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

SIGCOMM Tutorial – Intro to COSMOS
August 22, 2022

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

- List of presenters
  - Abhishek Adhikari
  - Julie Raulin
  - Agastya Raj
  - Bob Lantz (Zoom)
  - Zehao Wang (Zoom)
  - Panagiotis Skrimponis (Zoom)
  - Jennifer Shane (Zoom)

- How do you benefit from this tutorial?
  - Go to the wiki
  - Understand high level motivation
  - Try the SDRs
    - Outdoor/indoor at sub-6 and mmWave
  - Try Mininet-optical
    - Vision is to be a digital twin of the cosmos optical testbed

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:30PM</td>
<td>Signup Instructions</td>
</tr>
<tr>
<td>1:50PM</td>
<td>Cosmos Testbed Overview</td>
</tr>
<tr>
<td>2:10PM</td>
<td>Introduction to Experimentation</td>
</tr>
<tr>
<td>2:30PM</td>
<td>Hello World SDR Experiment</td>
</tr>
<tr>
<td>3:00PM</td>
<td>Introduction to Mininet-Optical</td>
</tr>
<tr>
<td>3:30PM</td>
<td>Mininet-Optical Experiment</td>
</tr>
<tr>
<td>4:00PM</td>
<td>Coffee Break with Educational Toolkit</td>
</tr>
<tr>
<td>4:20PM</td>
<td>Massive MIMO</td>
</tr>
<tr>
<td>4:40PM</td>
<td>Optical Testbed Tutorial</td>
</tr>
</tbody>
</table>

[Image of Cosmos Testbed logo]
Developing Future Wireless Networks

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

- Millimeter-wave
- Optical x-haul
- Multi-antenna
- Edge cloud
- Environmental monitoring
- Internet-of-Things (IoT)
- Networking & communications
- Transportation systems

NSF PAWR COSMOS wireless testbed in West Harlem, NYC

Courtesy of Columbia Engineering
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),
Wireless Testbeds (PAWR)

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

POWDER-RENEW
Salt Lake City

COSMOS
New York City

AERPAW
Research Triangle

ARA
Central Iowa
**COSMOS: Envisioned Deployment**

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

- **To NJ Edge**
- **To Silicon Harlem**
- **To COSM-IC**
- **32 Avenue of the Americas (32 AoA)**
- **Deployed**
- **Ongoing/Planned**

- **Large (rooftop)**
- **Medium (street-level)**
- **Small (portable)**
Columbia Large Node (lg1)
Medium Nodes (md1 and md2)

200-level (Amsterdam Ave.)

100-level (West 120th St.)

Medium antenna with GPS

Medium node coverages

Live camera view
CCNY Large and Medium Nodes (lg2 and md3)
COSMOS: Project Timeline

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

*Deployments affected by the COVID-19 pandemic and supply chain.
Key Technology: Software-Defined Radios

A large node sector or a medium node

Fiber & Power Passthrough
Optical MUX/DEMUX
Eth Switch & Chassis Manager
Sub-6GHz RF Front End
Power Supply & Management
USRP N310
RF Cables Passthrough (to Tx/Rx Antennas)
USRP-2974 (Krypton)
Fiber & Power Passthroughs
USRP-2974 + USRP N310
Tx/Rx Antennas
RF Front End, RoF
Medium-light node (lightpole-mounted)

Small portable
Hand-held
Small mobile node
Key Technology: mmWave

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

• End-to-end mmWave systems:
  • Facebook Terragraph 60 GHz radios
  • InterDigital 28 GHz 5G NR platform
  • InterDigital 60 GHz EdgeLink nodes


Key Technology: Optical Networking

- **Data Center @Columbia**
- **32 Avenue of the Americas (32 AoA)**
- **Silicon Harlem**
- **City College**
- **Columbia**

Add/Drop ROADMs
Calient S320 Optical Space Switch
Telemetry Instruments
Lumentum Transmission ROADMs & Line Amplifiers plus fiber

**Key Components:**
- **Add/Drop ROADMs**
- **Calient S320 Optical Space Switch**
- **Edgecore Cassini Switch & Lumentum 200G Transceivers**
- **Mininet-optical simulator**
- **Telemetry Instruments**
- **Lumentum Transmission ROADMs & Line Amplifiers plus fiber**

**Platforms for Advanced Wireless Research**

Rutgers and Columbia Sandboxes (sb1 and sb2)
COSMOS Sandbox1 (SB1)

- 2x USRP-2974
- 2x USRP N310
- 2x Xilinx RFSoC ZCU111
- 2x USRP X310
- Sub-6 GHz RF front-ends
- 2x IBM 28 GHz 64-element PAAM
- 2x Interdigital 5G-NR (28 GHz)
- 2x Interdigital MHU (28 GHz)
- 2x Interdigital EdgeLink (60 GHz)
- 2x Sivers PAAM 60 GHz
- 2x Servers, each with
  - 2x Intel Xeon 12-core, 192 GB RAM
  - Xilinx Alveo FPGA and Nvidia Tesla GPU
- ToR switch, power mgmt., optical mux, …
- X-Y Tables with movable mmWave antennas
COSMOS Sandbox2 (SB2)

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

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

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)

---

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.

Pilot Experiment: mmWave

- 28 GHz channel measurements in the COSMOS testbed area in a dense urban canyon environment
  - Representative (potential) deployment sites of mmWave BSs (building rooftops, street lightpoles, etc.)
  - Extensive measurements on long sidewalks (up to 1,100 m) with fine-grained link step size (1.5/3 m)
- 41+ million measurements were collected from 2,600+ links on 22 sidewalks in 4 different sites
  - Characterizations of path gain, effective beamforming gain, SNR coverage, and achievable data rates

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

Pilot Experiment: mmWave

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

Pilot Experiment: Smart Intersection

- Smart intersection as a core smart city asset
  - Low latency, high bandwidth wireless links, sensor data acquisition
  - Edge cloud computing and machine intelligence for interaction with pedestrians

- **Real-time** (latency) – useful for traffic interaction/management
  - Vehicle speed: 10 km/h → ~3 m/s → ~0.1 m in 1 frame of a video (@30 fps)
  - Useful to prevent accidents, target round-trip latency = 1/30 second

---

Use Case: 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

---

Support for 5G Experimentation

SDR based 5G:

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

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

ORAN and SMO/Orchestration (SB10 – reserved for ONAP/ORAN members)
   • ONAP Tutorials
   • OSM Tutorials
   • ORAN Tutorials
Education and Outreach

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

COSMOS Research Experiences for Teachers (RET) program

Columbia Girls’ Science Day

Students in Frederick Douglass Academy using the COSMOS toolkit

COSMOS Wireless Testbed – Summary

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

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

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