

General Trends on Testbeds for 5G & Beyond, and Testbeds Federations Use Cases (Research & Open- Source Projects Perspectives)

*ITU-T ETSI IEEE Joint SDOs Brainstorming Workshop on Testbeds Federations for 5G
& Beyond: Interoperability, Standardization, Reference Model & APIs*

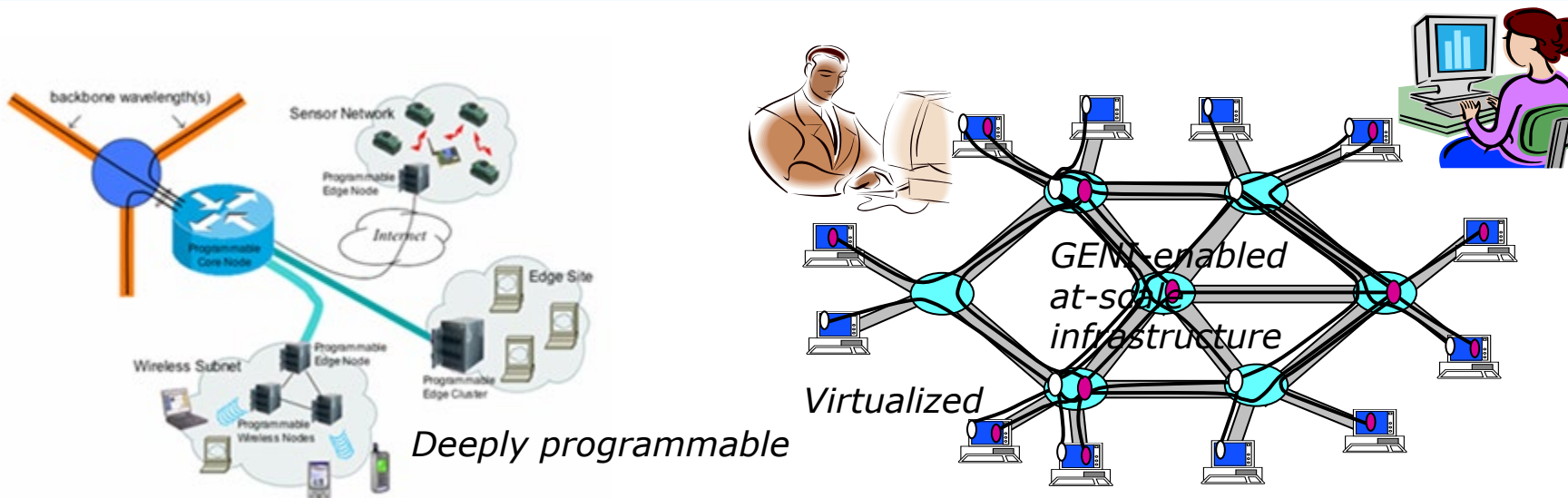
15-16 March 2021

Acknowledgements

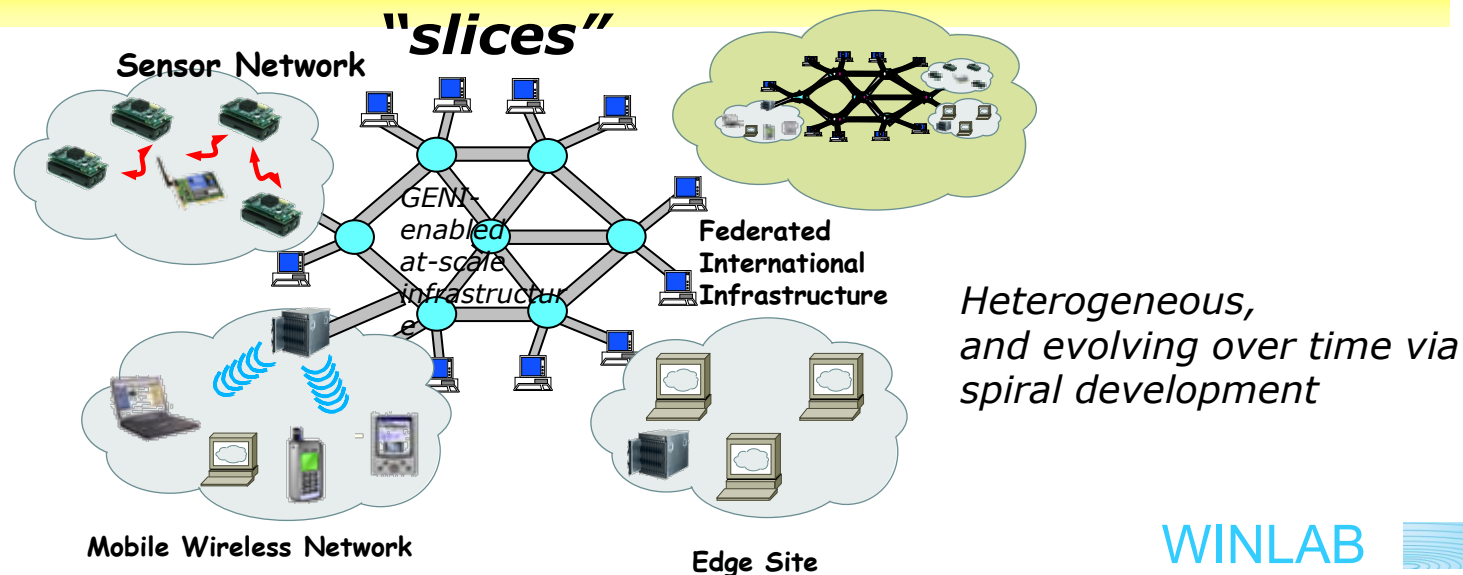
- GENI GPO
- National Science Foundation (NSF) and Platforms for Advanced Wireless Research (PAWR) Program
- O-RAN and ONAP Alliances
- Katarzyna Keahey, Abhimanyu Gosain, Joe Breen, Andrew Buffmire, Jonathan Duerig, Kevin Dutt, Eric Eide, Mike Hibler, David Johnson, Sneha Kasera, Earl Lewis, Dustin Maas, Alex Orange, Neal Patwari, Daniel Reading, Robert Ricci, David Schurig, Leigh Stoller, Kobus Van der Merwe, Kirk Webb, Gary Wong, Dipankar Raychaudhuri, Gil Zussman, Thanasis Korakis, Dan Kilper, Tingjun Chen, Jakub Kolodziejcki, Michael Sherman, Zoran Kostic, X. Gu, Harish Krishnaswamy, Sumit Maheshwari, Panagiotis Skrimponis, Crag Gutterman, Ismail Guvenc, Brian Floyd, Mihail Sichitiu, Rudra Dutta, Thomas Zajkowski, Jason Proctor, Lavanya Sridharan, Vuk Marojevic, Gerard Hayes, David Love, David W. Matolak, Yufeng Xin, Mike Barts, Asokan Ram, Ilya Baldin, Anita Nikolich, Inder Monga, Jim Griffioen, KC Wang, Tom Lehman, Paul Ruth, Zongming Fei
- ... and many other contributors

GENI

GENI: Infrastructure For At-Scale Experimentation

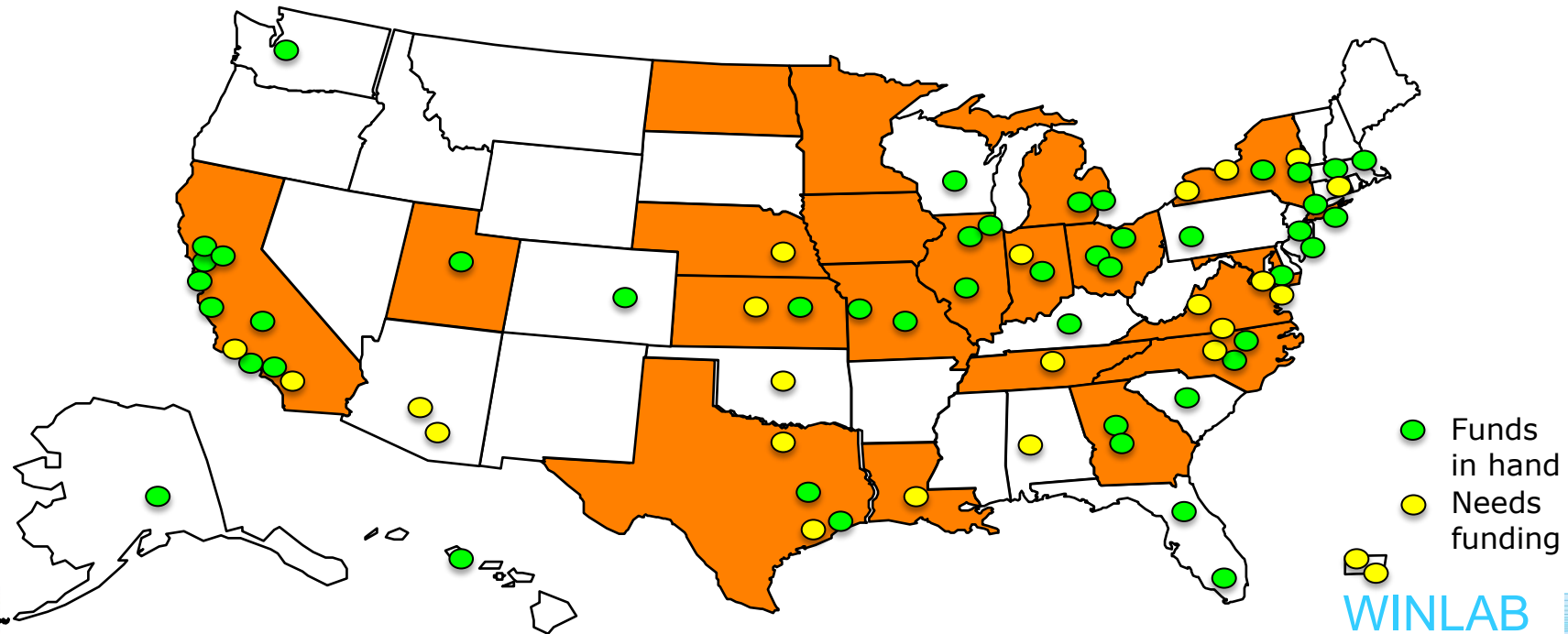


Programmable & federated, with end-to-end virtualized "slices"

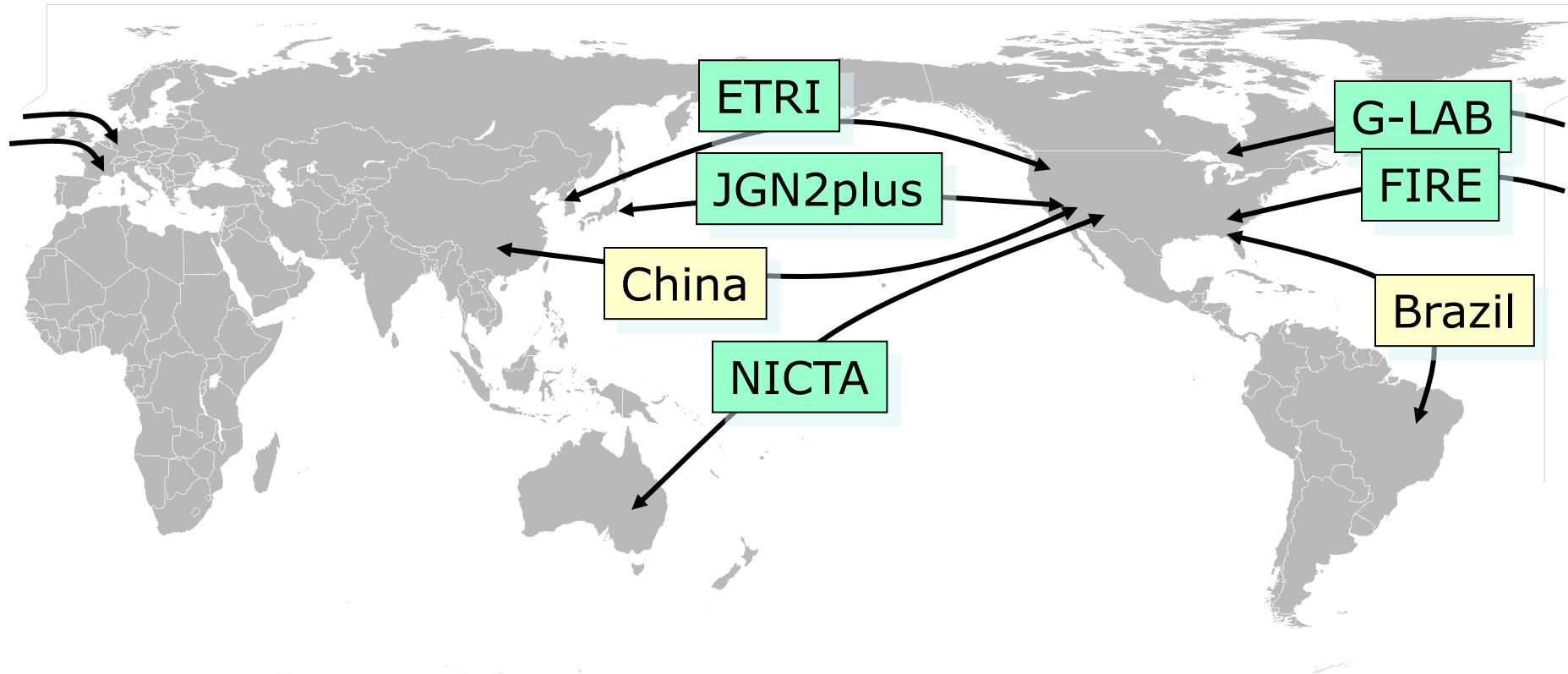


GENI provides a virtual lab for networking and distributed systems research and education

- ❑ GENI started with exploratory, rapid prototyping 12 years ago
- ❑ GENI design assumes federation of *autonomously owned and operated* systems
- ❑ Yearly prototyping cycle for an idea: develop, integrate and *operate*
- ❑ Experimenters use the testbed *while we are building it out*
- ❑ Even prototypes have “activist” users, and must evolve to satisfy those users or fade away. Two of five original design frameworks predominate now.
- ❑ “Horizontal” dataplane slicing as a service (or sometimes just engineered)
- ❑ “Vertical” control plane APIs to negotiate and allocate resources



Efforts Around the World!



- The GENI project is actively collaborating with peer efforts outside the US, based on equality and arising from direct, “researcher to researcher” collaborations.

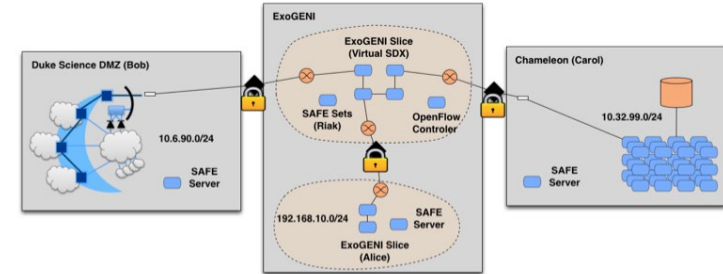
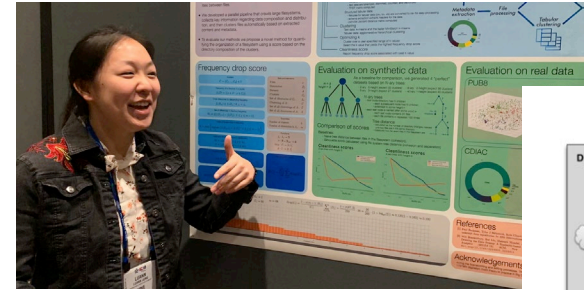
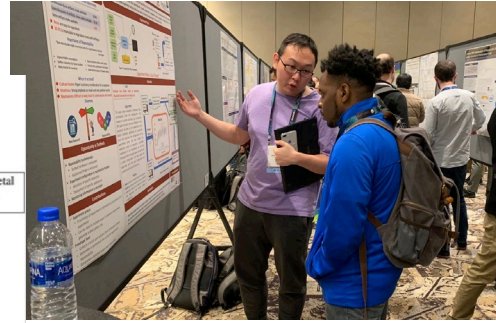
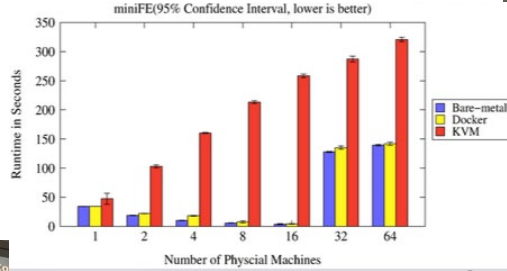


CHAMELEON

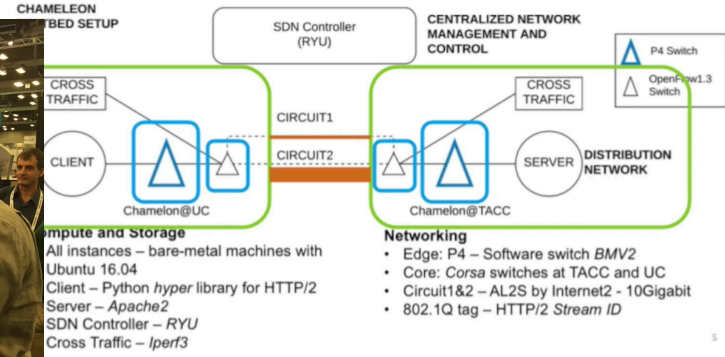
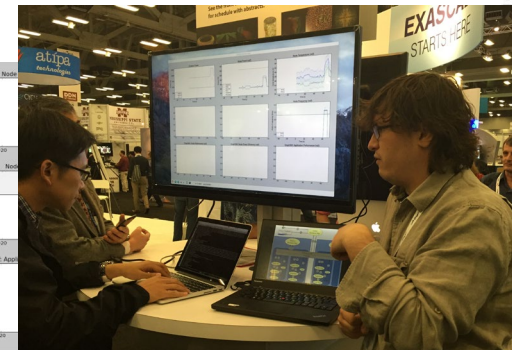
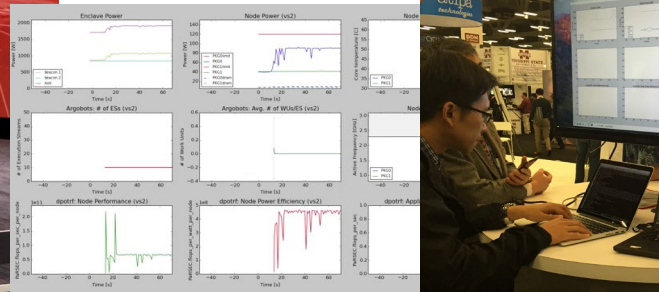
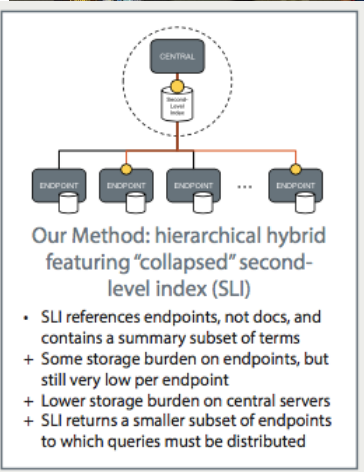
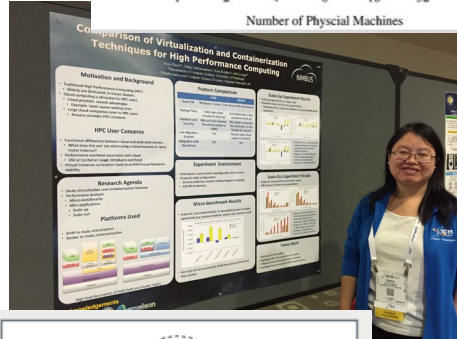
CHAMELEON IN A NUTSHELL

- ▶ We like to change: testbed that adapts itself to your experimental needs
 - ▶ Deep **reconfigurability** (bare metal) and isolation (CHI) – but also ease of use (KVM)
 - ▶ CHI: power on/off, custom kernel, serial console access, stitching, Bring Your Own Controller (BYOC)
 - ▶ Managing experimental configurations: library of images, snapshotting, and orchestration
 - ▶ Support for **reproducibility** and sharing via literate programming (Jupyter) and digital publishing
- ▶ We like to be all things to all people: balancing large-scale and diverse
 - ▶ **Large-scale**: ~large homogenous partition (~15,000 cores), 5.5 PB of storage distributed over 2 + 1 sites connected with 100G network...
 - ▶ ...and **diverse**: Intel (Haswell, SkyLake), ARMs, Atoms, FPGAs, GPUs, IB, Corsair switches, etc
- ▶ We like to be efficient: cost-effective to deploy, operate, and enhance
 - ▶ Powered by **OpenStack** with bare metal reconfiguration (Ironic), **compatible** with all other clouds
 - ▶ Significantly **enhanced OpenStack** to support advance reservation, networking experiments, etc.
- ▶ We live to serve: open, production testbed for Computer Science Research
 - ▶ Started in 10/2014, testbed available since 07/2015, recently renewed till end of 2024
 - ▶ Currently 5,000+ users, 600+ projects, 100+ institutions

NO EXPERIMENT WILL BE LEFT BEHIND!



Supporting research projects in architecture, operating systems design, virtualization, power management, real-time analysis, security, storage systems, databases, networking, machine learning, neural networks, data science, and many others.



PAWR

PAWR program seeks to maintain U.S. leadership in advanced wireless networking innovation

PAWR is funded by the National Science Foundation and a wireless Industry consortium of 35 wireless companies and associations. The PAWR Project Office (PPO) manages the program and is co-led by US Ignite and Northeastern University.



PAWR platforms will allow investigation into some of the most important areas of wireless innovation and development

mmWave: enabling R&D and systems testing with millimeter-wave bands including 28GHz and 60GHz.

Virtualization and Network Slicing: disaggregating network functions and enabling software control and/or dedicated delivery through network slicing.

Microservices Architecture: implementing 4G/5G Core for assembling, controlling, and composing network services.

Artificial Intelligence: using measurement datasets in AI-driven systems to automate network optimization.

Spectrum Optimization: experimenting with signal propagation, spectrum interference, and shared frequencies.

Massive MIMO: using fully programmable massive antenna arrays in the 2.5-2.7GHz and 3.5-3.7GHz frequency bands to enable FDD, full duplex research.

Virtualized and Open RAN: examining the RAN CU-DU split and opportunities for open source RAN management.

Resilient and Secure 5G and Beyond Networks: protecting against attack, intrusion, and degradation.

Applications/Services: scaled environments for testing advanced applications for Smart and Connected Community networks that involve Cyber-Physical Systems, Cyber-Security, Internet of Things, Robotics, Smart and Connected Health, and Big Data.

Researchers will use PAWR testbeds to prove out concepts in an array of disciplines



Cybersecurity Testing



AI-Enabled Network Functions



Programmable Massive MIMO Arrays



Accelerated Virtualization of Network Architectures



Millimeter Wave Performance Optimization



Dynamic Spectrum Management



Open Source Hardware & Software Development



Communications Impacts of Unmanned Aerial Vehicles

PAWR platforms were chosen to be geographically diverse and research focus independent



POWDER

Salt Lake City, UT

Software defined networks
and massive MIMO

AVAILABLE TODAY !!



COSMOS

West Harlem, NY

Millimeter wave and
backhaul research

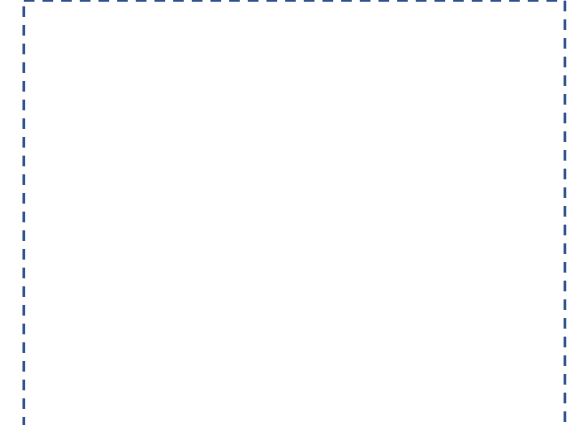
AVAILABLE TODAY !!



AERPAW

Raleigh, NC

Unmanned aerial vehicles
and mobility



Rural Broadband Platform

TBD

Coming late 2020

Colosseum – *World's largest RF emulator, located at Northeastern University in Boston*

AVAILABLE TODAY !!



REVIEW

POWDER: Platform for Open Wireless Data-driven Experimental Research

powderwireless.net



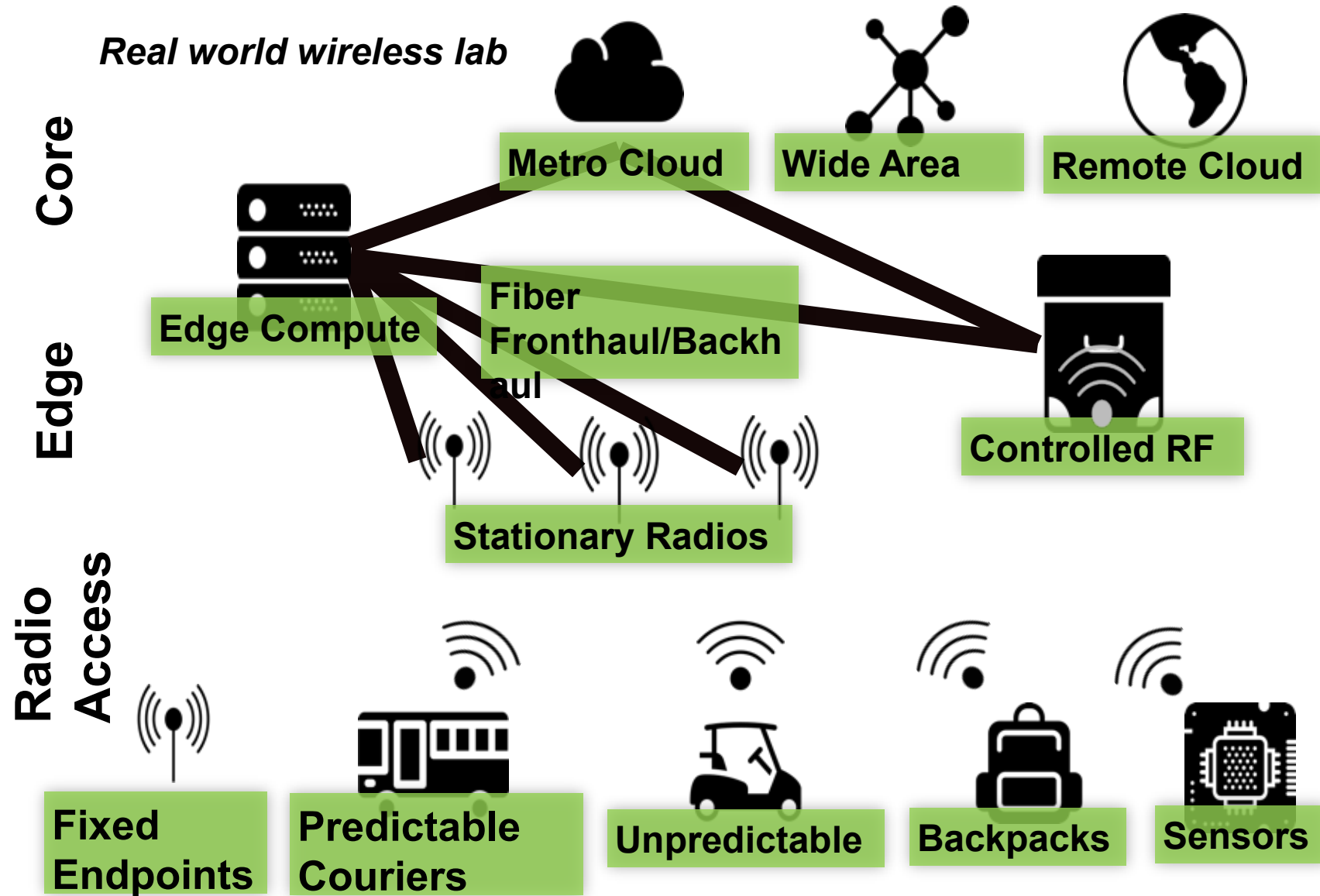
**Platforms for Advanced
Wireless Research**





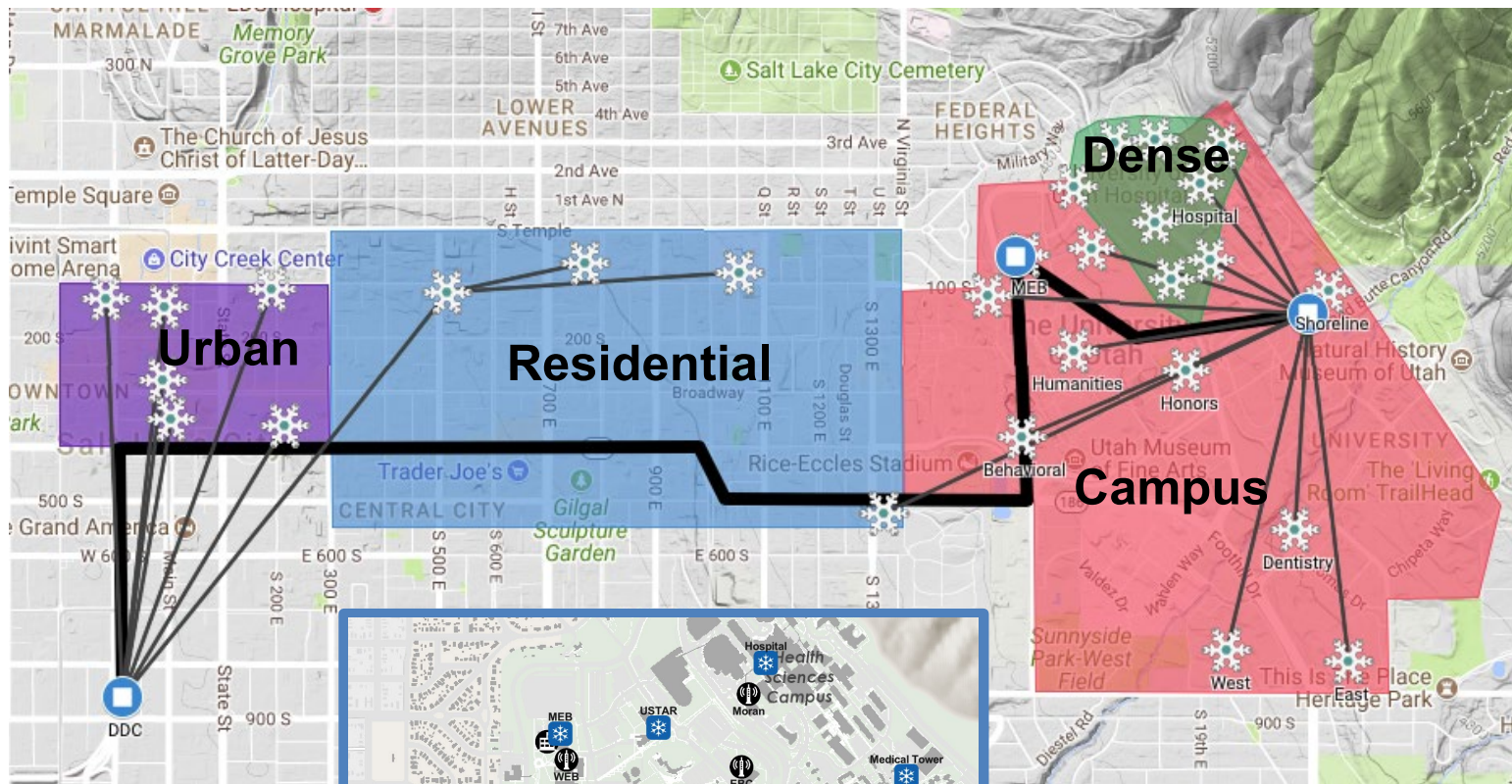
The POWDER Platform

powderwireless.net





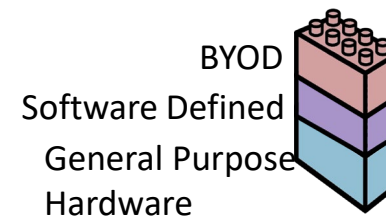
POWDER Deployment



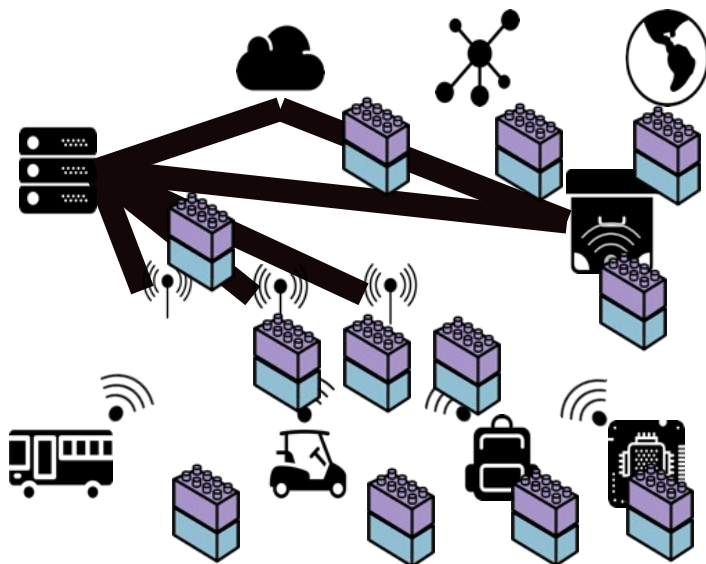
Current deployment:
powderwireless.net/map



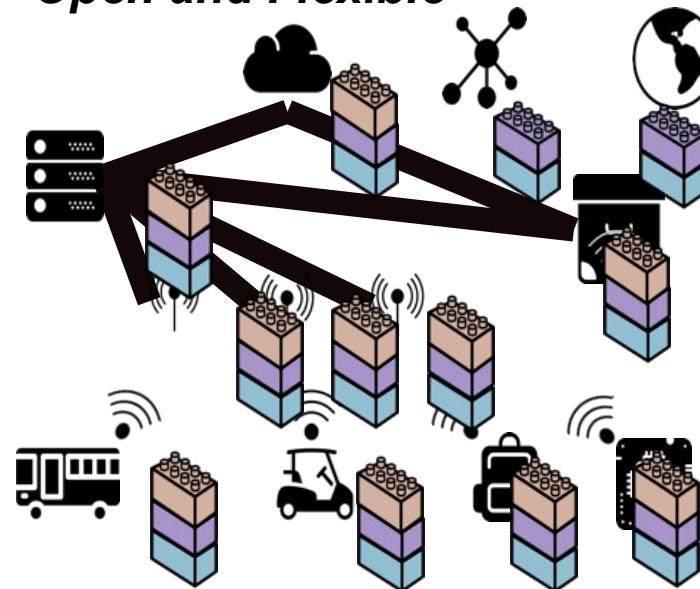
POWDER Building Blocks



E2E software defined



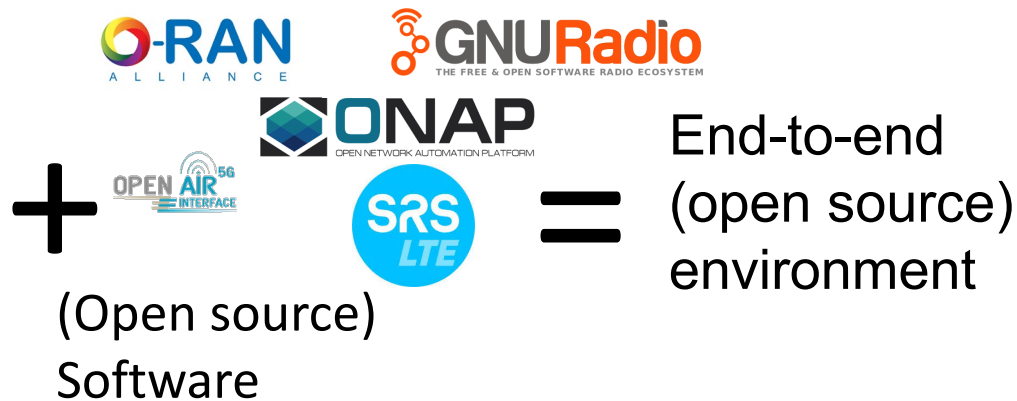
Open and Flexible



Software defined + Open Source



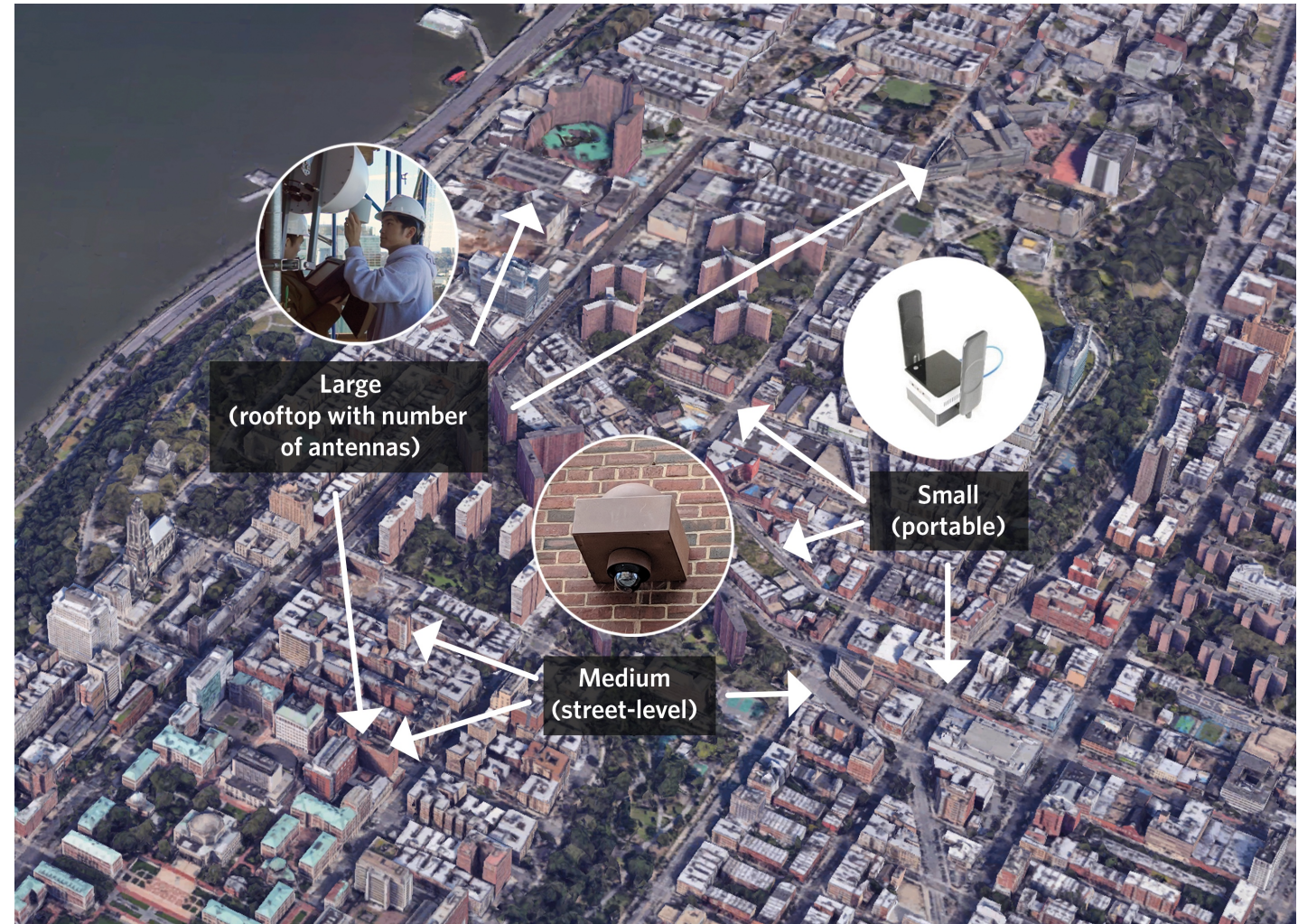
General Purpose Hardware



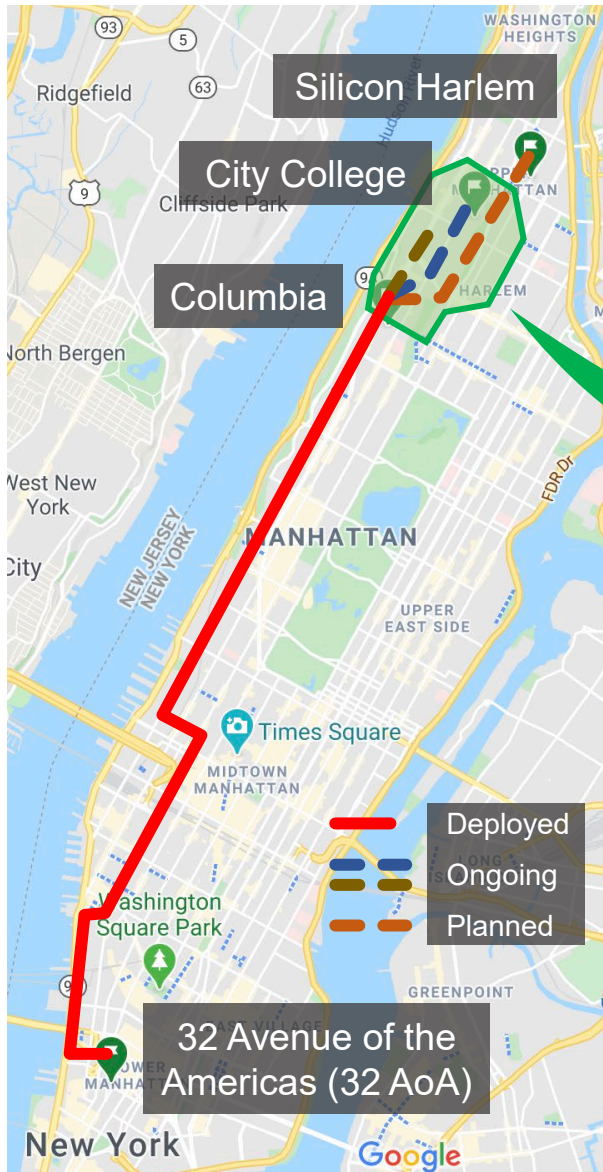
**COSMOS: An Open, Programmable,
City-scale Testbed for Experimentation
with Advanced Wireless Systems and
Edge-computing Concepts**

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



Large (rooftop)



Medium (street-level)



Small (portable)





AERPAAW

<https://aerpaw.org/>



PAWR Project Office

AERPAAW: Aerial Experimentation and Research Platform for Advanced Wireless



AERPAW Project Vision and Scope

- **Funding:** NSF's PAWR program in Sep. 2019 (\$9M + \$15M in kind resources from PAWR consortium)
- **AERPAW Vision:** Serve as a unique technological enabler for advanced wireless research, leveraging unmanned aerial systems (UAS) with world class expertise and partners
- **Project Heart:** Programmable radios, programmable UAS, on a programmable network
- Managed by the PAWR project office (PPO): US Ignite & Northeastern
- Contributions from PAWR Industry Consortium members – NI, Keysight, CommScope, Facebook, AT&T, Interdigital ...



AERPAW:
 \$24M NSF
 PAWR Project
 with a focus on
 aerial wireless

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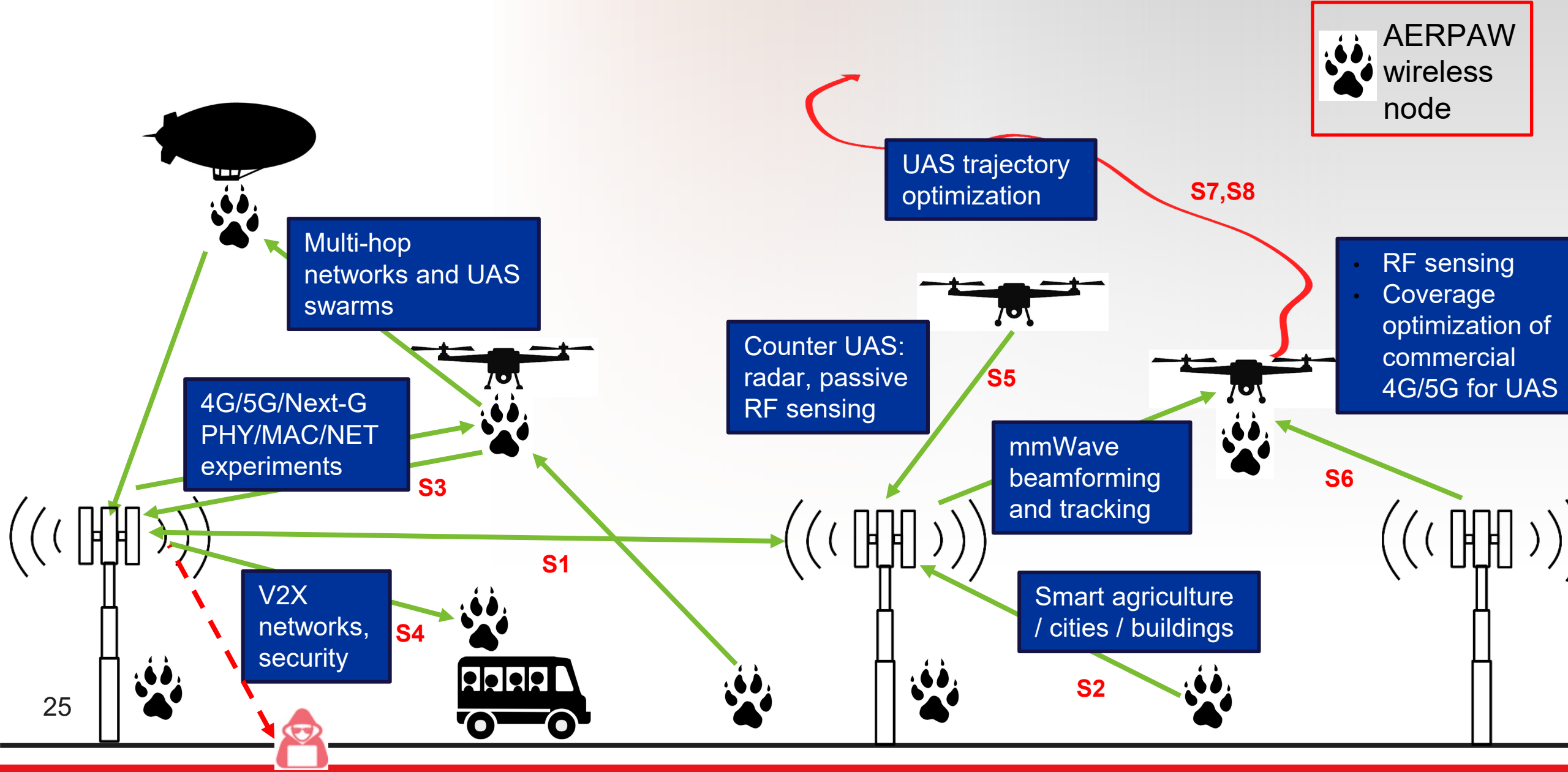
Fixed Node Availability

- Early 2021
- Early 2022
- Early 2023



Experiment Examples

Lead User Group: group-aerpaw-leaduser@ncsu.edu

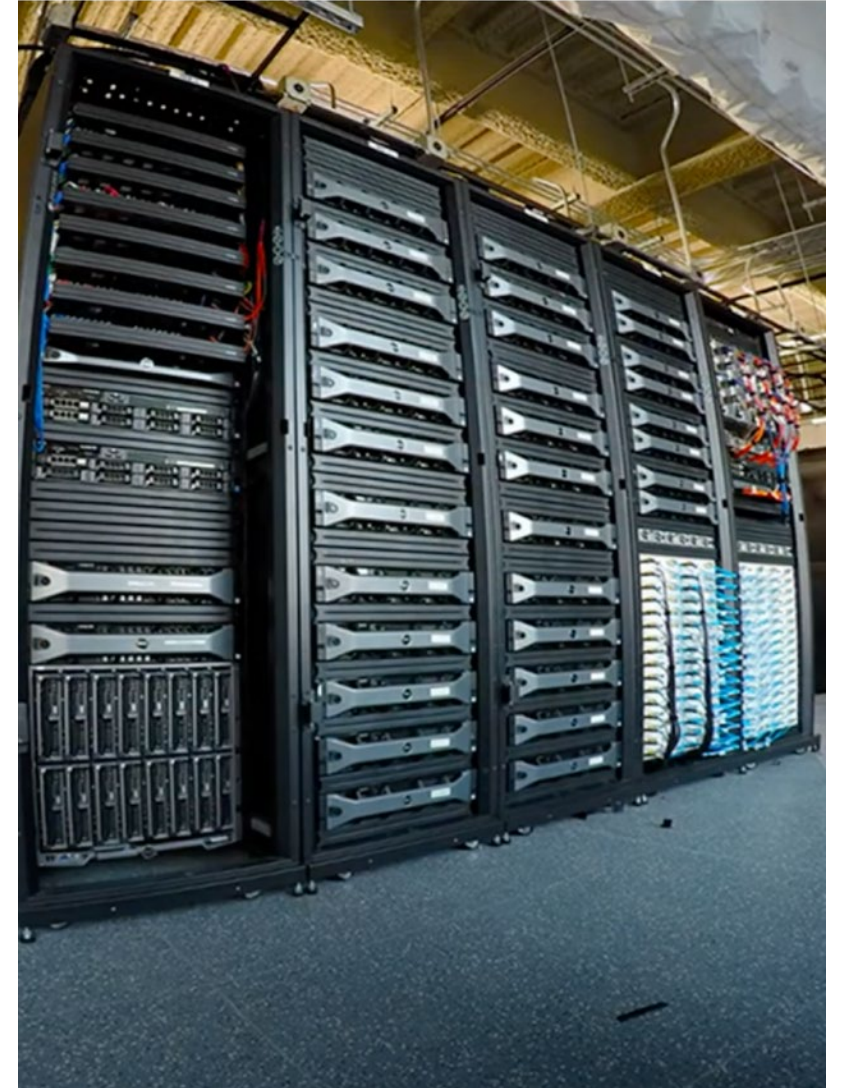


Colosseum

Colosseum is the world's largest wireless network emulator with granularity at the RF signal level

- 256 x 256 100 MHz RF channel emulation
- 128 Programmable Radio Nodes
- Computing resources (CPU, GPU, FPGA)
- Access control and scheduling infrastructure
- Supports remote shared access
- Colosseum supports a containerized software environment with full-stack, end-to-end experiments

northeastern.edu/colosseum



FABRIC



FABRIC: Network Construction Kit for the Future Internet

<https://fabric-testbed.net/>

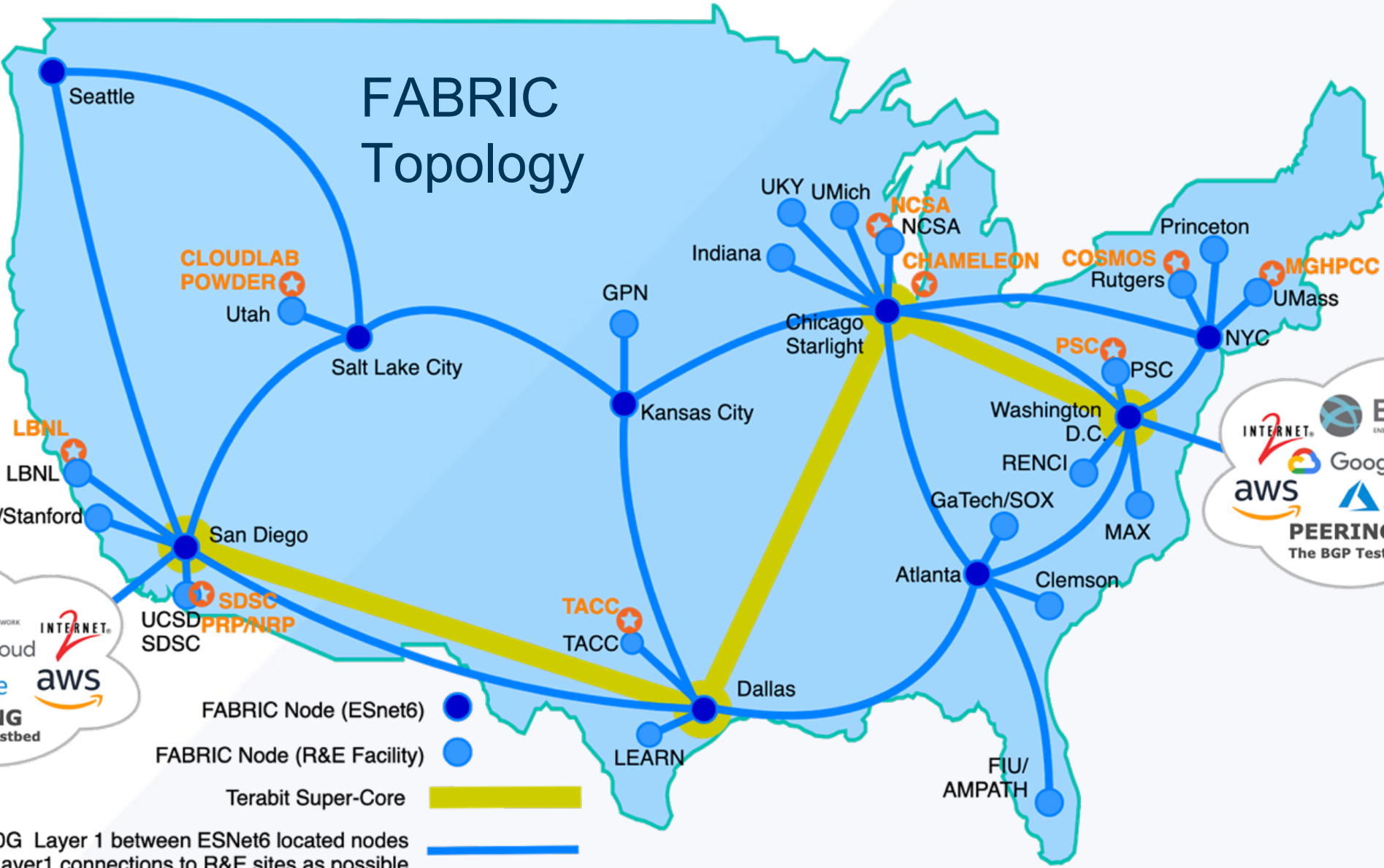


Why FABRIC?

- Change in economics of compute and storage allow for the possibility that future Internet is more stateful than we've come to believe
 - “If we had to build a router from scratch today it wouldn't look like the routers we build today”
 - Explosion of capabilities in augmented computing - GPUs, FPGAs
 - Opportunity to reimagine network architecture as more stateful
- ML/AI revolution
 - Network as a ‘big-data’ instrument: real-time measurements + inferencing control loop
 - Network vendors have caught on to it:
 - “Self-driving network” - Juniper CTO [Kireeti Kompella](#)
 - Provisioning, cyber-security, other applications
- IoT + 5G - the new high-speed intelligent network edge
- New science applications
 - New distributed applications - data distribution, computing, storage
- A continuum of computing capabilities
 - Not just fixed points - “edge” or “public cloud”
 - Network as part of the computing substrate - computing, fusing, processing data on the fly



FABRIC Topology



ESnet
 ENERGY SCIENCES NETWORK
 Google Cloud
 Azure
 aws
PEERING
 The BGP Testbed

INTERNET
 ESnet
 ENERGY SCIENCES NETWORK
 Google Cloud
 aws
 Azure
PEERING
 The BGP Testbed

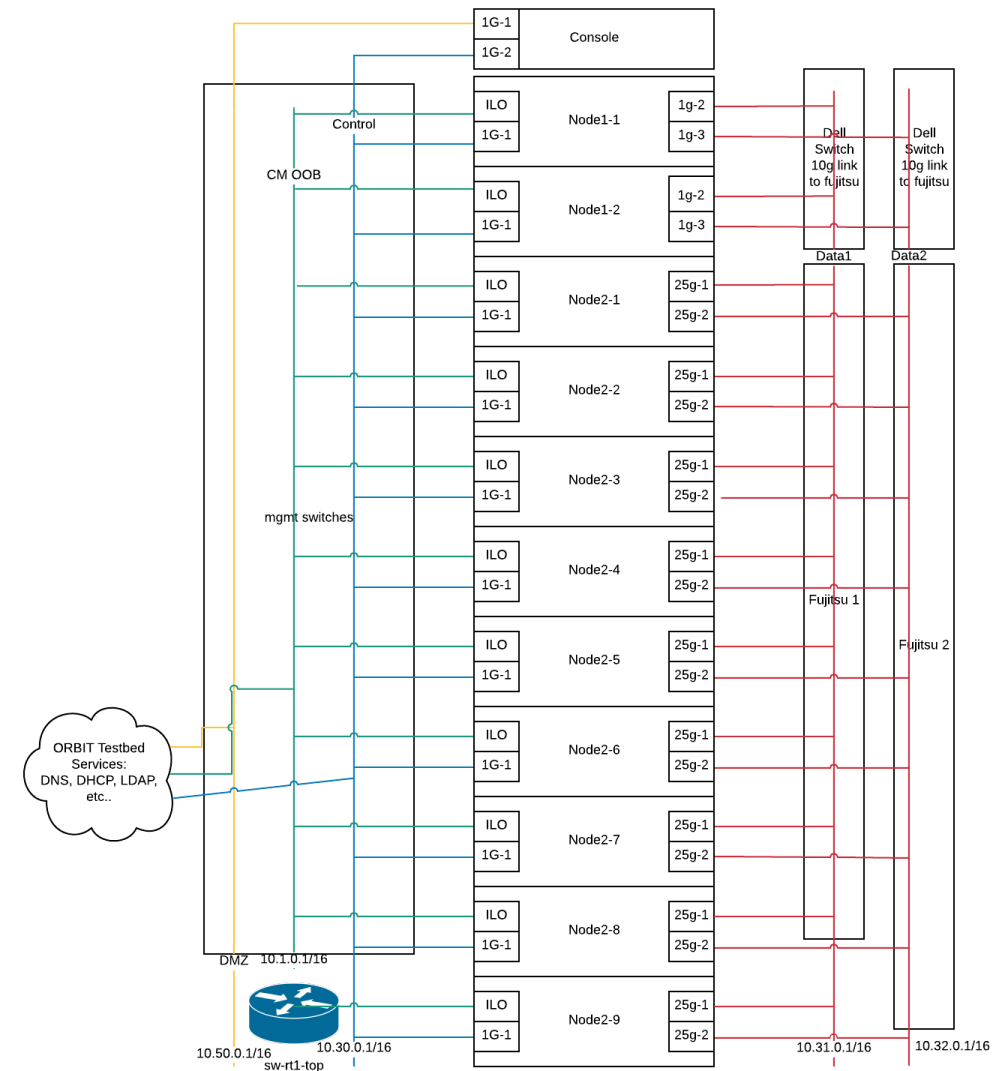
- FABRIC Node (ESNet6) ●
- FABRIC Node (R&E Facility) ●
- Terabit Super-Core —
- 100G Layer 1 between ESNet6 located nodes —
- 100G Layer1 connections to R&E sites as possible —



FEDERATIONS

O-RAN/ONAP (Candidate) OTIC NA East

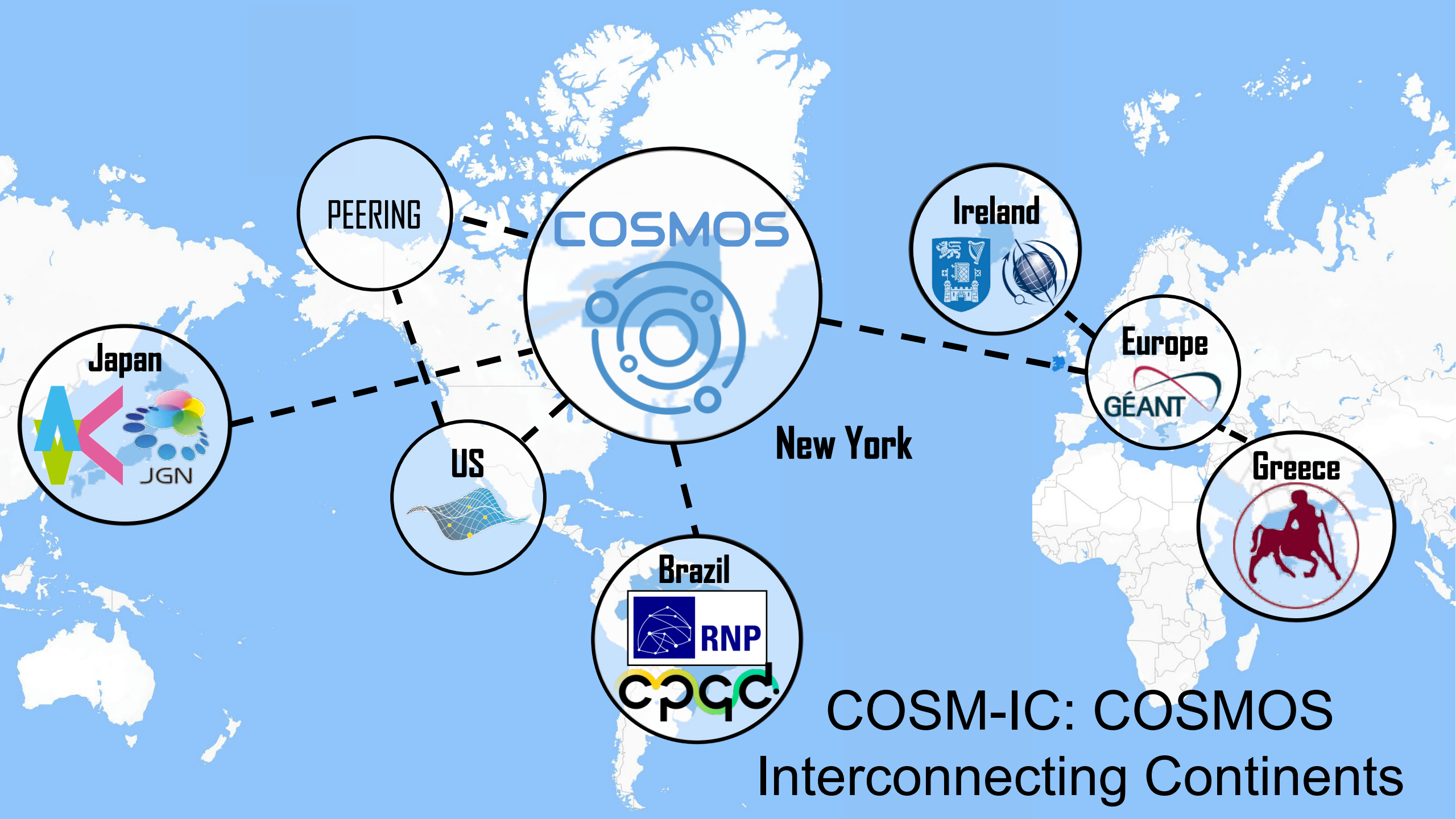
- Used for ONAP PoCs since 2018
- Environment
 - Entry point at console located at console.sb10.orbit-lab.org
 - 14 Ubuntu servers, all managed by OpenStack
 - Control Node and Compute Nodes
- Access Methods
 - Organizations can gain access by requesting an account – details at: <https://wiki.onap.org/pages/viewpage.action?pageId=45298557>
 - Tunnels to other testing and integration labs around the world



FAB

- FAB (FABRIC Across Borders) is the international expansion of FABRIC to Asia and Europe
 - Funded by NSF IRNC (International Research Network Connections) program
- Led by Anita Nikolich
- Includes sites in Japan (University of Tokyo), UK (University of Bristol), EU (University of Amsterdam and CERN)
 - To be deployed in 2021-2023 timeframe similar to the rest of FABRIC
 - Linked by available capacity on IRNC trans-oceanic links
- Brings new use-cases
 - Astronomy/Cosmology, High-Energy Physics, Urban Sensing/IoT
 - Computer Science: 5G across borders, P4/SDN, Cyber-security/Censorship evasion





PEERING

COSMOS

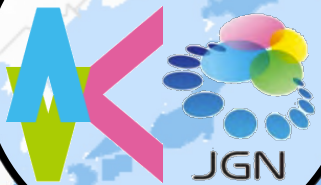
Ireland



Europe



Japan



US



New York

Brazil



Greece



COSM-IC: COSMOS
Interconnecting Continents