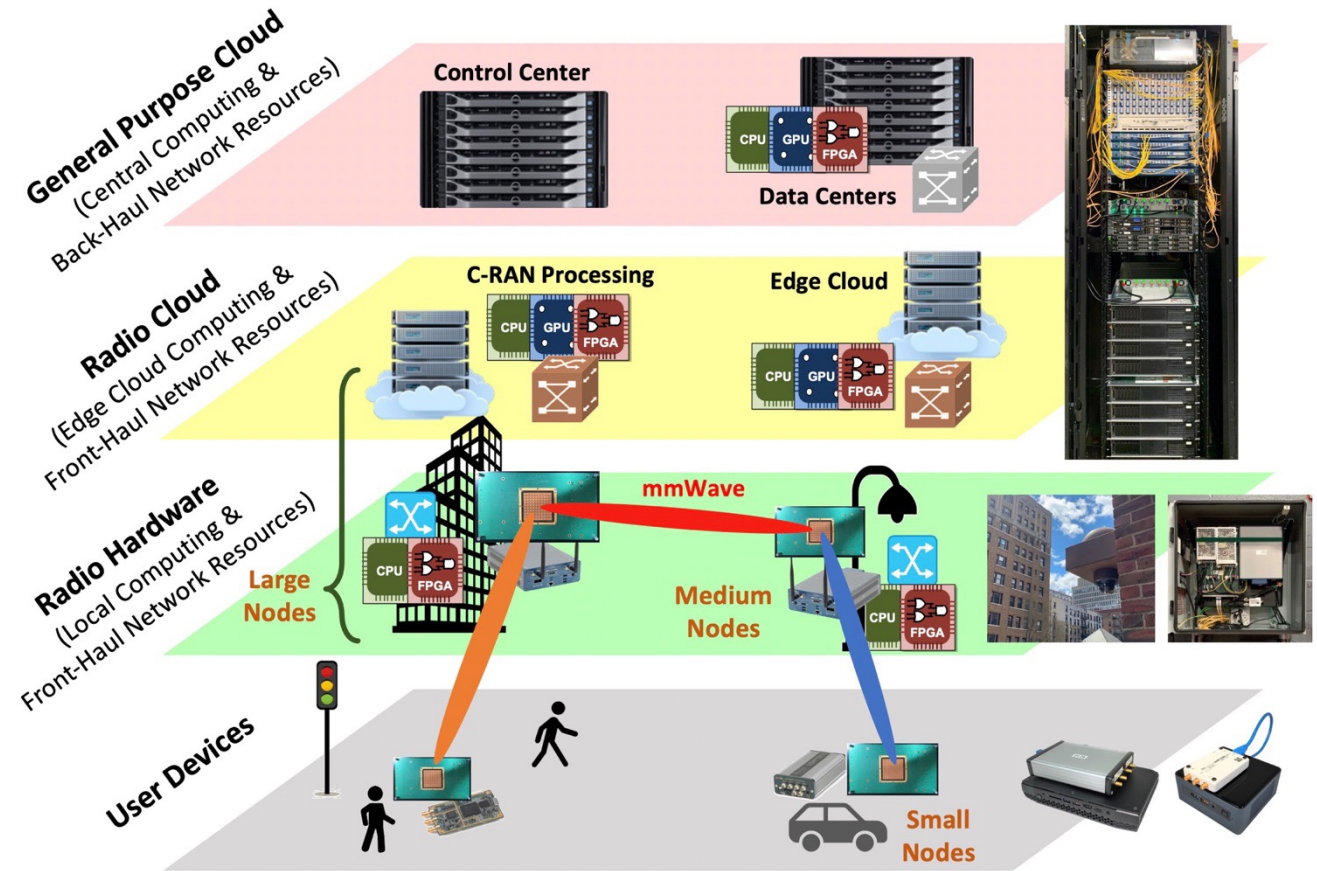
COSMOS's multi-layered computing architecture

- 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' mmWave Front Ends and Systems

- **Programmable mmWave front ends with different baseband options:**
  - IBM 28 GHz 64-element PAAMs
    - Integration in Sandboxes 1 & 2
    - Experiment with adaptive beamforming and mmWave MIMO communications
  - Sivers IMA 60 GHz WiGig transceiver
  - Various SDR and baseband options
    - Up to ~500 MHz bandwidth using the Xilinx UltraScale+ RFSoC platform

Millimeter-Wave Front Ends
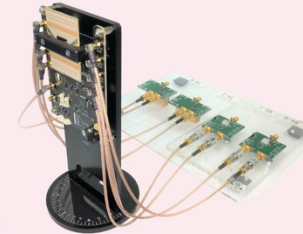
IBM 28 GHz Phased Array Antenna Module (PAAM)

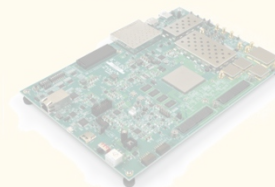Sivers IMA 60 GHz Phased Array

SDR and Baseband

USRP 2974

USRP B210

USRP N310

Xilinx RFSoC

End-to-End Systems

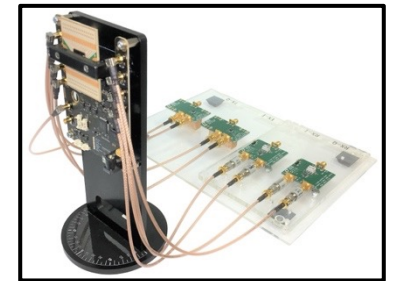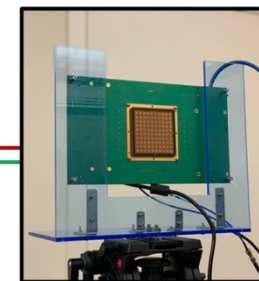InterDigital 28 GHz 5G NR Platform

InterDigital 60 GHz EdgeLink Node

Facebook 60 GHz Terragraph Radio

COSMOS' mmWave Front Ends and Systems

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    - Up to ~500 MHz bandwidth using the Xilinx UltraScale+ RFSoC platform

- **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
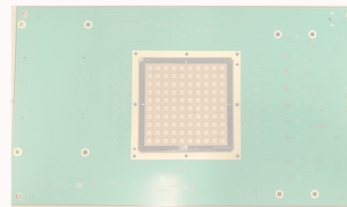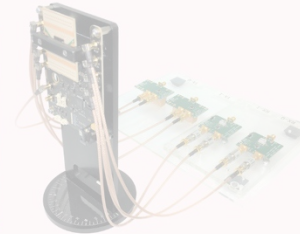
IBM 28 GHz Phased Array Antenna Module (PAAM)

Sivers IMA 60 GHz Phased Array

SDR and Baseband

USRP 2974
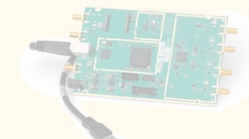
USRP B210

USRP N310

Xilinx RFSoC

End-to-End Systems

InterDigital 28 GHz 5G NR Platform

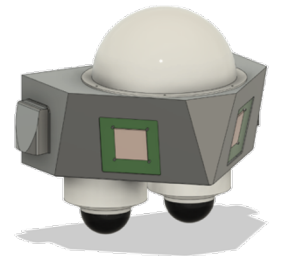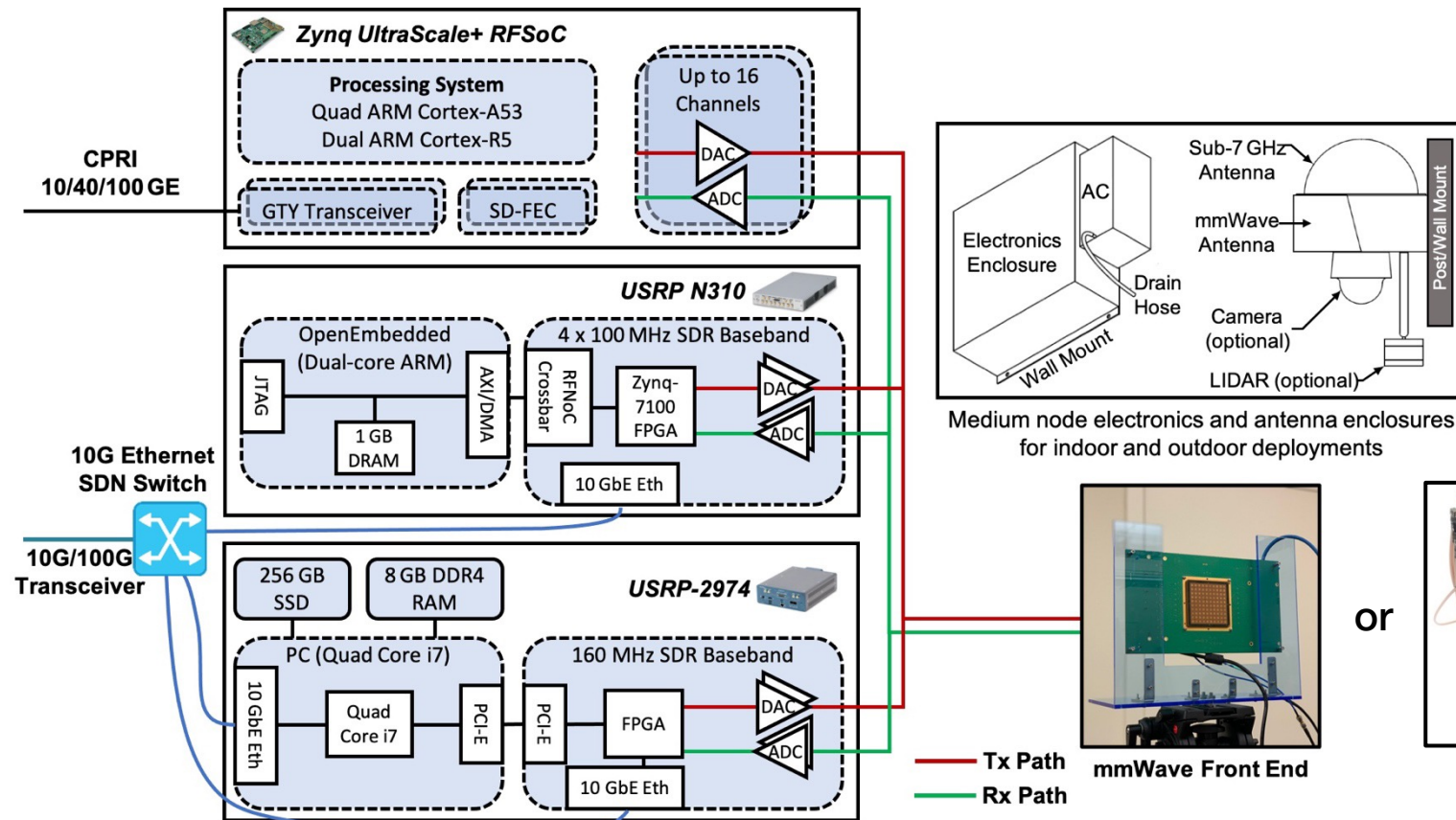InterDigital 60 GHz EdgeLink Node

Facebook 60 GHz Terragraph Radio

COSMOS' mmWave SDRs

- Diagram of a 28 GHz SDR using the IBM 28 GHz PAAM subsystem board
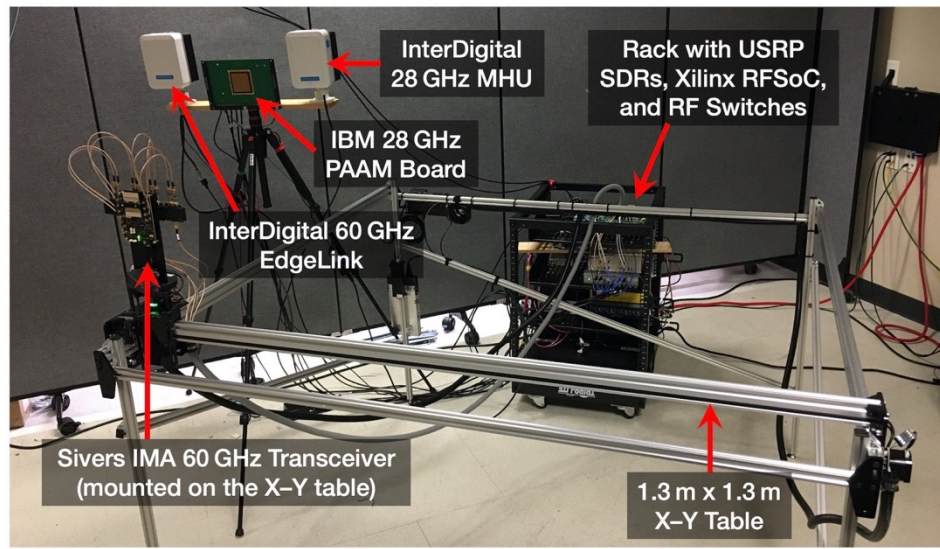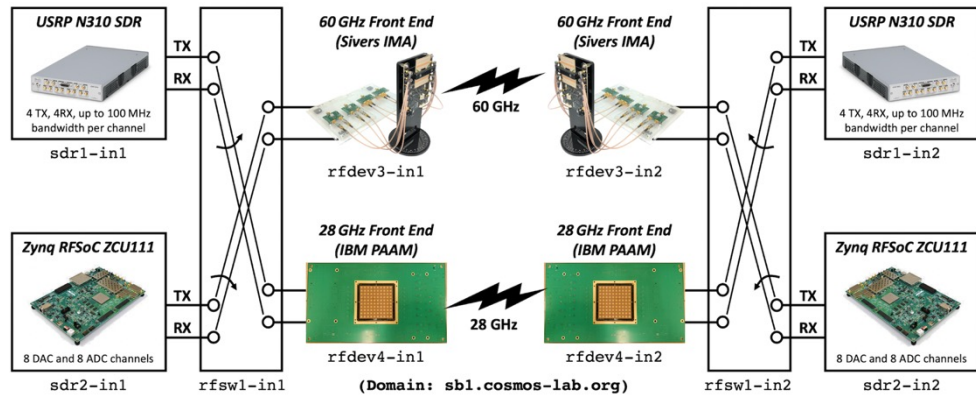 - Signal processing can be spread between radio node & edge cloud RAN
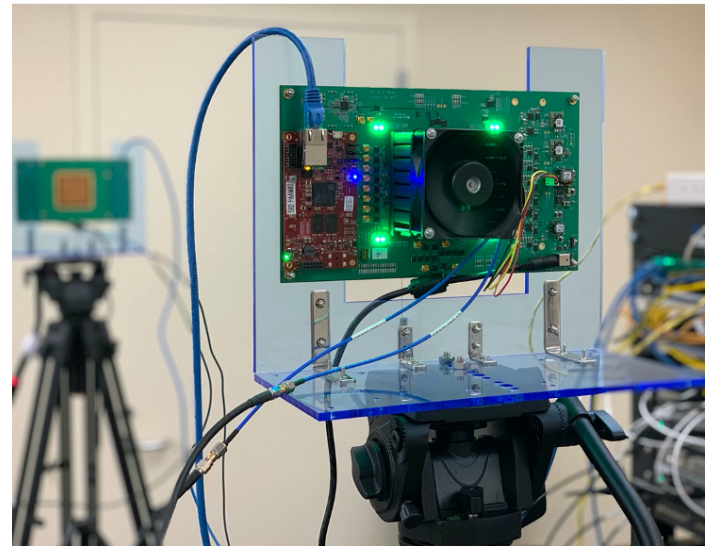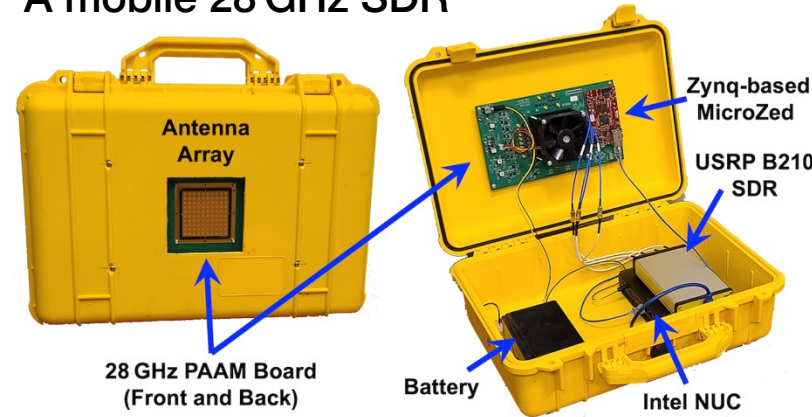

Host compute servers

Medium node electronics and antenna enclosures for indoor and outdoor deployments

mmWave Front End

or

COSMOS' mmWave SDRs

A mobile 28 GHz SDR

A medium node with two 28 GHz SDRs

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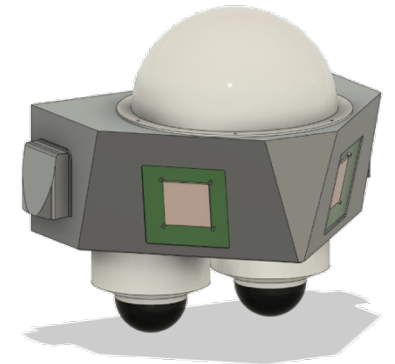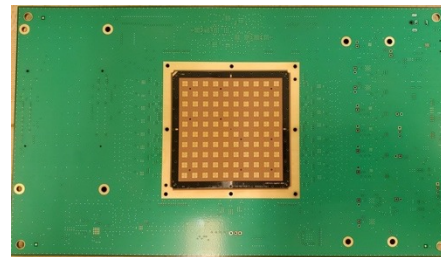
Outdoor deployment at CCNY

IBM 28 GHz PAAM Subsystem Board
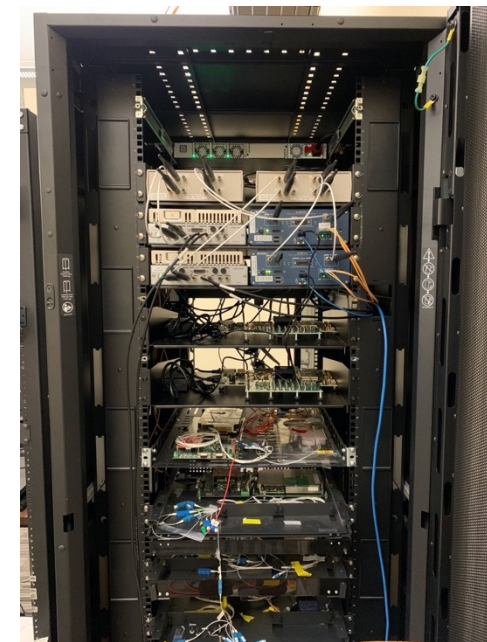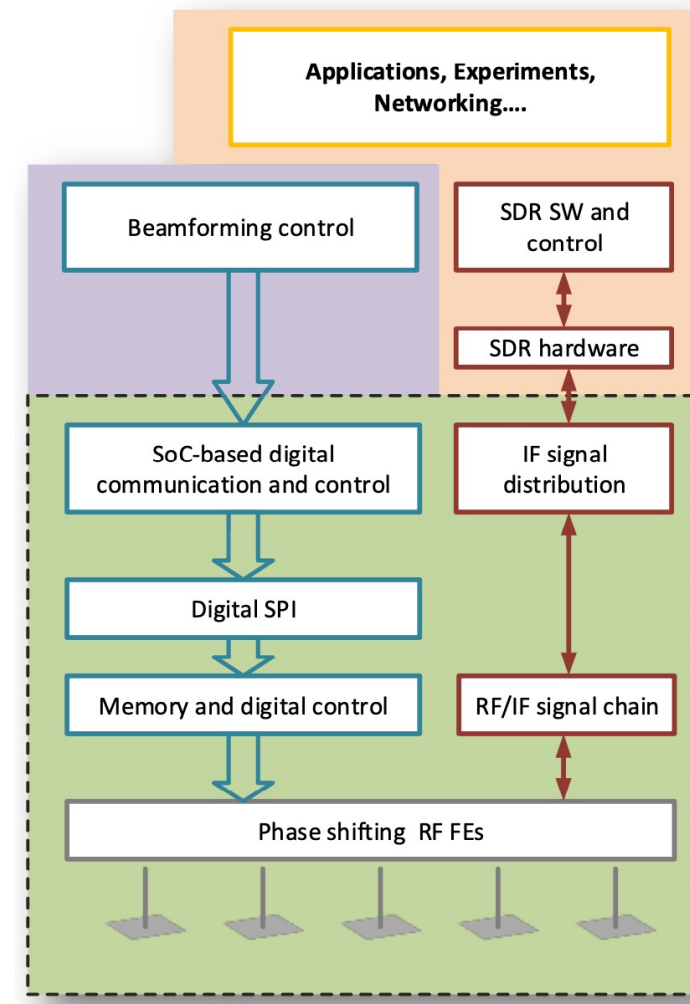
Two main control/data paths:

- TX/RX beamforming control
- TX/RX radio signal

Three key components:

- ▮ 28 GHz PAAM subsystem evaluation board
- ▮ Beamforming control
- ▮ SDR hardware and application software

IBM 28 GHz PAAM subsystem board

(▮ + ▮)

Applications, Experiments, Networking....

Beamforming control

SDR SW and control

SDR hardware

SoC-based digital communication and control

IF signal distribution

Digital SPI

Memory and digital control

RF/IF signal chain

Phase shifting RF FEs

COSMOS' hardware and software (▮)

- 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 MTT-S International Microwave Symposium (IMS'21)*, 2021. **Finalist of IMS'21 Advanced Practice Paper Competition (APPC)**

# IBM-Ericsson 28 GHz 64-element PAAM

- **Multi-function module**
  - 8 simultaneous 16-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
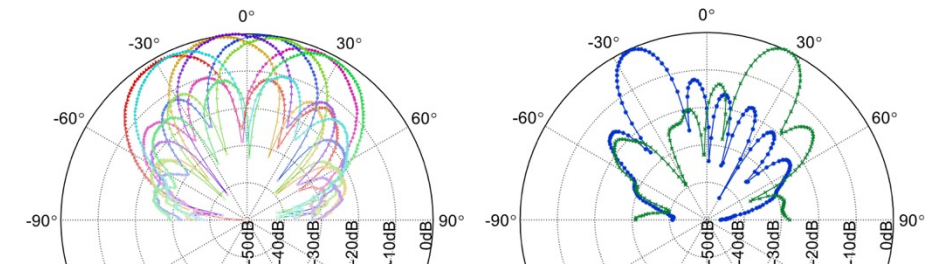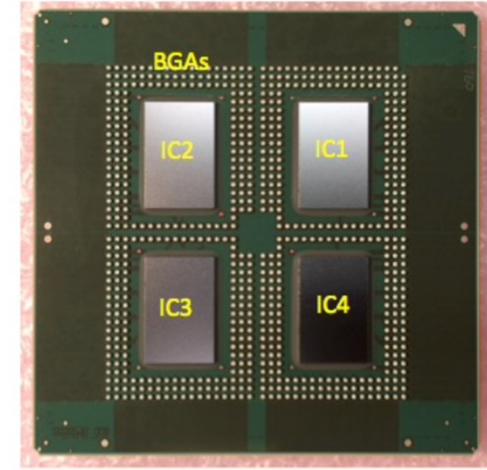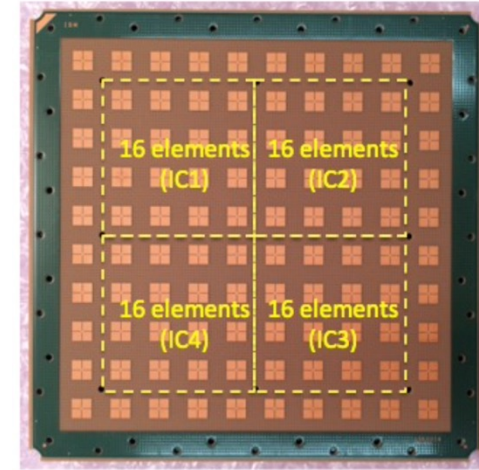
- X. Gu, et al. "Development, implementation, and characterization of a 64-element dual-polarized phased-array antenna module for 28-GHz high-speed data communications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 67, no.7, pp. 2975-2984, 2019.
- X. Gu, et al. "A multilayer organic package 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)**

28 GHz PAAM Subsystem Board: Architecture
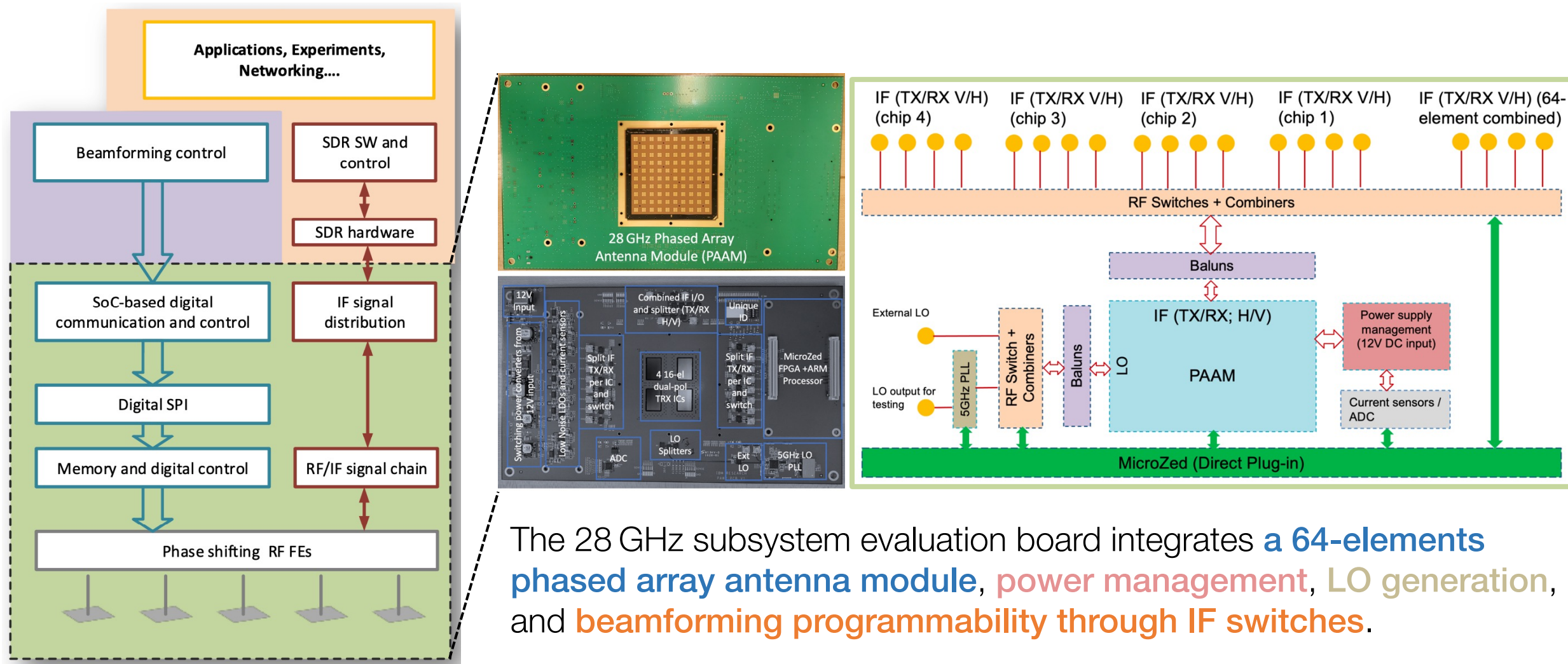
The 28 GHz subsystem evaluation board integrates a 64-elements phased array antenna module, power management, LO generation, and beamforming programmability through IF switches.
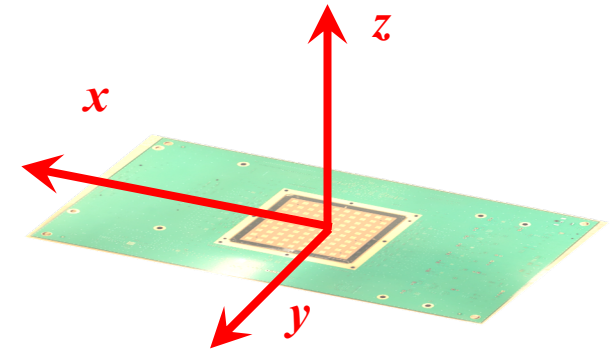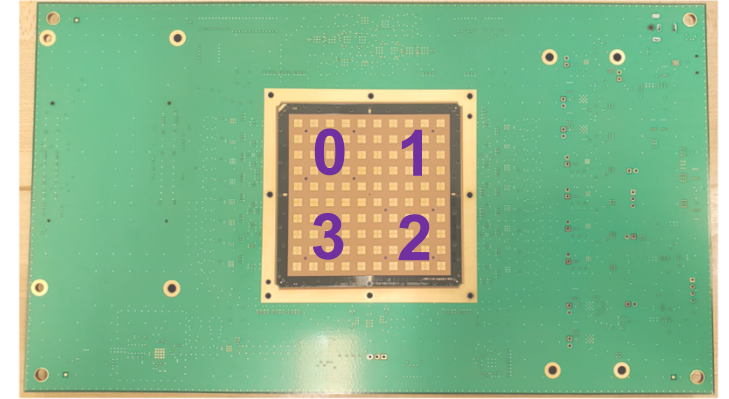
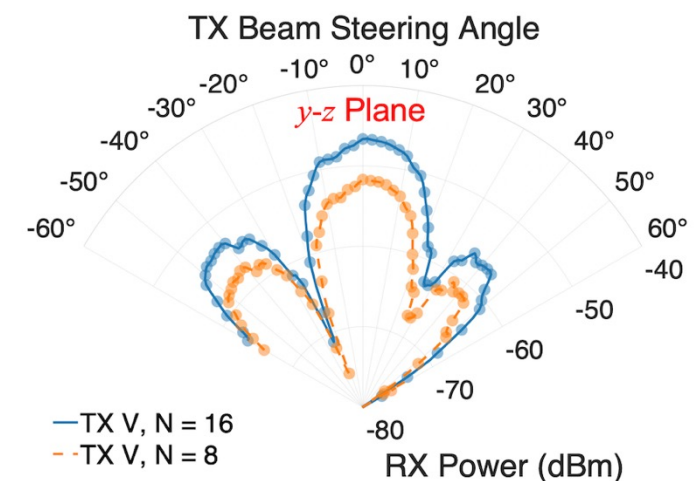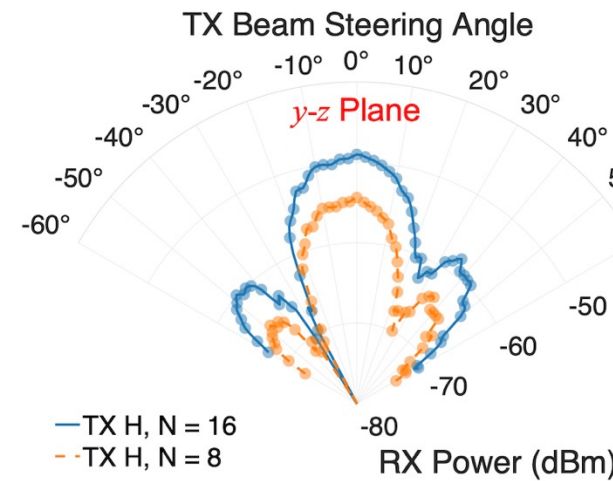# 28 GHz PAAM Subsystem Board: API

- **Subsystem board-level API commands**:
  - `paam_board.set_lo_switch(bool external)`
  - `paam_board.pll_init()`
  - `paam_board.set_if_tx_h(bool combine)`
  - `paam_board.set_if_tx_v(bool combine)`
  - `paam_board.set_if_rx_h(bool combine)`
  - `paam_board.set_if_rx_v(bool combine)`
  - `paam_board.get_adc_vals()`

- **IC-level API commands**:
  - `paam.enable(ic, fe_list, txrx, pol)`
  - `paam.steer_beam(ics, txrx,pol, theta, phi)`
  - `paam.switch_beam_index(ic, txrx, pol, beam_index)`
  - `paam.set_arbitrary_beam(ics, txrx, pol, gains, phases)`

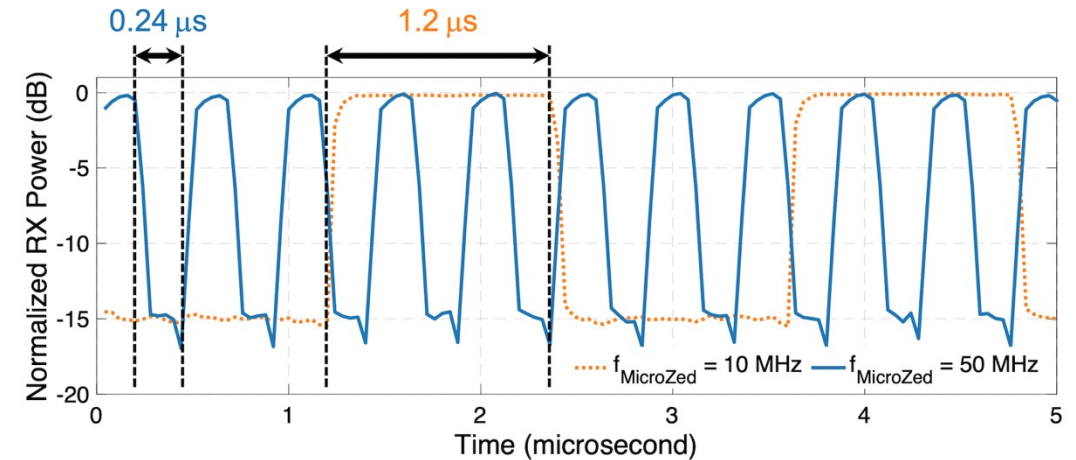# 28 GHz PAAM Subsystem Board: Beamforming
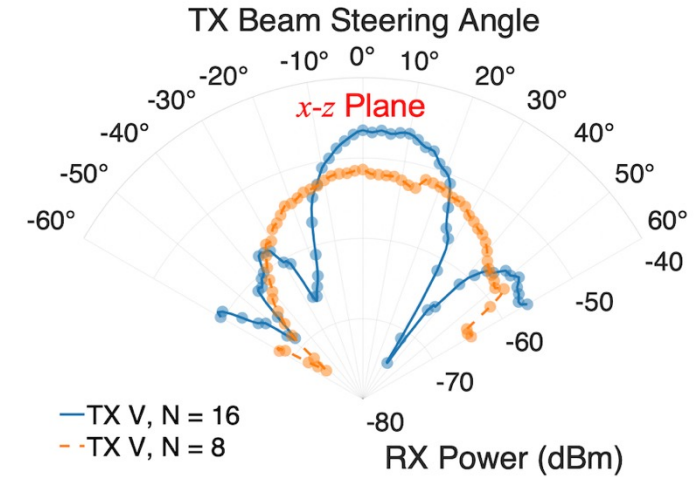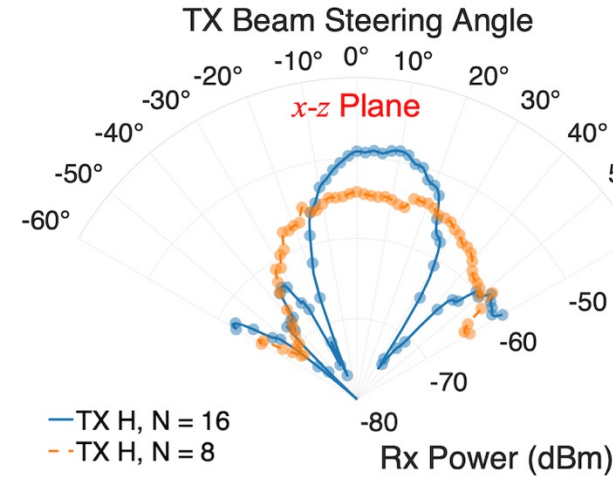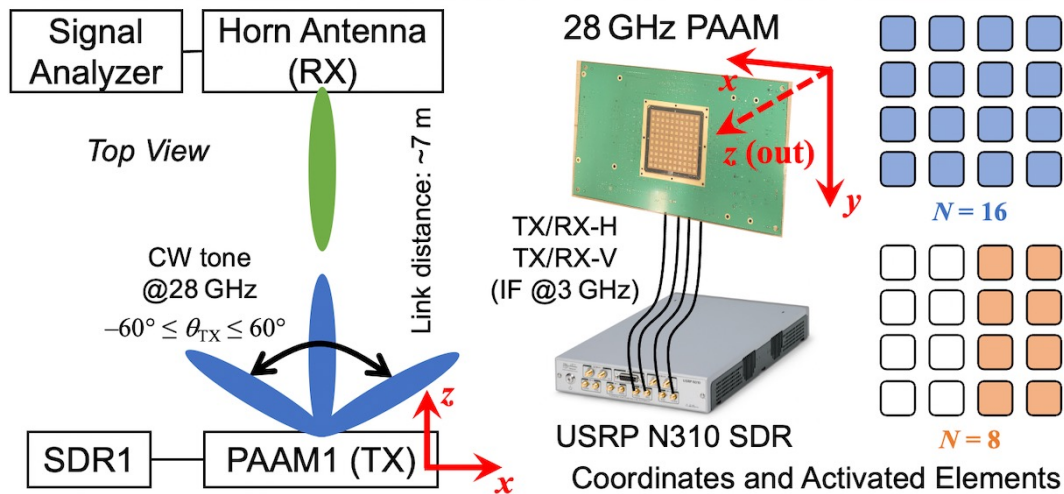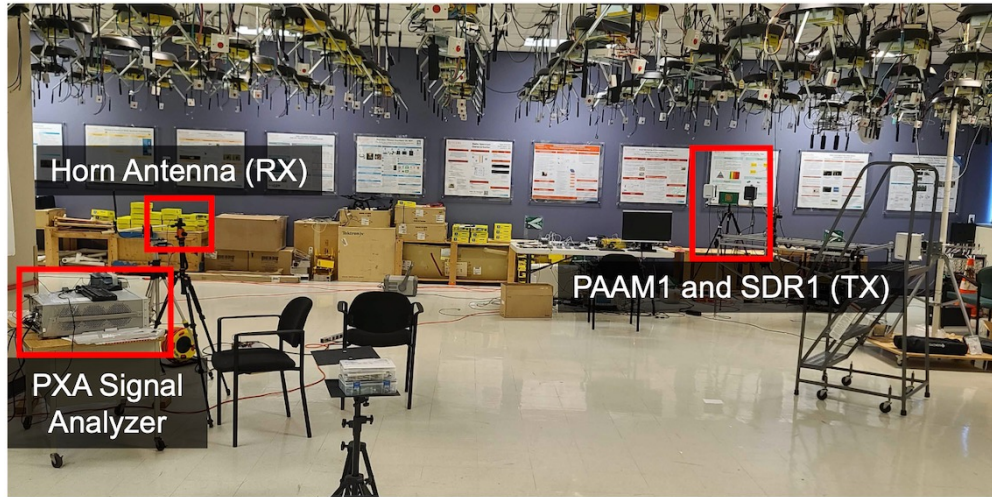
Example beam pattern measurements using the IBM 28 GHz PAAM subsystem boards in Sandbox 1
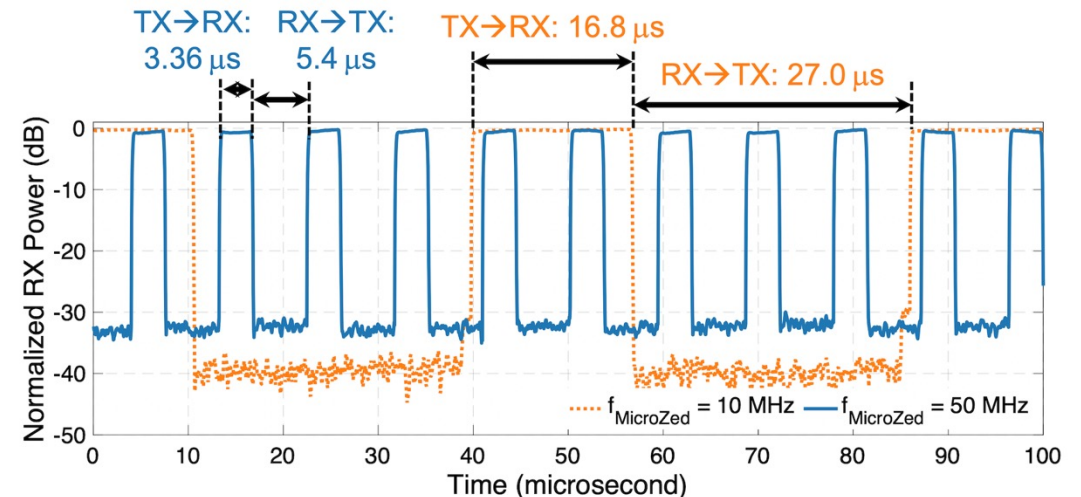
28 GHz PAAM Subsystem Board: Timing

Fast TX/RX beam-switching

- A pre-recorded codebook with a number of TX/RX beamforming directions

- TX/RX beam switching: 0.24 usec ($f_{microzed}$ @50 MHz)

Fast TX-RX and RX-TX switching

- Required for TDD operation since the same antenna element(s) are shared between TX and RX

- TX $\rightarrow$ RX switching: 3.36 usec ($f_{microzed}$ @50 MHz)

- RX $\rightarrow$ TX switching: 5.40 usec ($f_{microzed}$ @50 MHz)

Example Experiment: 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 [–30°, 30°] in the azimuth plane
  - The *RENEWLab Sounder* framework with USRP support (https://github.com/renew-wireless/RENEWLab)
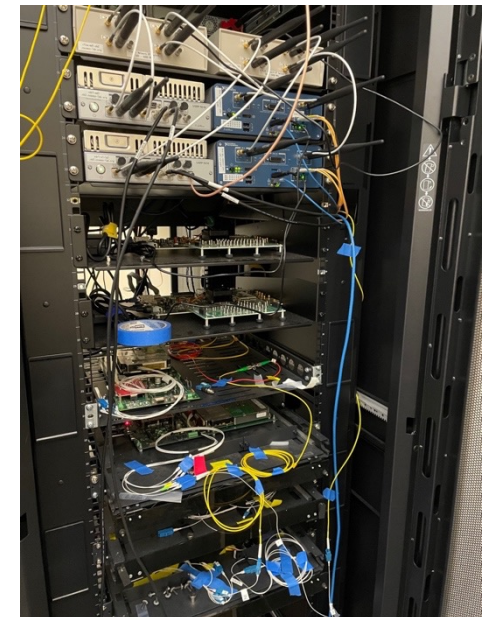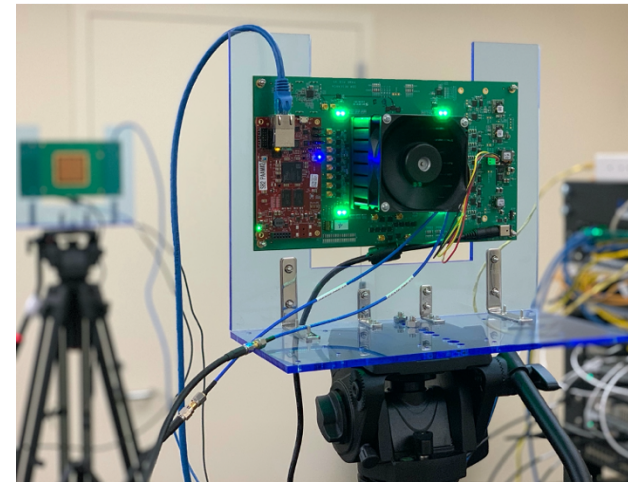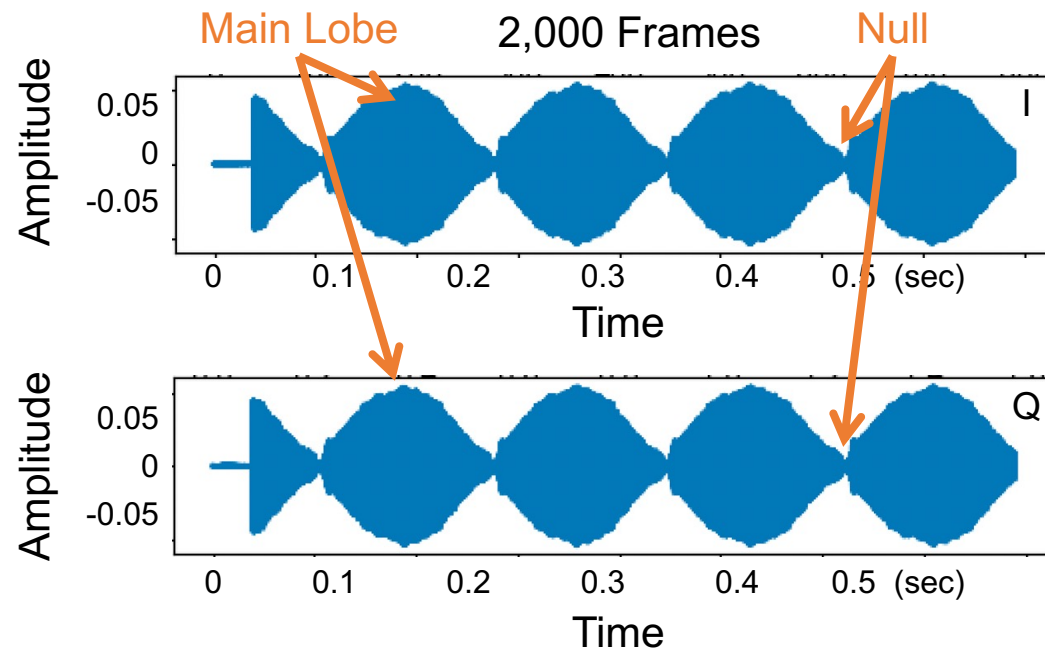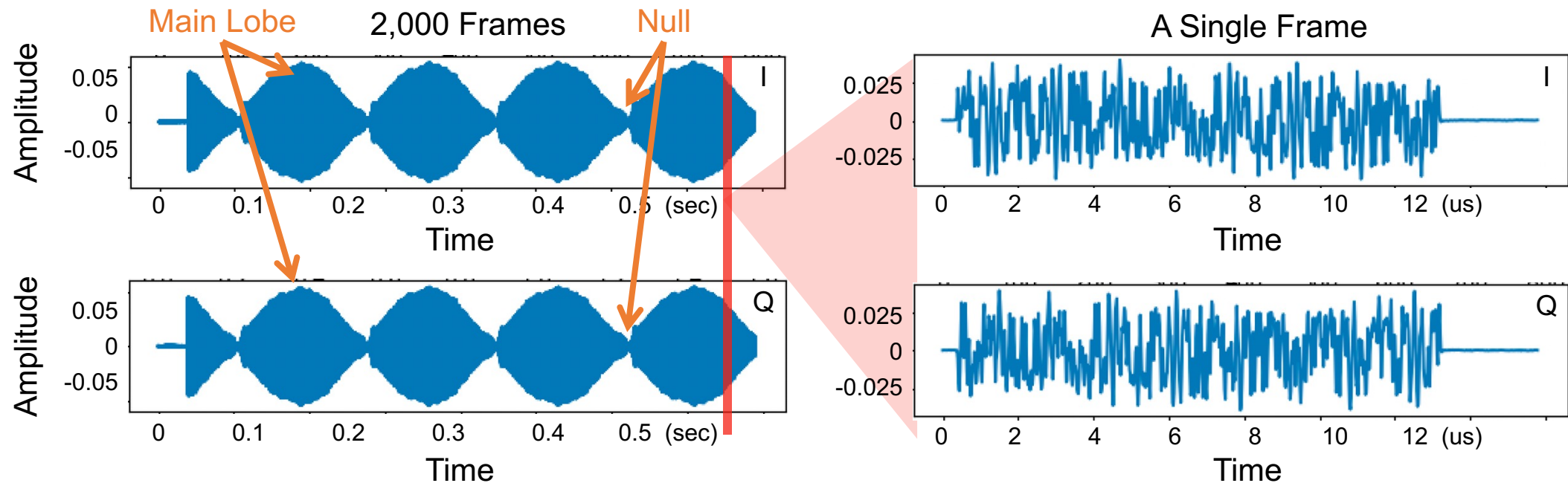
Example Experiment: 28 GHz Channel Sounding

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Tutorials and Example Experiments

IBM 28GHz PAAM Basics

Description

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

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

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

- X. Gu, A. Paidimarri, B. Sadhu, C. Baks, S. Lukashov, M. Yeck, Y. Kwark, T. Chen, G. Zussman, I. Seskar, and A. Valdes-Garcia, "Development of a compact 28-GHz software-defined phased array for a city-scale wireless research testbed," in Proc. IEEE International Microwave Symposium (IMS'21), 2021.

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

Last updated: Mar. 26, 2022

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

Summary

- COSMOS: A ~1 sq. mile city-scale programmable advanced wireless testbed in West Harlem, NYC

- One key technological building block of COSMOS: Programmable and open-access SDRs with different baseband options, computational capabilities, and form factors
    - 28 GHz front end based on the IBM phased array antenna modules (PAAMs)
    - 60 GHz front end based on the Sivers IMA WiGig transceivers
    - USRP SDRs (2974, N310, and B210) and Xilinx RFSoC board
    - Indoor deployment at Rutgers & Columbia available for community use
    - Ongoing outdoor deployment in CCNY

- Example experiments and tutorials

Acknowledgements

Thank you!

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

https://tingjunchen.com/

tingjun.chen@duke.edu