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

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

Cloud enhanced 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

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

- Colosseum: A massive RF channel emulator from DARPA SC2

- Other testbeds: 5TONIC, ADRENALINE, Arena, Bristol Is Open, CORNET, FED4FIRE+, FIT, …
Objective: Take it Outside
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COSMOS Wireless Testbed

Videos

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

COSMOS: Project Timeline

- Dark fiber b/w Columbia and 32AoA lit up
  - Oct. 2017
- Project start
  - Apr. 2018
- Pilot completion and the first COSMOS workshop/tutorial
  - May 2019
- IBM 28 GHz PAAM boards delivered
  - Sept. 19
- FCC Innovation Zone
  - Sept. 2020
- IBM 28 GHz PAAM boards delivered
  - Nov. 2020
- Dark fiber b/w Columbia and CCNY lit up
  - Dec. 2021
- COSM-IC
- Phase 1 completion
  - During 2022*

*Deployments affected by the COVID-19 pandemic and supply chain
Columbia Large Node (Ig1)

Large antenna

RF front ends and fiber to large sector

Software-defined radios (SDRs)

Large sectors

s1

s2

s3

Software-defined radios (SDRs)
Medium Nodes (md1 and md2)

200-level (Amsterdam Ave.)

100-level (West 120th St.)

Medium node coverages

Live camera view

Medium antenna with GPS
Rutgers and Columbia Sandboxes (sb1 and sb2)
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’ 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
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• End-to-end mmWave systems:
  • Facebook Terragraph 60 GHz radios
  • InterDigital 28 GHz 5G NR platform
  • InterDigital 60 GHz EdgeLink nodes
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
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

InterDigital 28 GHz MHU

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

USRP N310 SDR

60 GHz Front End (Sivers IMA)

rfdev1-in1

60 GHz Front End (Sivers IMA)

rfdev2-in1

60 GHz Front End (Sivers IMA)

rfdev3-in2

60 GHz Front End (Sivers IMA)

rfdev4-in2

Antenna Array

28 GHz PAAM Board (Front and Back)

Battery

Zynq-based MicroZed

USRP B210 SDR

Intel NUC

A medium node with two 28 GHz SDRs

Ongoing
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

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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

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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)`
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\text{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 → RX switching: 3.36 usec (f\text{microzed} @50 MHz)
- RX → TX switching: 5.40 usec (f\text{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)
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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.


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More details can be found on [https://wiki.cosmos-lab.org/wiki/Tutorials#SDRandWireless](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
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- The COSMOS paper at ACM MobiCom’20: Dipankar Raychaudhuri, Ivan Seskar, Gil Zussman, Thanasis Korakis, Dan Kilper, Tingjun Chen, Jakub Kolodziejski, Michael Sherman, Zoran Kostic, Xiaoxiong Gu, Harish Krishnaswamy, Sumit Maheshwari, Panagiotis Skrimponis, Craig Gutterman

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Thank you!

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