# Report on U.S. Resources and Capabilities for Accelerating Open RAN


*Open Radio Access Network Advisory Group*

*National Spectrum Consortium*


*February 2023*

national spectrum consortium®

# TABLE OF CONTENTS

# Report on U.S. Resources and Capabilities for Accelerating Open RAN

## OVERVIEW

The United States federal government and commercial wireless industry have prioritized the development and deployment of Open Radio Access Networks (Open RAN). These networks have the potential to bolster U.S. leadership in wireless technology, a key component of nearly every new modern infrastructure, security, and defense system under development today.

As stated in the recently issued Request For Comments issued by the National Telecommunications and Information Administration (NTIA):

> *With the passage of the CHIPS and Science Act of 2022, Congress has taken a proactive step in driving the adoption of open, interoperable, and standards-based RAN and supporting a more competitive and diverse telecommunications supply chain. This historic $1.5 billion investment aims to support U.S. leadership in the global telecommunications ecosystem, foster competition, lower costs for consumers and network operators, and strengthen our supply chain. Today's fifth generation wireless technology (known as "5G") infrastructure market is highly consolidated, with a small group of vendors making up the majority of the marketplace. This lack of competition can reduce supply chain resilience and security, contribute to higher prices, make it challenging for new, innovative U.S. companies to break into the market, and ultimately will exacerbate the digital divide. Additionally, certain equipment and services produced or provided by particular vendors in this marketplace have been deemed to pose an unacceptable risk to the national security of the United States.*

Given the urgency and sizeable investment behind Open RAN, the National Spectrum Consortium (NSC) – working with its partners in the Department of Defense (DOD) – established an Open RAN Advisory Group to provide recommendations on programs and policies that might accelerate the development of a robust, US-based wireless networking ecosystem.

Despite a number of successful ongoing Open RAN deployments worldwide, the Open RAN ecosystem is still under development. To unlock the full potential of Open RAN for 5G, Beyond 5G, and 6G, additional resources are needed to make it easier for more players (e.g., equipment suppliers, network integrators) to participate in both basic and applied research and development, and to deliver innovations that meet the greatest challenges of next-generation wireless connectivity.

In this report, the Advisory Group seeks to outline, according to NSC members, current requirements for Open RAN test and integration facilities to grow and scale the ecosystem in the U.S. In addition, the Advisory Group undertook an effort to catalog currently existing domestic resources available for accelerating Open RAN development. **Open RAN technology is not the same as 5G technology, and it has specific requirements for ensuring interoperability with both new and existing network systems (greenfield and brownfield network deployments respectively).**

Today in the U.S., numerous labs and testbeds support wireless testing and research. However, network operators and the research and development community (industry-, university-, and government-led) are vocal about their concern that few of these facilities – outside of closed vendor and Mobile Network Operator (MNO) labs – can perform end-to-end Open RAN testing to ensure interoperability and performance. Further, they note that most Open RAN test and development platforms today are not accessible to non-traditional telecom technology providers, and those that are broadly available, are under-resourced.

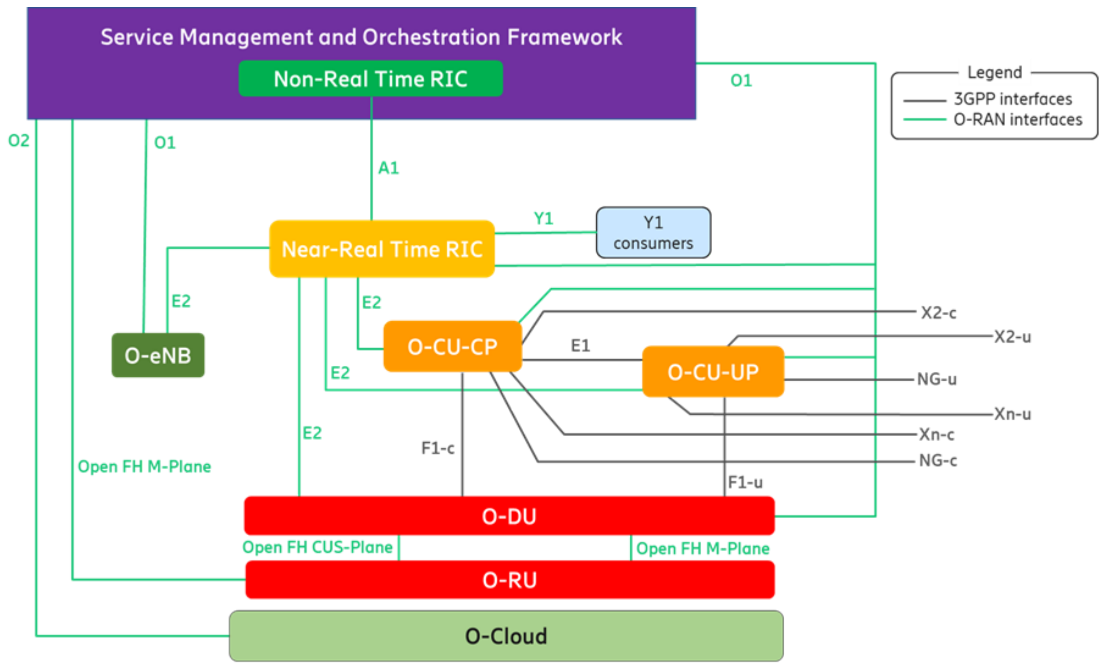
In this report, we present the results of a study by the NSC Advisory Group on facilities across the US with the ability to deliver some of the testing, development, and prototyping resources needed for Open RAN. The process of our study involved several steps:

1. Gathering input from the government, industry, and academic wireless communities on the types of resources needed for accelerating Open RAN development and deployment
2. Identifying the Open RAN capabilities at existing research facilities in the U.S. through surveys and interviews
3. Analyzing and articulating the gaps between what is needed and what existing facilities can provide to accelerate Open RAN efforts

Our findings suggest there is a solid foundation for continued Open RAN development, and for facilitating Open RAN technologies so they can be adopted into commercial networks. **However, as many have stated, not everything needed to accelerate Open RAN is available today, and of those resources that are available, many are not accessible to smaller technology companies and the broader research and innovation community**.

If the federal government truly has the goals of "supporting a more competitive and diverse telecommunications supply chain…[and]…fostering competition," then we must address known technical and accessibility gaps in the development of open networking technologies as quickly as possible. Only by solving these resource challenges can we take full advantage of Open RAN to diversify the telecom supply chain and expand our telecom innovation ecosystem.

*Figure 1.1. Logical Architecture of O-RAN as defined in [documentation by the O-RAN Software Community (OSC)]() – The Open RAN initiatives are designed to create supplier diversity, unlock innovation, and transform the RAN technology landscape from closed purpose build appliances to COTS server-based agile systems that evolve at the speed of software.*




## TYPES OF OPEN RAN TESTING AND DEVELOPMENT NEEDED

There are two major categories of Open RAN research and testing support needed by the wireless community. The first primarily involves commercial hardware and software with at least open interfaces, while the second emphasizes programmable architectures that include both open interface and open source software, or other configurable reference software – usually non-commercial.

In the first category, research teams or companies are primarily seeking to address questions of interoperability and performance parity. For example, users may need to test new radio units (RUs) supporting the O-RAN fronthaul interface specification with central units (CUs) and distributed units (DUs) from different companies. They may also need to test and quantify the performance of new Open RAN solutions against traditional network implementations.

To meet these requirements, a testing platform must be able to offer on-demand access to an end-to-end network infrastructure with commercial equipment including components that can be swapped in and out. It must: maintain multiple commercial mobile cores, CUs, DUs, and RUs; offer emulation and simulation capabilities; maintain critical network testing equipment (including Open RAN specific testing capabilities); and offer support for over-the-air network testing in a range of frequency bands.

In addition, facilities for Open RAN interoperability and performance testing must have sufficient physical space, expert personnel in the relevant technologies and applicable specifications and international standards, and the operational processes needed to support external users – including their security and intellectual property protection requirements – at scale.

In the second category of Open RAN testing and development, researchers are primarily aiming to experiment with and innovate on more advanced network features enabled specifically by open and virtualized systems. A user, for example, may want to develop a new solution for dynamic spectrum sharing, evaluate Open RAN and 3GPP security standards for gaps and research improvements, or test the effectiveness of automated network resource allocation across a variety of environments and scenarios.

Facilities supporting this level of advanced research and development must have the ability to offer on-demand access to an end-to-end, fully programmable network infrastructure with reference systems that researchers can extend and build upon. Supporting these advanced science, technology, and innovation efforts requires full configurability and visibility.

They must: maintain open source mobile cores, open interface and open source virtualized CUs, virtualized DUs, and real and emulated RUs with software-defined radios where applicable; provide open source Open RAN Radio Intelligent Controller (RIC) implementations; offer access to open interface and open source mobility stacks for RAN operation; offer emulation and simulation capabilities; support advanced massive multiple input and multiple output (MIMO) developments; maintain critical network testing equipment; and offer support for over-the-air network testing in a range of representative frequency bands.

Like the first category of testing platforms, facilities in this second category must also have sufficient physical space, expert personnel, and the operational processes needed to support external users – including their security and intellectual property protection requirements – at scale. Additionally, they must be able to provide support and low-cost access to smaller companies and research teams.

## OPEN RAN TESTING AND DEVELOPMENT RESOURCES AVAILABLE IN THE U.S.

The NSC Advisory Group gathered detailed information on more than 20 organizations offering or proposing to offer research and testbed facilities for Open RAN development. Information on these facilities is compiled in organizational profiles at the end of this report. Broadly, however, the organizations break down into several categories:

1. Independent organizations with facilities that can support commercial Open RAN testing
2. Facilities designed for advanced Open RAN research and development
3. Wireless carriers with Open RAN resources and expertise, as well as broad partnership reach
4. Technology solution providers with internal labs focused largely on their own commercial objectives
5. Advanced research labs with resources that could be dedicated to Open RAN research and development by agreement if interests and goals are aligned

Some organizations fall into multiple categories, and the individual profiles included in the addendum of this report provide information about the specific resources and services they offer. However, we can generalize about what facilities exist to meet different Open RAN needs, as well as who has access and under what conditions.

*Figure 1.2 Facilities for Open RAN Testing and Development Listed by Type*

| Facilities with commercial testing services | University and other research labs and testbeds (non-operator) | Operator research labs and testbeds | Vendor labs and testbeds | Government labs and testbeds |
|---|---|---|---|---|
| • CableLabs/Kyrio<br>• COSMOS<br>• UNH IOL<br>• POWDER<br>• TIP Menlo Park<br>• Booz Allen<br>• MITRE<br>• LinQuest | • POWDER<br>• COSMOS<br>• Northeastern<br>• Virginia Tech<br>• Texas A&M<br>• CableLabs<br>• TIP Menlo Park<br>• AERPAW<br>• ARA (launching spring 2023) | • AT&T<br>• Verizon<br>• DISH<br>• T-Mobile | Many examples including: Dell, NEC, Fujitsu, Viavi, Keysight, Spirent, etc. | • Pacific Northwest National Lab (PNNL)<br>• NIST Communications Technology Lab (CTL)<br>• Idaho National Lab (INL) |

### 1. Facilities with Commercial Testing Services

*Organizations referenced in this category: CableLabs/Kyrio, COSMOS, University of New Hampshire Interoperability Lab, POWDER, TIP Community Lab in Menlo Park, Booz Allen Hamilton testbed, MITRE lab, LinQuest lab*

There are facilities outside of internal company labs with the ability to do commercial Open RAN interoperability and performance testing in the U.S., but in their current form, they cannot provide the complete assurance network operators need for commercial deployments of new Open RAN technology.

To start, there are facilities that have been designated as Open Test and Integration Centers (OTICs) by the O-RAN Alliance. The O-RAN Alliance does not encompass all aspects of Open RAN, but it does focus on creating specifications to enable open interfaces, and thus more virtualized, and interoperable networks. A lab run by Kyrio, the for-profit subsidiary of CableLabs, was named the first OTIC in North America in August of 2022. The COSMOS testbed in New York City – which is run by an academic team from Rutgers University, Columbia University, and New York University Brooklyn – was named the second in the region in early December 2022 under the sponsorship of AT&T and DISH.

An OTIC is defined as providing "a collaborative, open, and impartial working environment," with the goal of being able to support conformance and interoperability testing for O-RAN Alliance members. The initial North American OTICs have recently hosted O-RAN plugfests and proof-of-concept (PoC) demonstrations, but these tests and demos largely require customized set-ups each time they are run, and funding limits what equipment, processes, and personnel these facilities can dedicate toward those efforts and maintain on an ongoing basis. Importantly, these OTICs have also not yet certified Open RAN solutions as meeting commercial-grade performance and interoperability requirements in end-to-end testing.

Two other academic research sites have hosted O-RAN plugfests and PoC demos as well. They include the nonprofit University of New Hampshire Interoperability Lab (UNH-IOL), and the POWDER testbed at the University of Utah. UNH-IOL and POWDER have very different strengths. UNH-IOL has decades of experience supporting paying external customers with conformance and performance testing, but it has not directed many of its efforts specifically toward Open RAN. The facility largely relies on outside users to bring in their own hardware and software for use with the lab's computing and test resources.

POWDER has developed some unique resources and services that will support Open RAN testing needs – including remotely accessible outdoor network infrastructure – but it has a small operational team. The academic setting, while open to a wide array of users not associated with the traditional industry ecosystem, is also very unlike a commercial research facility, and POWDER is still in the early stages of implementing a paid usage model. Hands-on engineering support for experimenters is limited.

Outside of the academic sphere, a handful of additional facilities are also paving the way for Open RAN interoperability and performance testing. The most well-known of these is the TIP Community Lab in Menlo Park, California. The O-RAN Alliance officially recognizes test results performed in TIP Community Labs, and aside from CableLabs (also a TIP Community Lab), the Menlo Park facility is the one other TIP site in the US that has hosted O-RAN plugfests.

Beyond plugfests, projects at the Menlo Park site are funded by the companies involved, with TIP providing lab space, equipment, and support funded by Meta.

Also notable are the Booz Allen Hamilton 5G testbed in Maryland, MITRE 5G labs, and the LinQuest lab. The Booz Allen Hamilton facility is developing an inventory of commercial network components from different vendors and has begun exploring Open RAN testing with a focus on the security of O-RAN interfaces. MITRE is partnering with multiple other organizations and facilities, and has O-RAN interoperability testing (although not certification) as one of its focus areas. LinQuest is primarily focused on the national security sector, but is also assembling a collection of network components from multiple vendors and has equipment for compliance, interoperability, security, and performance/stress testing.

## 2. University and Other Research Labs and Testbeds

*Organizations referenced in this category: POWDER, COSMOS, Northeastern University/Colosseum, Virginia Tech, Texas A&M University, University of Maryland 5G Security Testbed, CableLabs/Kyrio, TIP lab in Menlo Park*

Many companies in the wireless industry have their own labs and testbeds for Open RAN research, but the work supported at these facilities is primarily (and rightly) motivated by individual corporate objectives. These sites are also difficult for startups and other small or non-traditional network engineers and developers to access.

Additionally, there are numerous 5G testbeds across the U.S., including the testbeds designated by the Department of Defense at select military bases beginning in 2020. However, these testbeds leverage traditional commercial network components for application-driven research. They were not designed as networking testbeds, but instead were built with the goal of testing specific network-enabled use cases (e.g., smarter warehousing technology). They are not broadly capable of supporting advanced Open RAN research, which requires an open, flexible, and fully configurable environment.

The U.S. facilities that are tailored for advanced Open RAN research overwhelmingly exist at academic institutions. These test environments have the advantage of being both flexible and accessible, but they often have limited operational capacity for serving customers with distinct support requirements. Different university facilities also have different areas of focus within Open RAN and are at different stages of development and deployment. All need additional funding to support research efforts that are not directly sponsored by individual companies.

Three university test sites primed for further Open RAN research – POWDER, COSMOS, and the research facilities at Northeastern University in the Boston area – are part of the Platforms for Advanced Wireless Research (PAWR) program. The PAWR program, which was originally created and funded by the National Science Foundation and a consortium of industry partners, was specifically designed to provide shared, open network infrastructure as a way of driving wireless research and innovation.

POWDER and COSMOS offer end-to-end programmable network infrastructure with significant computing and software resources. They have varying indoor and outdoor network assets and varying experience supporting Open RAN research initiatives.

Northeastern University's main wireless research facility is Colosseum, a gigantic RF emulator running on an Open RAN framework. Colosseum supports sophisticated network modeling and can be used to test Open RAN features and functions before they are transported to a live network.

Outside of the PAWR program, Virginia Tech – through the Commonwealth Cyber Initiative – and Texas A&M University are building their own flexible test network environments. While many of the physical components of these facilities are still being deployed, the teams running them have already acquired the assets needed for deployment. Equally if not more importantly, they have significant university system support and expertise in open networking that exists in few other places around the country.

There is also the University of Maryland, which has a research lab focused on 5G security issues operating at the direction of a consortium including the trade association CTIA, Ericsson, MITRE, SecureG, AT&T, T-Mobile, and US Cellular. While external users are not supported today, the goal is to expand access in the future to continue to advance research into wireless security issues. There are potential implications for Open RAN development, although currently, the lab runs with more traditional commercial radio systems.

Beyond the university ecosystem, both CableLabs and the TIP lab at Menlo Park are supporting advanced Open RAN research. Like the other facilities in this category, these research labs have a variety of networking, computing, and software resources suited for Open RAN development, and expert researchers on staff. CableLabs, however, was built up and is still heavily influenced by the interests of its cable industry members, and the TIP lab in Menlo Park is sponsored by Meta.

Importantly for CableLabs, industry projects that do not fit the conditions for internal funding are routed through its wholly owned commercial subsidiary, Kyrio. Kyrio maintains greater flexibility in its customer engagements, and, as stated above, the Kyrio lab has also been certified by the O-RAN Alliance as an Open Test and Integration Center (OTIC).

### 3. Operator Labs and Testbeds

*Organizations referenced in this category: AT&T, Verizon, DISH, T-Mobile*

All U.S. wireless carriers operate labs and other test facilities that are geared toward commercial product development and the testing and integration of new technologies – including value-added applications – that can be deployed in their own networks. To varying degrees, U.S. carriers also support research to benefit the wireless community at large, whether through participation in organizations like the O-RAN Alliance, or through partnerships with academic researchers and some smaller companies that can demonstrate the potential value of their technology innovations.

There is some interest from carriers in opening up their research facilities more broadly and providing services to support external users testing Open RAN solutions. DISH, which has started commercial deployments that include Open RAN technologies – and has a vested interest in seeing the establishment of a robust U.S.-based Open RAN ecosystem – has specific plans to move in this direction in 2023.

DISH intends to offer access to its test and integration facilities to academic and small-company innovators and is currently seeking partnerships with universities, suppliers, and other researchers developing Open RAN solutions. The company is focused on establishing low-cost, “bite-sized” testbed access rules with a permanent staff of test professionals who can assist small companies and academic groups.

Outside of DISH’s plans, no wireless operator is currently establishing a formal policy or process for onboarding and supporting external users at their lab and testbed sites. Additional funding could shift their efforts, but this is not the business they are in today. AT&T, for example, has partnered with DISH to co-sponsor COSMOS from the NSF PAWR program as one of the OTIC facilities in the US rather than creating an Open Testing and Integration Center on its own.

The operators, however, are an integral part of accelerating Open RAN adoption and deployment. They are a driving force behind the open networking movement, network standards development, and Open RAN plugfests and proof-of-concept demonstrations. Their participation in directing Open RAN development – and specifically enabling a larger innovation ecosystem and more diverse supply chain – is critical.

In particular, the carriers have three important assets: vast expertise (including leadership in the O-RAN Alliance and other wireless innovation organizations), partnership reach, and spectrum holdings. Details on those assets from AT&T and Verizon are available in the profiles at the end of this report. Although T-Mobile did not participate in this exercise, the company's status in the commercial wireless market, and publicly available information on its research activities and facilities, suggest the carrier occupies a similar position to the other national carriers.

## 4. Vendor Labs and Testbeds

Vendor companies in the telecom industry invest significant money in their own research and development. However, as with the wireless carriers – and in many cases even more so – their efforts are directed toward commercial product development along with testing to ensure successful integration with partner solutions. Dell, for example, does some research collaboration with academic institutions, but the company primarily uses its own facilities to demonstrate how Dell platforms conform to the functional and performance requirements of network operators. Fujitsu, meanwhile, builds and demonstrates different Open RAN use cases for enterprise, government, and industrial applications through its multi-vendor Mobile Integration and Testing Center.

Several companies have said on and off the record that they are considering opening their labs to external users, but those plans have not yet been realized, and some companies would only pursue those efforts in limited form if government funding became available.

Because this report was designed to provide information on resources available to a broad base of users, very few vendor companies shared detailed information on their capabilities. This does not mean, however, that vendor companies do not have resources to support further Open RAN development. Many telecom technology providers could support testing, prototyping, and deployments to prove Open RAN capabilities at scale if the government chose to fund projects with those objectives. Where they are less likely to step in is where more fundamental research still needs to take place. These companies are primarily motivated to make their own products succeed, and not to expand the competitive field by supporting the research and development work of startups and academic researchers.

An exception may be the test environment vendors such as Viavi, Keysight, and Spirent. These vendors are presently working with multiple Open RAN technology providers both in the test vendors' labs and in the providers' labs to support Open RAN solution development and evaluation.

### 5. Government Labs and Testbeds

*Organizations referenced in this category: NIST 5G Communications Technology Lab (CTL), Pacific Northwest National Laboratory (PNNL), Idaho National Laboratory (INL)*

As a counterpoint to technology labs run by commercial companies, there are a number of national labs specifically dedicated to advanced research, and to furthering the aims of federal government departments and agencies. These facilities do not focus on product development, but rather on advancing a particular field of study in ways that complement the efforts of the private sector.

The national labs profiled in this report include the NIST 5G Communications Technology Lab (CTL), Pacific Northwest National Laboratory (PNNL), and Idaho National Laboratory (INL). The NIST lab acts as the research arm of the Department of Commerce and has ongoing research directed at making it easier for network operators to adopt Open RAN technologies. However, that focus does not include any kind of product or ongoing compliance testing. Instead, the NIST lab is interested in activities such as developing new tools to enable conformance testing that could then be handed over to the commercial sector.

PNNL is likewise only geared toward cutting-edge research, rather than direct support of commercial products. It is focused on advancements in 5G and 5G applications research with an emphasis on Department of Energy (DOE)/commercial use cases. There is no specific emphasis on Open RAN.

Finally, INL specializes in advanced research projects with high-security requirements. Telecommunications research in the lab falls under the INL Wireless Security Institute and is focused on 5G device and network security research with an emphasis on identifying, validating, and reporting on 3GPP protocols themselves.

All of the national labs are generally not open to the public, but they do conduct sponsored research and commercial collaborations. Resources can be made available by agreement, particularly if there is government interest and a national need.

## OPEN RAN RESEARCH AND TESTING GAPS

As stated previously, there are two major categories of Open RAN research and testing support needed by the wireless community: Open RAN interoperability and performance parity testing to speed commercial deployments, and advanced Open RAN research and development to accelerate innovation and significantly expand the telecom supplier ecosystem.

The facilities examined in this report can be divided along those categories as shown in the chart below. However, it is critical to point out that there are still serious limitations in how these labs and testbeds can be used by researchers, and in how much support they can offer.

In Category A, for example, there are no facilities currently offering Open RAN certification. This is partly because while there is a formalized test specification for the open fronthaul interface today, specifications and standards for additional Open RAN components still need to be established. It is also partly because all of the facilities cited need more Open RAN-specific testing expertise and Open RAN-specific testing equipment. In Category B, different types of research are supported at different facilities, and at different levels of comprehensiveness and accessibility.

*Figure 1.3 Research Facilities Listed by R&D Category – Varying Levels of Access Offered to External Users*

<table>
<tr><th>CATEGORY A<br>Open RAN interoperability and performance parity testing</th><th>CATEGORY B<br>Advanced Open RAN research and development</th></tr>
<tr><td>Supports Open RAN interop and performance testing:<br>● CableLabs/Kyrio – OTIC<br>● COSMOS, NSF PAWR Testbed – sponsored as an OTIC by AT&T and DISH<br>● TIP Menlo Park</td><td rowspan="3">● AERPAW, NSF PAWR testbed<br>● Booz Allen<br>● CableLabs/Kyrio – OTIC<br>● COSMOS, NSF PAWR testbed – sponsored as an OTIC by AT&T and DISH<br>● Idaho National Lab (INL)<br>● LinQuest Lab<br>● MITRE (w/UMD ARLIS and Northeastern University, security focus)<br>● NIST Communications Technology Lab (CTL)<br>● Northeastern University<br>● Pacific Northwest National Lab (PPNL)<br>● POWDER, NSF PAWR testbed<br>● Texas A&M testbed<br>● TIP Menlo Park<br>● Virginia Tech CCI xG testbed<br><br>*ARA, NSF PAWR testbed, scheduled to launch in spring of 2023</td></tr>
<tr><td>Supports network interop and performance testing and could extend into specific Open RAN compliance:<br>● UNH IOL<br>● Booz Allen<br>● LinQuest Lab<br>● MITRE (w/UMD ARLIS and Northeastern University, security focus)<br>● Texas A&M</td></tr>
<tr><td>Specializes in Open RAN and could extend into Open RAN interop and performance testing:<br>● POWDER, NSF PAWR Testbed<br>● Virginia Tech CCI xG testbed</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Operator research facilities – AT&T, DISH, T-Mobile, Verizon<br>Wireless operators drive a significant amount of Open RAN development activities, and their various facilities can and are used to support both testing and research efforts. Outside of DISH, however, no wireless operator is currently establishing a formal policy or process for onboarding and supporting external users at their lab and testbed sites – and DISH is still in the planning phase. Operators more often partner with outside test facilities for broad testing and research activities, as evidenced by AT&T's and Verizon's use of partner labs to host Open RAN Plugfests and POC fests.</td></tr>
</table>

There are a couple of broad and important areas where Open RAN research and development (R&D) gaps exist. First, most of the facilities working on Open RAN in the U.S. and serving external users need additional personnel. There is a significant need for more researchers with RF and network computing expertise; personnel with extensive wireless telecommunications, science, technology, and standards/specifications development experience; and engineers that can support system operations at Open RAN labs and testbeds.

Very few of the facilities cited above have the human resources to take equipment and/or software and a test case from numerous external, third-party users and run experiments on their behalf. If the goal is to enable small-to-medium-sized companies and academic innovators to demonstrate new Open RAN technology and concepts at scale, then more support is needed to configure experiments and troubleshoot operations.

Second, many facilities rely on or plan to rely on revenue from users, and some also require that those users bring in their own project-specific equipment and software, which can be expensive. The inherent cost of test equipment and environments is a critical barrier to entry for new, small U.S. companies entering the Open RAN marketplace. Reducing usage costs will be necessary to address the accessibility challenges.

Beyond personnel, and the issue of usage costs, this report identifies specific gaps in the current R&D ecosystem for the two types of testing and development required to accelerate Open RAN.

For interoperability and performance testing, the wireless community needs facilities with a wide mix of commercial equipment (traditional RAN and Open RAN) and software available **on demand**. It is not enough for labs to work with partners to set up the configuration of hardware and software needed just for a one-time, pre-planned plugfest. These components must be acquired, installed, and maintained for ongoing usage. This includes commercial mobile cores; service management orchestration and non-real-time RIC capabilities; near-real-time RICs; CUs, DUs and open RUs; user endpoints; and specific Open RAN network testing equipment. Many facilities have a subset of what is needed, but not everything that is required end to end. Furthermore, no facility listed has the necessary volume and diversity of solutions to support wide-scale testing and experimentation.

In addition, the wireless community needs the ability to test commercial solutions with actual over-the-air data transmissions in a real-world environment. This includes the availability of outdoor and indoor spaces and access to spectrum. Unfortunately, spectrum access is limited in most cases to FCC experimental program licenses and special temporary authority (STA) licenses; both of which come with significant constraints. STAs are temporary, and though experimental program licenses cover longer periods of time, they, many times, only allow low-power transmissions in a controlled environment. Not all spectrum bands are accessible with these licenses (C-Band frequencies, for example, are not accessible), and access that is granted can be revoked when the spectrum owner believes there could be interference with their own operations.

For advanced feature research and development, the wireless community needs facilities with at-scale *open architectures* available **on demand**. A few sites with open architectures that are broadly available to external users do exist. That said – even more than is the case with commercial testbeds – the current breadth and scale of these facilities are still severely limited.

Like their commercial counterparts, open architecture facilities need end-to-end test environments, but with open, programmable versions of the necessary network components. This includes open source mobile cores; service management orchestration and non-real-time RIC capabilities; near-real-time RICs based on configurable open source implementations; CUs, DUs, and open RUs that are deployed across more than a few fixed nodes; user endpoints; and specific Open RAN network testing equipment. They also need to maintain stable yet fully reconfigurable open interfaces and open source mobility stacks, which require ongoing development and integration work to keep up with the state of the art.

Spectrum access is equally as much of a challenge for advanced Open RAN research facilities as it is for facilities supporting interoperability and performance testing. And in the case of critical emerging bands, even more so.

Advanced research facilities have some additional needs in the Open RAN space as well. For example, few resources are available today for advanced massive MIMO research, and for at-scale testing of artificial intelligence/machine learning (AI/ML) mechanisms that will add more intelligence and automation into network operations. These gaps must be addressed individually and as teamed, mutually-reinforcing efforts.

Further, meaningful effort should be encouraged toward rapid development of flexible operational structures for collaborative Open RAN research and testing facilities. Near-term opportunities should be sought to foster multi-lab virtual "collaboratory" approaches allowing flexible federation of facilities and processes across key industry, academic, and government labs.

*Figure 1.4 Availability of Open RAN Testing and Development Capabilities*

| **Capabilities Needed for Open RAN Testing and Development** | **Availability/Status** |
|---|---|
| Multiple and diverse range of commercial mobile cores, gNodeBs, CUs (hardware and software), DUs (hardware and software) | Does not exist at volume outside of internal company facilities |
| Multiple and diverse range of new commercial open RUs and programmable reference RUs | Does not exist at volume outside of internal company facilities |
| Open source mobile cores, CUs, DUs | Open source CUs, DUs still in development |
| SDRs with RF frontends supporting a range of frequency bands | Exists in a few places, outdoor deployment extremely limited |
| Programmable massive MIMO arrays | Extremely limited |
| Commercial and open source near-real-time RIC implementations | Limited availability |
| Access to non-real-time RIC platforms within SMO | Limited availability |
| UE devices – both commercial mobile devices with SIM cards and programmable modules supporting a range of frequency bands | Most facilities do not have diversity and volume |
| Open source mobility stacks that have been configured to work with software defined radios for over-the-air cellular research use | Limited proven deployments outside of a controlled lab |
| Massive computing power including edge compute capacity | Available in several places |
| Backhaul connectivity | Available in several places |
| Physical network components such as enclosures, cables, and mounting equipment | Available, but more always needed |
| Volume of test equipment to support Open RAN-specific testing | Does not exist at volume outside of internal company facilities |
| Simulation capabilities | Some availability |
| Channel emulation capabilities | Limited availability |
| Access to spectrum across a wide range of frequency bands | Does not exist outside of carriers |
| Physical space – indoors and outdoors | Available in several places |

| | |
|---|---|
| Significant number of expert personnel – advanced wireless technology, Open RAN conformance, operational support | Additional expert personnel needed nearly everywhere |
| Formal operational processes and other resources for on-boarding and supporting a broad pool of external users | Limited to a few facilities |

# *APPENDIX 1:* PROFILES OF U.S. OPEN RAN RESEARCH AND TESTING FACILITIES

The above report on U.S. resources and capabilities for accelerating Open RAN is based on information gathered through surveys and interviews with wireless testing and research organizations across the U.S. The NSC's Open RAN Advisory Group solicited recommendations from its members and the membership of the Open RAN Policy Coalition (ORPC) on which organizations to approach for the study with the guidance that facilities in the report should be available – at least to some degree – for external use by researchers across industry, government, and the academic community.

The collected results of the Advisory Group's efforts are detailed in the research facility profiles that follow. Each of the organizations – included here in alphabetical order – completed an online survey of capabilities and participated in an interview conducted by at least two Advisory Group members.

This report covers the Open RAN testing capabilities of:

- AERPAW, NSF PAWR Testbed
- ARA, NSF PAWR Testbed
- AT&T - Open RAN Testing Capabilities
- Booz Allen Hamilton 5G Testbed
- CableLabs and Kyrio
- COSMOS, NSF PAWR Testbed
- DISH - Open RAN Testing Capabilities
- Idaho National Laboratory
- LinQuest Testbed
- MITRE 5G Lab
- NIST Communications Technology Laboratory
- Pacific Northwest National Laboratory (PNNL)
- POWDER - Platform for Open Wireless Data-driven Experimental Research
- Texas A&M Testbed
- Telecom Infra Project (TIP) Lab
- University of Maryland (UMD) 5G Security Testbed
- University of New Hampshire Interoperability Lab (UNH-IOL)
- Verizon Boston Innovation Lab
- Virginia Tech Commonwealth Cyber Initiative (CCI) xG Testbed

**AERPAW, NSF PAWR Testbed**

Advanced Feature Research

The AERPAW testbed in North Carolina, part of the National Science Foundation-created Platforms for Advanced Wireless Research (PAWR) program, was created to study the convergence of wireless technology and autonomous drones. Today it largely supports internal researcher use and some research teams from other academic institutions. Support for more external use is planned, although the cost model is still being developed.

The AERPAW testbed includes an open network environment with software-defined radios (SDRs) and open-source software. However, Open RAN is not a main research focus today beyond basic graduate student work. With additional funding, AERPAW would assign permanent resources to work on Open RAN testing and development.

***Notable Characteristics***

- Outdoor network deployment – AERPAW has one fixed node with both SDR and commercial Ericsson equipment operational at its Lake Wheeler field site today. (Lake Wheeler is also where AERPAW has permission to fly drones.) Four additional nodes with SDR equipment will become available in spring 2023.

- AERPAW is operating in the 3.3-3.55 GHz band for 5G and 1.7/2.1 GHz band for LTE. This spectrum is available via FCC Innovation Zone license*. The Innovation Zone license acts like an FCC experimental program license, but with some added flexibility for external users of the testbed.

- **Experimental program licenses provide access to select spectrum bands to research institutions for low-power transmissions in a controlled environment. Access is not granted or is revoked when the spectrum owner believes there could be interference with their own operations.*

- Outdoor testbed use is strictly run by the operations staff of AERPAW and has automatic guardrails to control drones and prevent them from violating FAA regulations.

- Indoor resources/capabilities – The AERPAW development environment enables experimenters to simulate outdoor activities and run end-to-end simulations of their experiments. There is a 32-port Keysight Propsim available to simulate the RF environment. The AERPAW sandbox uses real hardware to move experiments from the development environment.

- Mobile core, gNodeB, and user endpoints (UEs) – Ericsson, OAI, Open5GS, srsRAN, and GNUradio are the primary building blocks available.

- Compute – Cloud access along with edge computing is available. The edge comes in two flavors ground-based (high function) and airborne (lower function due to battery power and weight limits)

***Capacity to Offer Services to External Users for Testing and Development***

- Engagement – Researchers contact AERPAW directly.
- Personnel – The staffing ranges from 5+ Senior Research Associates, 5+ graduate students, and 5+ undergraduate students, totaling up to 15+ people.
- Remote Access – Academic researchers can access cloud-based testbed resources remotely.

**ARA, NSF PAWR Testbed**

## Advanced Feature Research

The ARA testbed in Central Iowa is part of the National Science Foundation-created Platforms for Advanced Wireless Research (PAWR) program. The goal of the ARA platform is to provide a real-world at-scale living lab for research, education, and innovation in advanced wireless and its applications in rural industries and communities (e.g., agriculture automation, drone applications, and rural STEM education).

The ARA testbed will launch in spring 2023. While it will be available to external researchers, the cost model for industry use is still being defined. The ARA team plans to provide the software and hardware infrastructures needed for Open RAN research, education, and innovation.

***Notable Characteristics***

- Outdoor network deployment – The ARA testbed will launch with four fixed node locations and multiple user endpoint (UE) sites. Each node will include both commercial and SDR-based equipment. Spectrum is available at low-band (e.g., 470-806 MHz), mid-band (e.g., 3400-3600 MHz), and mmWave bands (e.g., 24.25-29.5 GHz) via FCC Innovation Zone license*. The Innovation Zone license acts like an FCC experimental program license, but with some added flexibility for external users of the testbed.

  **Experimental program licenses provide access to select spectrum bands to research institutions for low-power transmissions in a controlled environment. Access is not granted or is revoked when the spectrum owner believes there could be interference with their own operations.*

- Indoor network deployment – The ARA development environment will enable experimenters to emulate outdoor activities and run end-to-end emulations of their experiments. The ARA sandbox features DevOps platforms as well as an at-scale experimenter testbed with more than two dozen SDRs currently, and more than 50 planned for installment. These SDRs enable testing in an indoor setting before outdoor field testing and deployment.

- Mobile core, gNodeB, and user endpoints (UEs) – Skylark Wireless, Ericsson, OAI, srsRAN, and ONF mobile platforms are the primary building blocks available.

- Network Testing Equipment – ARA has Keysight Fieldfox, RF sensors, and signal generators.

- Compute – Edge and cloud access is available with both private edge clouds and large commercial clouds accessible from the infrastructure.

***Capacity to Offer Services to External Users for Testing and Development***

- Engagement – Researchers contact ARA directly.
- Personnel – ARA is supported by the Center for Wireless Communities and Innovation (WiCi) at Iowa State University. The Center has 20+ faculty members, 4+ research and administrative staff members, and 10+ Ph.D. students, as well as several Masters and undergraduate research assistants. The infrastructure is still under construction and expected to go online in spring 2023.
- Remote Access – Secure remote access for experimenters will be available.
- IP Protection – Non-disclosure agreements are supported.

**AT&T - Open RAN Testing Capabilities**

## Operator Research Facilities

AT&T operates several internal labs and testbeds and is open to partnering with universities, suppliers, and other researchers looking into Open RAN. It is not clear that there is currently an existing, well-defined policy for testbed access or research partnership, or a specific method for which a partner could apply for such access. However, outside of vendor testing for direct deployment on its own network, AT&T has: established intern programs; worked on no-cost collaborations with academics; and signed product evaluation agreements with some startups. Additional funding could help with creating a more standardized process for opening up AT&T testbeds and supporting new experimenters on a more formal basis.

While AT&T partners with academic institutions, the carrier's own facilities are generally not focused on Open RAN research for its own sake, but rather on commercial product development and integration.

AT&T's main assets for Open RAN testing and development are its talent pool, partnership reach, and spectrum holdings.

***Notable Characteristics***

- Indoor and Outdoor 5G testing facilities –
    - Middletown, New Jersey – Deployment of an indoor 5G private cellular network with technology from multiple vendors covering the network core, transport, and RAN. Includes anechoic chambers. There is also outdoor space for some radio testing. AT&T may create a private 5G network kit that can move from this New Jersey site to other locations including outdoor testbeds like COSMOS, which is an AT&T partner.
    - 5G Innovation Lab in Texas – Designed for internal use, the lab includes an Ericsson standalone core, small cells, DAS, and edge computing equipment. AT&T uses the facility to demonstrate proof of concept.
    - Oakton, Virginia Lab – Designed for network experimentation with DC universities and businesses, as well as the federal government.
    - Alpharetta, Georgia – Focus on virtual RAN experimentation with local 5G radio towers and Faraday cages. Remote cores located in Texas and elsewhere connect to the Alpharetta radio labs.
    - San Ramon, California – Software lab focused on automation and analytics that can be connected via the Internet to select testbeds.

    - Redmond, Washington – AT&T internal certification lab with sandbox capabilities that are occasionally used by other testbeds.
    - Mobile core, gNodeB, and user endpoints (UEs) – AT&T can offer NSA or SA, either 3GPP standard or pre-standard equipment.
- RIC, CU, and DU – Current AT&T implementations include ORAN-SC G-Release, ONF SDRAN 1.4.1, and fully commercial deployments.
- Network Testing Equipment – Available through partnerships with vendors.
- Channel emulation – AT&T has an 8-port channel emulation system.
- mMIMO – AT&T has some testing options available, but making them available on demand would require funding.
- Compute – Capacity available within one optical hop. AT&T also has edge computing capabilities and can provide connectivity to public cloud computing services.
- Satellite connectivity – In addition to fiber and wireless, satellite connectivity could be made available on-demand from AT&T with funding.

***Capacity to Offer Services to External Users for Testing and Development***

- Personnel – AT&T has a vast pool of engineering talent, including the original technical lead for the O-RAN Alliance orchestration framework concept born out of the Linux Foundation. However, AT&T's human resources are not heavily focused on serving external researchers/customers.
- Remote Access – Many of AT&T's testing resources can be made available over the Internet.
- Security and IP Protection – Any potential external partner would have to be qualified and would have to comply with AT&T Security Policy and Requirements (ASPR).
- O-RAN Alliance – Alliance member.
- Spectrum – AT&T could offer access to licensed spectrum, provided adequate safeguards and compliance are considered.

**Booz Allen Hamilton 5G Testbed**

Advanced Feature Research and potential for Interoperability and Performance Parity Testing

The Booz Allen Hamilton (BAH) 5G Testbed is based in Maryland and supports government and industry researchers with 5G research. It occupies 25,000 square feet of space and includes workstations plus one server room with racks to accommodate 78 servers. The team at the testbed is 100% dedicated to supporting external clients, with five members focused specifically on interoperability testing. However, the facility is not broadly open for public use.

Currently, the BAH team is working to enable multi-vendor components in the facility for Open RAN research, but they have not finalized a cost model for the testbed. Open RAN work to date has focused on securing O-RAN interfaces and orchestration systems. Additional funding could be used to support vendor-specific equipment purchases.

***Notable Characteristics***

- Outdoor capabilities – While there is no standing outdoor network at the facility, the team has experience obtaining spectrum access for outdoor testing through STA licenses from the FCC.

- Indoor deployment – The indoor testbed focuses on carrier-grade 5G network infrastructure and on generating data that can be used for security research. The team's main Open RAN efforts focus on securing O-RAN interfaces and orchestration systems.

  **Over-the-air network testing is available indoors across the b41, n78, n261, and b48 frequency bands.*

- Network Testing Equipment – The testbed includes network testing equipment from multiple vendors.

- Mobile cores – The testbed maintains Nokia mobile cores (NSA and SA), the open source Open5GC core, and 5G-In-A-Box from Amarisoft. There are ongoing challenges with integrating testbed components with these different cores.

- RIC, CU, DU, and RU – The BAH facility has CUs and DUs from JMA Wireless and Ericsson, but they are not publicly available. The team plans to support O-RAN-compliant CUs and DUs, as that technology matures, but they do not have those components or a RIC implemented today. The team did recently acquire an O-RAN-compliant commercial radio. They also maintain software-defined radios.

- AI/ML capabilities – The Booz Allen testbed focuses on AI/ML mechanisms for anomaly detection and mitigation. The team is currently working closely with a vendor for spectrum detection and sharing using AI/ML.

- Datasets – The facility has extensive modeling and simulation capabilities, and the BAH team uses datasets to generate network scenarios. However, these datasets are not public, and the majority come from clients when using the testbed.

- Compute – The testbed maintains compute capacity within one optical hop and provides edge compute capacity and connectivity to public cloud services.

***Capacity to Offer Services to External Users for Testing and Development***

- Personnel – The BAH team includes subject matter experts in telecom, RF, mission-specific use cases, DOD spectrum and wireless policy, and offensive and defensive cybersecurity. The testbed team is100% dedicated to supporting external clients, with five members focused specifically on interoperability testing.

- Remote access – Remote access to external partners is provided case by case based on agreement.

- Security and IP protection – The testbed provides physical security and data security. US Citizen and Non-US Citizen security processes are in place. The IT department has an internal system that regularly scans the overall testbed.

- O-RAN Alliance – Alliance contributor.

**CableLabs and Kyrio**

Advanced Feature Research and Interoperability and Performance Parity Testing

CableLabs, based in Louisville, Colorado, is a non-profit that supports the broad needs of the cable broadband industry. Their research is supported by funding from their member companies. For research projects that are deemed to have value for the whole membership, CableLabs will fund or secure outside funding and conduct the research projects themselves. Industry projects that do not fit the conditions of "for the good of the industry" are routed through their commercial entity, Kyrio. Kyrio's lab has been certified by the O-RAN Alliance as an Open Test and Integration Center (OTIC).

The team and available resources of CableLabs are largely geared toward research and development of advanced capabilities required for member companies' wired and wireless infrastructure. This includes all the components of an Open RAN architecture (CU, DU, RU, and RIC). Present RIC support is non-real-time with near-real-time to be added soon.

The Kyrio OTIC lab, however, supports specific Open RAN conformance and interoperability testing. Although CableLabs and Kyrio share a base of personnel, space, and equipment, their missions and funding structures differ.

***Notable Characteristics***

- Outdoor network deployment – CableLabs has FCC experimental and Special Temporary Authority (STA) licenses in place for low-, mid-, and high-band FR1 spectrum, and can support FR2 (mmWave). They have radios and antennas available that support these bands, and they are well-resourced for conducting outdoor research where signal propagation encounters all the impairments present in the real world.

- Indoor network deployment – The indoor test capabilities include dedicated workbenches and lab facilities for each project. Anechoic chambers are available for RF testing.

- Mobile core, gNodeB, and user endpoints (UEs) – CableLabs offers access to mobile cores and has both Viavi and Keysight infrastructure in-house to emulate system and traffic at standards-based interfaces.

- Network testing equipment – The testbed includes network test and emulation equipment from numerous vendors including Viavi and Keysight.

- RIC, CU, and DU – Numerous vendors and open-source products are available for inclusion in testing. All the available spectrum can be used with CableLabs-owned RU(s), or the client can provide the necessary RU(s). Bare metal servers are also available to install CU, DU, or RIC/App software on.

- Multi-dimensional test capabilities – Can conduct R&D, Compliance (3GPP, ETSI, O-RAN, etc), Interoperability, Security, and Performance/stress testing.

- Compute – CableLabs maintains compute capacity within an optical hop and provides edge compute capacity.

- Test and certification expertise:
    - O-RAN Alliance Certification.
    - O-RAN OTIC (Open Testing and Integration Center) Lab - first OTIC lab in the Americas.
    - CTIA Wi-Fi TRP/TIS.
    - Open Wi-Fi TIP Community Lab.
    - TIP non-ideal FH Lab.
    - ISO-17025 Certification – enables labs to demonstrate they operate competently and generate valid results, thereby promoting confidence in their work.

***Capacity to Offer Services to External Users for Testing and Development***

- Engagement – Well-defined processes and contracting vehicles are available. CableLabs structures reply  to service requests with detailed SOWs, scheduling, roles and responsibilities, deliverables, and costs.

- Personnel – The staffing ranges from Ph.D. researchers to test engineers, totaling up to 200+ people.

- Remote Access – Resources and services are remotely accessible.

- Security – Unique capabilities exist to view and inspect network communications between system components for testing for standard cybersecurity measures, as well as the ability to analyze both source code and compiled binary executables for various types of cybersecurity weaknesses. These capabilities allow the team to assess the composition, security posture, and potential vulnerabilities in system components.

- IP Protection – CableLabs is vendor agnostic and not looking to gain from others' IPs. Non-disclosure agreements can be put in place as needed. Note that CableLabs-conducted research is assumed to be widely distributed to the member companies as a benefit of their membership.

- O-RAN Alliance – CableLabs is an O-RAN Alliance contributor and designated by the Alliance as an Open Test and Integration Center (OTIC).

**COSMOS, NSF PAWR Testbed**

Advanced Feature Research and Interoperability and Performance Parity Testing

The COSMOS testbed, part of the National Science Foundation-created Platforms for Advanced Wireless Research (PAWR) program, covers sites across Rutgers University in New Jersey, Columbia University in West Harlem, and New York University Brooklyn. COSMOS supports academic researchers and researchers from the commercial wireless industry with funding from both research grants and industry users. It has been certified by the O-RAN Alliance as an Open Test and Integration Center (OTIC) under the sponsorship of AT&T and DISH. The price for using the testbed is determined based on the engineering support labor required.

Academic researchers can access select testbed resources remotely and conduct experiments without COSMOS team involvement. This includes software, computing, and radio resources indoors, and two outdoor radio nodes also connected to software and computing resources. COSMOS has also implemented a near-real-time RIC and virtualized CUs and DUs for use by O-RAN Alliance members, as well as AI/ML scenarios and tutorials for advanced research and development.

To scale its operations, COSMOS would need to recruit additional personnel, which presents challenges both with funding and finding people with the right expertise. Additional funding could also be used to support additional equipment rentals. COSMOS currently buys about 30% of its equipment and rents about 70%. Some equipment can be borrowed from AT&T as an OTIC co-host.

***Notable Characteristics***

- Outdoor network deployment – COSMOS has made one large outdoor node and one medium outdoor node available to users in West Harlem. These nodes use software-defined radios and open-source software. Additional outdoor nodes are under construction.

- Access to spectrum is available via FCC experimental program licenses* and the designation of the COSMOS site in West Harlem as an FCC Innovation Zone. The Innovation Zone designation covers numerous frequency bands and acts like an FCC experimental program license, but with some added flexibility for external users of the testbed.

  **Experimental program licenses provide access to select spectrum bands to research institutions for low-power transmissions in a controlled environment. Access is not granted or is revoked when the spectrum owner believes there could be interference with their own operations.*

- Indoor deployment – The indoor facilities associated with COSMOS cover 27,000 square feet of space. That space includes an interior lab with shielded space that acts like an anechoic chamber, a region of open floor space measuring 25 meters by 20 meters, a small mechanical engineering lab, an additional larger engineering lab, a server room, and available cubicles.

- COSMOS maintains commercial equipment from numerous vendors.

- Mobile core, CU, DU – The COSMOS team maintains multiple open-source and commercial mobile cores, both 5G NSA and SA. COSMOS also offers a virtualized CU and DU for Open RAN testing.

- Fronthaul interface – COSMOS supports fiber and wireless fronthaul interface testing with the ability to programmatically inject delay and attenuation.

- RIC and end-to-end testing – COSMOS supports testing from the ONAP/O-RAN-SC service management orchestrator to multiple near-real-time RIC implementations.

- Network testing equipment – COSMOS has optical power meters, optical spectrum analyzers, and network analyzers.

- AL/ML capabilities – All COSMOS servers have GPUs and FPGAs, and all have tutorial AI/ML implementations. COSMOS also has datasets for training AI/ML models.

- Emulation capabilities – COSMOS maintains a channel emulation system with eight ports.

- Massive MIMO – COSMOS offers four 16 TX/16 RX antenna arrays connected to 16 software-defined radios in its indoor facility.

- Compute – Compute capacity from less than a microsecond to millisecond to 100s of milliseconds is available. COSMOS also provides access to public cloud computing services.

***Capacity to Offer Services to External Users for Testing and Development***

- Personnel – COSMOS currently has four staff members with testing expertise to support the testbed's new status as an OTIC, and the team is hoping to hire additional personnel.

- Remote access – Academic researchers can access select testbed resources remotely and conduct experiments without COSMOS team involvement. This includes software, computing, and radio resources indoors, and two outdoor radio nodes also connected to software and computing resources.

- Security and IP protection – COSMOS signs non-disclosure agreements as needed and has implemented numerous security measures as required by the O-RAN Alliance for OTIC certification. Remote-access services are access-segregated at various levels.

- O-RAN Alliance – Designated as an Open Test and Integration Center (OTIC) by the O-RAN Alliance, and sponsored as an OTIC by AT&T and DISH.

**DISH - Open RAN Testing Capabilities**

## Operator Research Facilities

DISH has built an extensive internal test facility in service of its nationwide buildout of an Open RAN-enabled 5G network. Not only is DISH interested in testing interoperability among its own existing and future vendors, but DISH also has a vested interest in seeing the establishment of a robust US-based Open RAN ecosystem. DISH has always intended to open up its test and integration facilities to academic and small-company innovators as a part of this effort, and DISH is currently seeking partnerships with universities, suppliers, and other researchers developing Open RAN solutions. It has developed and begun to offer an elastic lab construct for testing and configuring network solutions, and it has plans to scale up this offering significantly.

There does not yet exist a well-defined policy or set of business rules for testbed access or research partnerships at DISH, or a specific method for which a partner could apply for such access. However, DISH is seeking input from the NSC and its members on how to design those policies and business rules. DISH is also designing a digital front-end to enable scalable and on-demand use of lab resources by companies of all sizes.

DISH is focused on establishing low-cost, "bite-sized" testbed access rules with a permanent staff of test professionals who can assist small companies and academic groups. DISH intends to create a transparent payment structure with "cloud-like" incremental fees. DISH would be open to possible subsidies or other incentives to ensure that smaller companies can access the testbed as needed.

***Notable Characteristics***

- Indoor and Outdoor 5G testing facilities
    - Elastic, scalable 5G network test lab-as-a-service powered by DISH's commercial virtualized O-RAN 5G deployment.
    - Cloud-native principles provide declarative environments, CI/CD, and observability.
    - Hybrid cloud infrastructure and networking supports discrete and parallelized lab "instances."
- Mobile Core
    - Open source 5G SA release 17; Nokia and Oracle CNFs.
    - Runs on AWS EKS (Amazon Elastic Kubernetes).
- RAN
    - Mavenir, running on Dell + VMWare TKG (Tanzu Kubernetes Grids).
    - Radio Units (RU): Fujitsu.

- Massive MIMO – DISH reports being able to test and report on third-party massive MIMO solutions.
- Network testing equipment – Equipment available from Spirent, Keysight, and others.
- Transport – Cisco-provided transport.
- Compute – Capacity available within one optical hop. DISH also has edge computing capabilities and can provide connectivity to public cloud computing services.
- Certification – The DISH lab can certify 3GPP compliance and provide device clearance and certification. It can also certify network functions as cloud native.

***Capacity to Offer Services to External Users for Testing and Development***

Note that the services listed below are what DISH intends to make available for testbed users; these features are not yet accessible to researchers or companies outside of DISH.

- Repeatable configurations
  - Labs set up with consistency between instances and/or sessions with tests executed against a known baseline.
  - Labs automatically reset to fixed conditions after every session.
  - Declarative approach (IaC, Helm, etc) to minimize manual steps and enable lab-to-lab comparisons.
- Production-grade
  - Lab will reflect DISH production networks and have a mechanism to measure drift when not possible.
  - Avoids contrived lab-only scenarios and with an uncertain relation to actual production environments.
- Scalable
  - Right-sized capacity based on the needs of the current session of testing.
  - Reduced costs for early-stage testing encouraging experimentation and new entrants.
  - Ability to scale upwards for later-stage testing.

- Elastic
  - On-demand time increments with an ability to parallelize to increase development velocity.
  - Allow for multiple independent operations/parties simultaneously thereby minimizing bottlenecks.
  - Sessions fit for purpose to maximize efficiency and minimize cost.
- Observable
  - Labs with pre-built observability and data exposure mechanisms, with the ability to customize.
  - Data captured and efficiently disseminated to meet United States government standards.
  - Unit-under-test data, test (emulation) data, system metrics, logs, etc.
- Spectrum – DISH would include access to its licensed spectrum.
- O-RAN Alliance – Alliance member.
- Remote Access – Remote access can be provided.

**Idaho National Laboratory**

## Advanced Feature Research

Idaho National Laboratory (INL), located in Idaho Falls, Idaho, acts as part of the research arm of the Department of Energy (DOE), focusing particularly on projects with high-security requirements. The lab is not generally open to the public, but in addition to supporting internal DOE research, the lab team conducts sponsored government research and commercial collaborations.

Telecommunications research in the INL lab is under the INL Wireless Security Institute and is focused on 5G device and network security research with an emphasis on identifying, validating, and reporting on 3GPP protocols themselves. INL is only designed for new research, and not for ongoing activities like interoperability or conformance testing.

INL maintains an annual budget, while also receiving funding from other parts of DOE, academia, and commercial entities to fund the Wireless Security Institute.

***Notable Characteristics***

- Security capabilities – INL, like other National Labs, can meet high physical and infrastructure security requirements that surround the actual research projects on 3GPP protocol security.
- Research Depth – The 5G Security research is limited to *products that are supplied with the actual software source code*. The researchers examine both the protocols themselves and the code to implement them for threats and vulnerabilities. Results are documented and made available.
- Outdoor network deployment – Rural “quiet area” is available as a test range. Unlicensed and Innovation Zone spectrum available. CBRS would have no barrier provided the system under test has SAS connectivity interface.
- Indoor network deployment – There are anechoic chambers available indoors.
- Mobile core, gNodeB, and user endpoints (UEs) – Commercial 5G core supporting SA and NSA, 3GPP R16 is available.
- Network testing equipment – Test equipment available, inventory list not provided. INL does *not* currently maintain specialized Open RAN test equipment and would need RAN test and emulation platforms to support controlled Open RAN research.
- RIC, CU, and DU – CU/DU established. RICs are not yet available.
- Multi-dimensional test capabilities – Can conduct R&D and Security.
- Compute – INL private computing resources can be used.

***Capacity to Offer Services to External Users for Testing and Development***

- Project work – The Wireless Security Institute forms collaborative research agreements and responds to select calls for proposals. Commercial customers may also propose research projects in the security domain.
- Personnel – The staffing is limited. Research staff is 2-3 people with an operational staff of 20 engineers and technicians.
- Security – Due to other activities at INL campus, security is very high.
- IP Protection – NDAs are supported.

**LinQuest Testbed**

Advanced Feature Research and potential for Interoperability and Performance Parity Testing

LinQuest hosts a testbed in a 25,000-square-foot space that also includes workstations and one server room with five or six racks to accommodate 78 servers. The team has been working to enable multi-vendor components in the testbed, but the cost model is still under investigation. Projects are billed at an hourly rate.

The team at the testbed is 100% dedicated to supporting clients, which include internal researchers as well as government and commercial customers primarily in the national security sector. Five members of the team are dedicated specifically to interoperability testing.

The facility is mainly supported by internal funding. Additional funding could be used to support specific vendor equipment based on government requirements.

***Notable Characteristics***

- Indoor resources – 25,000-square-foot space with workstations and compute resources. The team is acquiring commercial network components from multiple vendors. The anechoic chamber enables over-the-air testing across a range of frequency bands (C-band, B78, B41, N261, B48).
- Mobile core – 5G commercial core available.
- RIC, CU, DU – There is no available RIC. Testbed has a collocated CU and DU (data plane and control plane).
- Network testing equipment – The testbed includes advanced network testing equipment supporting compliance, interoperability, security, and performance/stress testing.
- AI/ML Capabilities – The LinQuest testbed supports internal AI/ML research with a high-performance computing environment.
- Compute – Computing capacity is available, but not in proximity to a radio access network.
- Emulation – The testbed specializes in emulation.

***Capacity to Offer Services to External Users for Testing and Development***

- Remote access is available for staff only via VPN.
- Intellectual Property and Security: The testbed provides physical security and data security.

**MITRE 5G Lab**

Advanced Feature Research (Security) and potential for Interoperability and Performance Parity Testing

MITRE is pursuing a federated approach to the creation and operation of their 5G Lab/Testbed. The main location is MITRE's offices in McLean, Virginia, which are associated with and interconnected with University of Maryland (UMD) in College Park, Maryland (5G RAN environment) and Northeastern University (NEU) in Burlington, Massachusetts (5G RAN and other environments including outdoor RF Testing).

The federated approach looks to leverage the different capabilities of various strategic partners in an interconnected manner to avoid duplication of resources. The recent CTIA lead Security Testbed where MITRE hosts the Core and UMD hosts the RAN environment, and the collaboration with NEU which exists within an FCC-mandated Innovation Zone, are two recent examples of this federated approach.

Presently, the MITRE 5G Lab supports internal MITRE 5G project teams as well as other DOD-based project teams. They are pursuing the mechanisms (e.g., contractual, legal) to open the lab to non-DOD US Governmental Agencies as well as non-US Governmental entities.

The team and available resources at MITRE are growing to meet the internal and projected external demands with a present focus on 5G security (both defensive and analysis of vulnerabilities and opportunities) and O-RAN interoperability confirmation but not certification. The present 5G environment is characterized as vRAN with multiple single-vendor systems with CU, DU, RU subsystems as well as multiple Cores. Specifically, MITRE currently has virtualized CU, DU, and RU from a single vendor up and running in the lab, but not a true Open RAN multi-vendor implementation. There has been some work with a CU/DU from Capgemini and RU from Foxconn.

With additional funding, the testbed could expand into interoperability testing by purchasing more network testing hardware and expanding their hardware/software environment to include items such as base stations for security testing.

***Notable Characteristics***

- Indoor and Outdoor RF Environments – There are RF testing environments available as follows:
    - MITRE – McLean – Indoor screen room with RUs from various vendors. Extension to an outdoor trailer in progress.
    - UMD – College Park – Indoor screen room with Ericsson radio units (See ARLIS UMD profile).
    - NEU – Burlington – Outdoor RF testing environment with spectrum available under the FCC Innovation Zone rules. (See Northeastern Colosseum Arena profile).

- Network Elements – The following network elements are available and integrated internally and interoperating with all locations:
    - MITRE – McLean – Core networks include Ericsson NSA (Release 15), Affirmed SA (Release 16) and Ericsson Dual-mode NSA/SA. RAN equipment includes Airspan and Capgemini vRAN solutions. Open Fronthaul connectivity is available for additional RUs. MITRE uses Mavenir for a near-real-time RIC, and Capgemini for a non-real-time RIC.
    - UMD – College Park – Four Ericsson BBU and RRH combinations
- Network Testing Equipment – The testbed includes basic network testing equipment from Keysight and Rohde & Schwarz, as well as equipment for SIM provision and SIM interface traffic capture. For device testing, they have Nemo and QCOM QXDM tools. On the RAN they have RF signal capture and waveform analysis, R&S base station scanner. The Keysight test suite supports Core, CU, DU, RU and UE emulation.
- Compute – MITRE supports a private cloud environment locally with 3 Master and 5 Worker Kubernetes frameworks on bare metal for the SA Core. For the RAN environment, they have a Kubernetes framework with 3 Master on bare metal with no hardware accelerators. Additional compute capacity is within one optical hop.

***Capacity to Offer Services to External Users for Testing and Development***

- Personnel – The MITRE team consists of twelve employees and is being expanded. The UMD team currently has two employees.
- Remote Access – MITRE utilizes a secure router to establish VPN connection between remote users and the MITRE 5G test infrastructure.
- O-RAN Alliance – Alliance contributor.

**NIST Communications Technology Laboratory**

## Advanced Feature Research

The NIST Communications Technology Laboratory acts as the research arm of the Department of Commerce, focusing on research to support US economic competitiveness. The lab is not generally open to the public, but in addition to supporting internal research, the lab team conducts sponsored research and commercial collaborations. NIST can be contacted about: commissioning research, sharing information on unsolved problems, and updating the agency on technology developments.

Research in the lab on Open RAN is geared toward making it easier for network operators to adopt Open RAN technologies. However, the NIST lab is only designed for new research, and not for ongoing activities like interoperability or conformance testing.

The NIST lab is largely funded by the Department of Commerce, with some additional funding received through commercial collaborations.

***Notable Characteristics***

- Network testing equipment – The NIST lab has the test equipment, hardware, and software platforms needed to support the Open RAN development research it is targeting.

- Development of measurement tools – The team at the NIST lab is interested in developing tools to enable Open RAN conformance testing, such as conformance testing harnesses (software that emulates the adjacent system to the one under development).

***Capacity to Offer Services to External Users for Testing and Development***

- Personnel – NIST can be contacted about commissioning research and has the staff to support conducting research projects. If the agency's annual budget were to be increased, the additional funding would go toward hiring more personnel.

- Manufacturer services – The NIST lab is available for briefings from the 5G O-RAN supplier ecosystem about unsolved problems or challenges. These briefings can help to inform the lab's research calendar, which is developed to support research into solutions for industry-wide issues.

- O-RAN Alliance – Alliance contributor.

**Northeastern University – Colosseum and Arena Testbeds**

## Advanced Feature Research

Northeastern University maintains several wireless research facilities, relying largely on grant-based funding, with additional funding generated by commercial customers. The university's primary facilities supporting Open RAN research are the Colosseum and Arena testbeds. Colosseum is a giant RF emulator deployment with software-defined radios (SDRs) connected to high-performance computing and enabled with emulation scenarios for experimentation. Arena is an indoor deployment of antennas connected to SDRs for over-the-air radio research.

Colosseum is available for academic, government, and industry use. Arena is most often used for internal research at the university but can be made available to external users under agreement.

The team at Northeastern is highly focused on wireless research and Open RAN. The group maintains an end-to-end Open RAN framework supporting experiments in emulation in Colosseum that can then be moved to Arena and other testbeds for over-the-air implementation. There is also a heavy emphasis on experimenting with artificial intelligence and machine learning in communications networks.

***Notable Characteristics***

- Emulation environment – Colosseum is a data center with 256 SDRs attached to high-performance compute capacity and connected via a fabric of highly programmable FPGAs. The testbed includes preset scenarios for experimentation, with more scenarios in development. Virtually all network components are emulated in software at Colosseum, although commercial radios can also be connected to the infrastructure to test with hardware-based gNodeBs.

- Colosseum runs on an Open RAN framework that is shared with Arena. (More details below)

- Indoor network deployment – Arena is an indoor network testbed composed of antennas mapped to SDRs that can act as base stations, gNodeBs, and user endpoints (UEs). Commercial phones can also be connected to the Arena infrastructure.

- Experiments run in containers on Colosseum can be transported to run over the air on Arena with the use of the same Open RAN framework. These container-based experiments can also be configured to work on the POWDER and COSMOS testbeds in Salt Lake City and New York City respectively.

- The Northeastern team has access to spectrum in the ISM bands and via an Innovation Zone designation by the FCC. The Innovation Zone designation covers numerous frequency bands and acts like an FCC experimental program license*, but with some added flexibility for external users of the testbed.

  **Experimental program licenses provide access to select spectrum bands to research institutions for low-power transmissions in a controlled environment. Access is not granted or is revoked when the spectrum owner believes there could be interference with their own operations.*

- Northeastern University also maintains a large anechoic chamber that is not directly part of the Colosseum or Arena testbed

- Outdoor netted drone cage – Northeastern maintains a netted drone case for wireless research that is about half the size of a football field. Research typically takes place using unlicensed wireless bands.

- Channel emulation – Colosseum offers full stack emulation across 256 SDRs.

- Mobile core, CU, DU – Northeastern maintains multiple open-source software-based mobile cores, and open-source software-based CUs and DUs.

- RU and fronthaul interface – In early 2023, Northeastern will implement a programmable open radio unit (ORU) based on the 7.2 split and compliant with the O-RAN fronthaul interface. Additional commercial RUs compliant with O-RAN will also be integrated into the platform and connected to virtualized CUs and DUs.

- RIC and end-to-end testing – Northeastern maintains all necessary software components for end-to-end open RAN testing and development including a basic service management orchestrator, a non-real-time RIC, and a near-real-time RIC integrated with CU and DU software, and radio hardware. The team has also developed a catalog of xApps and rApps addressing functions including spectrum sharing, network slicing, neutral host deployments, and coverage optimization.

- AI/ML Capabilities – In addition to Colosseum and Arena, Northeastern runs the OpenRAN Gym platform for the collection of data and experimentation with AI and ML in Open RAN networks. The platform includes a framework that exposes certain parameters in open-source network software stacks to make it easier to track specific performance metrics. Datasets are used to train AI/ML models, and users can work with existing datasets and models or contribute their own.

- Network testing equipment – Northeastern has equipment available for testing spectrum and wireless transmission, but not for O-RAN interoperability testing.

- Compute- Northeastern has significant computing infrastructure and makes available both edge compute capacity and connectivity to public cloud services.

***Capacity to Offer Services to External Users for Testing and Development***

- Personnel – Northeastern network testbeds are staffed by university faculty, 80-90 Ph.D. students, and 10-15 full-time researchers who are the primary contact for external users or testbed customers.

- Remote Access – Colosseum is accessible to researchers remotely. Arena can also be accessed remotely, but all engagement must go through Northeastern staff for approval and monitoring of spectrum use.

- Security and IP Protection – Northeastern signs non-disclosure agreements as needed and can provide services in a controlled-access environment. Classified work can also be supported, but it requires specific funding for ensuring clearance.

- O-RAN Alliance – Alliance contributor.

**Pacific Northwest National Laboratory (PNNL)**

## Advanced Feature Research

Pacific Northwest National Laboratory (PNNL) acts as the research arm of the Department of Energy (DOE), focusing particularly on projects with high-security requirements. The lab is not generally open to the public, but in addition to supporting internal DOE research, the lab team conducts sponsored government research and commercial collaborations.

Telecommunications research in the lab is focused on advancements in 5G and 5G applications with an emphasis on DOE/commercial use cases. PNNL is only designed for new research, and not for ongoing activities like interoperability or conformance testing.

PNNL maintains an annual budget, while also receiving funding from other parts of DOE, other government agencies, and commercial customers.

***Notable Characteristics***

- Indoor network deployment – There are walk-in anechoic chambers and faraday cages available indoors, with experimental station status covering most of the campus. Use of CBRS with a SAS connection is possible indoors and outdoors.
- Mobile core, gNodeB, and user endpoints (UEs) – Commercial 5G core supporting NSA and commercial RAN is available, along with open source cores supporting SA.
- RIC, CU, and DU – CU/DU are available. RICs are not yet available.
- Compute – PNNL private computing resources can be used, and connections to cloud computing resources are available.
- Security capabilities – PNNL can meet high-security requirements for research projects.
- Network testing – PNNL does *not* currently maintain specialized Open RAN test equipment and would need RAN test and emulation platforms to support controlled Open RAN research.

***Capacity to Offer Services to External Users for Testing and Development***

- Project work – PNNL forms collaborative research agreements and responds to select calls for proposals. Commercial customers may also propose research projects in PNNL's domain of expertise.

**POWDER - Platform for Open Wireless Data-driven Experimental Research**

Advanced Feature Research and potential for Interoperability and Performance Parity Testing

The POWDER-RENEW project is a collaboration between the University of Utah, Rice University, and Salt Lake City, with broad support from community, municipal, and state leadership. The purpose of the POWDER testbed is to enable innovative research across numerous technical areas including radio development for advanced networks such as 5G, Radio Access Network (RAN) architectures, network orchestration models, Massive MIMO, and much more. The testbed provides state-of-the-art radio, compute, storage, and cloud resources, as well as the ability to work with existing hardware and software frameworks, or to build new ones from the ground up. Researchers can access the platform on site in Salt Lake City, or remotely from anywhere in the world.

Typical users of POWDER include university students and faculty, O-RAN Software Community (OSC) Integration Project Team, O-RAN test vendors, and industry researchers.

***Notable Characteristics***

- Outdoor network deployment – POWDER's outdoor network includes eight rooftop base stations with multiple SDRs each, and ten fixed endpoints at ground level with SDRs. An additional six base stations (five on light poles and one rooftop) with multiple SDRs each and frontends to support CBRS transmissions are launching in January 2023. POWDER also includes a rooftop programmable massive MIMO array and two client sites with two 2x2 MIMO user endpoints each. Eight mobile endpoints with SDRs are located on shuttle buses that travel throughout the network footprint. Quectel devices are being used as 5G COTS user endpoints.

  Spectrum is available in sub-6 GHz bands via experimental program licenses* and POWDER's Innovation Zone designation. The Innovation Zone designation covers numerous frequency bands and acts like an FCC experimental program license, but with some added flexibility for external users of the testbed.

  CBRS operations are optimized for the SDRs via custom radio frontends.

  **Experimental program licenses provide access to select spectrum bands to research institutions for low-power transmissions in a controlled environment. Access is not granted or is revoked when the spectrum owner believes there could be interference with their own operations.*

- Indoor deployment – POWDER has several tightly controlled indoor environments: a wired test bench, a controllable attenuator, emulation capabilities, and an indoor over-the-air lab. The indoor over-the-air lab includes four SDRs with 10G fiber connectivity for flexibly pairing with computing resources, and four Intel i7-based NUC compute nodes with USB-3 attached radios (one SDR and one COTS 5G modem each).

- Mobile core, gNodeB, CU, DU, and UEs – Multiple open-source mobile 5G cores are available to be matched with gNodeBs or virtualized CUs and DUs. Multiple types of UEs are available.

- RIC – As a member of the O-RAN Alliance, POWDER makes it possible to run the reference RIC in connection with open-source mobility stacks. In addition, POWDER adds RAN slicing functionality to the reference RIC.

- Compute – Connectivity to near-edge compute is available with average latency under 100 microseconds, to edge compute cluster with an average latency of 500 microseconds, and to metro compute cluster with an average latency of 750 microseconds. Connectivity is also available to public cloud services.

- Build your own 5G network – POWDER enables experimenters to build their own 5G networks using open-source software stacks such as OpenAirInterface and srsRAN. These networks are end-to-end programmable, allowing full control over both the RAN and core parts of the network, as well as the services that run inside. These networks can be built in a small indoor test environment or in an outdoor environment with several gNodeBs and true mobile devices.

- Open RAN use case – The POWDER NexRAN use case allows closed-loop control of a RAN slicing implementation in an O-RAN ecosystem. RAN slicing is implemented in the srsRAN open-source mobility stack and is exposed through a custom service model to the NexRAN xApp, which executes on the near-RT RAN intelligent controller (RIC). This RAN slicing implementation realizes a form of slicing where different slices share a frequency band, UEs can be associated with slices, and a slice-aware scheduler in the base station implements the RAN resources associated with each slice. NexRAN is made available for easy use in the POWDER platform.

- Spectum monitoring - POWDER's RF monitoring capabilities span multiple vantage points and technologies, from rooftop sites with large sample rate SDRs, to small form factor fixed location and mobile units with modest SDR and compute resources, antennas allow for either specific band coverage (e.g., CBRS), or wide range for tuning in FR1 frequencies (e.g., 700 MHz to 6 GHz).

***Capacity to Offer Services to External Users for Testing and Development***

- Personnel – POWDER is run by the Flux Group that conducts research in operating systems, networking, security, and virtualization at the University of Utah, School of Computing. The group consists of three faculty members and over two dozen research staff, graduate students, and undergrads. It is part of the School of Computing at the University of Utah.

- Remote Access – POWDER offers detailed documentation for the user to join a project, start a new project, obtain secure access via public Internet, and so on. From basic concepts to advanced topics, the documentation makes it possible for the user to create a profile, reserve resources, and get started quickly via POWDER's LaaS model and BYoD/BYoS approach.

- Security and IP Protection – The POWDER team enters into non-disclosure agreements, offers intellectual property protection, and/or supports classified projects. All systems are password-protected, and there is no open access to the physical infrastructure. Individual projects are isolated from each other.

- O-RAN Alliance – Alliance contributor.

**Texas A&M Testbed**

Advanced Feature Research and potential for Interoperability and Performance Parity Testing

The RELLIS Spectrum Innovation Lab (RSIL) out of Texas A&M supports academic, public sector, and enterprise entities of all sizes. With a robust campus as well as available experts from across one of the largest universities in the country, customers and partners can leverage not only some of the latest commercially relevant networking technologies, but also leading field experts across multiple domains. Funding for research comes from several channels: grants (institutional, state, and federal), and revenue generated from customer projects. Notable funding partners include the state of Texas, the Department of Defense, the Department of Homeland Security, and enterprise partners such as MITRE and Squishy Robotics.

The team and available resources at the testbed are geared toward research and development of advanced features supported by Open RAN technologies, and even some that are not yet supported. This includes the development of network applications that tie into the non-real-time and the near-real-time RAN Intelligent Controller (RIC), and specifically to the use of artificial intelligence (AI) and machine learning (ML) in RAN optimization.

With additional funding, the testbed could expand into interoperability testing by being able to procure more commercially relevant technologies (hardware and software) to augment what has historically been homegrown (RIC).

***Notable Characteristics***

- Outdoor network deployment – The testbed encompasses over 2500 acres of property, with an outdoor network deployment that includes commercial equipment as well as six software defined radios across three fixed cabinet sites using open-source software stacks. The radios are coupled with two types of frontends: power amplifiers and omnidirectional antennas for operation in the sub-6 GHz band, and up-down converters and phased array antennas for operation in the 25-30 GHz mmWave band. There are also SDRs with battery packs available for indoor/outdoor/mobile experiments.

- Spectrum access includes:

    - ISM bands in a very remote area with low congestion
    - A Priority Access License (PAL) for CBRS spectrum plus general access
    - Licensed C-Band frequencies and 39 GHz mmWave spectrum from AT&T
    - Several experimental program licenses from the FCC
    - Access to 4.9 GHz through relationships with public safety

RSIL is located at a former Air Force base now owned and operated by the Texas A&M University System and situated about ten miles from the main campus. Unique characteristics include support for on-road testing at highway speeds and off-road testing over trails. RSIL also supports airborne testing up to 400 feet without FAA clearance needed. The adjacent Disaster City facility provides an emulated urban environment and railroad disaster situations. This is also supported by the university's own fiber network.

- Indoor deployment – RSIL's indoor facilities include an indoor network with six SDRs, sub-6 GHz omnidirectional antennas and 60 GHz phased array antennas, an OpenFlow compatible switch, and 20 commercial Android UE devices. The site also features commercial network equipment from Nokia, Ericsson, Airspan, and JMA Wireless. There is an anechoic chamber and additional research space to accommodate resident and visiting researchers. A recent grant from the state of Texas is funding the construction of a new building to house additional testing space, workspace, and research resources.

- Mobile cores – RSIL maintains multiple commercial and open-source mobile cores, both 5G SA and NSA.

- RIC, CU, DU, RU – RSIL maintains an in-house open-source RIC for use with on-site SDRs and bring-your-own hardware and software.

- Fronthaul interface – The combination of on-site dark fiber which supports CIPRI, and the testbed's Ribbon 5G Transport solution which supports eCIPRI means RSIL can support any O-RAN fronthaul split.

- Network testing equipment – The testbed includes basic network testing equipment from Keysight as well as remote testing supported by BeyondTrust. Via a service from AT&T, the testbed also utilizes what amounts to a NOC in a single pane of glass to collect network performance in a live – though not real-time – state.

- Massive MIMO – Massive MIMO facilities are available at TAMU partner institution Rice University.

- Channel emulation – The university is in the process of securing a channel emulator. Currently the team collects data in the field to then simulate in their channels, rather than being able to synthetically emulate traffic and activity.

- AI/ML – The in-house RIC has been tested with a variety of real-time and near-real-time AI/ML training, decision, and control algorithms. The university has numerous experts in AI/ML.

- Compute – RSIL offers edge compute at the RAN and the core. It also provides high-performance non-real-time compute at the TAMU HPC Center.

***Capacity to Offer Services to External Users for Testing and Development***

- Personnel – The testbed team is led by full-time faculty and staff and includes roughly 7 engineers as well as full-time contractors from AT&T. Business and operational support comes from the university at large.

- Remote Access – Researchers can connect to the testbed remotely via VPN (BeyondTrust). Researchers can deploy any software stacks they like, and can access COTS UEs attached to the network as needed.

  Radios, compute capacity, physical resources, air space, and spectrum are all available over web interface. Virtual machines are the preferred software install route, but bare metal compute is available. Containerized images, such as srsRAN with appropriate core, RAN, and RIC, are available for pre-configured install. Phased array control and a data analytics platform are also available via containers from IBM. Similar support for OAI containers is being developed.

- Security and IP Protection – The testbed team uses TAMU lawyers to support non-disclosure agreements, offer intellectual property protection, and support classified projects.

- O-RAN Alliance – Alliance contributor.

**Telecom Infra Project (TIP) Lab**

Advanced Feature Research and Interoperability and Performance Parity Testing

The Telecom Infra Project (TIP) Community Lab based out of Menlo Park/Fremont supports interoperability testing and plugfest activities from the commercial wireless industry. Projects are funded by the companies involved, with TIP providing lab space, equipment, and support funded by Meta. With recent developments, there have been significant reductions to the TIP lab, but 5G/Open RAN has been mostly unaffected. These changes will lead to lab consolidation, but impact is not expected for 5G/Open RAN.

With additional funding, the testbed could expand remote access and create a virtual lab with expanded connectivity.

***Notable Characteristics***

- Indoor network environment (no outdoor facility or access to spectrum) – Consisting of multiple sites, the Menlo Park (“404”) covers around 10-12 thousand square feet. Emulation provided via Spirent, Viavi TM500 (some emulation capabilities including core and UE).
- Mobile core, gNodeB, and user endpoints (UEs) – The TIP testbed offers emulated elements: RU, DU, CU, UE, TeraVM core emulator. Core is both NSA and SA. Available RICs are an O-RAN SC RIC deployed by HCL and a VMware near-RT RIC, but not commercial (non-GA).
- Network Testing Equipment – The testbed includes testing equipment from multiple vendors: Keysight, Spirent, Viavi, Ixia (now part of Keysight). Viavi RIC Test tool for RIC testing (traffic steering, etc.) will be available next 6-9 months. Fronthaul impairment is available from Calnex.
- RIC xAPPs/rAPPs testing – The lab has provided end to end capability to test use cases such as Traffic Steering, Uplink Channel Estimation, and Energy Savings where all use cases have demonstrated AI/ML driven optimization capabilities.
- Open RAN orchestration and automation testing – The lab has provided a multi-vendor test set-up consisting of RU, cDU, cCU, and 5G Core which has been used to validate maturity of Open RAN orchestration products. Activities were also carried out in the Open RAN CI/CD platform testing.

***Capacity to Offer Services to External Users for Testing and Development***

- Personnel – The TIP lab hires contractors with lab experience from Tech Mahindra and Amdocs, and provides radio/transport/core experts. Three to six months advance notice is needed to staff up and prepare for testing.

- Remote Access – TIP normally gives VPN access to partners.

- Security and IP Protection – The testbed provides bylaws, and participants agree to a project description defining each party's responsibilities. Multiple badging is used for access.

- O-RAN Alliance – Meta is an Alliance contributor.

**University of Maryland (UMD) 5G Security Testbed**

Advanced Feature Research in support of partner organizations

The University of Maryland (UMD), in association with CTIA, Ericsson, MITRE, Secure G, AT&T, T-Mobile, and US Cellular (the "Consortium"), have created an environment for advanced 5G Security analysis and testing. Research in the lab is focused on 5G security issues and responses exercised within a carrier-grade 5G environment.

The work undertaken by the lab is directed via CTIA by the consortium members. There is presently no mechanism to accept "outside" work or other equipment. However, the goal is the open the lab to other users at some point in the future though contractual and other legal mechanisms are still under development.

***Notable Characteristics***

- Network Elements and Location:
    - RAN (on the campus of UMD – College Park, MD):
        - Ericsson 5G Radios (4) supporting multiple FR1 licensed bands – BBUs and RRHs.
        - RF Screen Room (approximately 8' x 8' x 8') for Over the Air testing.
    - Core (at the MITRTE 5G Lab – McLean, VA):
        - Ericsson Dual Mode (NSA/SA) Enterprise Core.

***Capacity to Offer Services to External Users for Testing and Development***

- Availability – To date, all work conducted is for and at the direction of consortium members.
- Personnel – The present staff support at the UMD location is limited.

**University of New Hampshire Interoperability Lab (UNH-IOL)**

Interoperability and Performance Parity Testing

The University of New Hampshire Interoperability Lab (UNH-IOL) is a nonprofit lab housed at the university that has worked with the telecom sector to test and pre-test products for more than 30 years. It is fully funded by commercial use, with most companies buying access via a membership fee.

Members include large hardware and software vendors, as well as some smaller companies. Most engagements are with individual members or customers, but the lab can also work with a group of companies on topics of interest.

The IOL facility combines open lab space with some isolation chambers and a significant data center. It does not maintain a radio access network, nor any specific test equipment for Open RAN. However, it supports Open RAN plugfest activities with participants shipping in equipment and installing software as needed. Years of expertise and a sizeable staff provide the capabilities necessary for conformance and interoperability testing.

The IOL team is evaluating if there is enough commercial demand to purchase equipment that would support specific Open RAN development activities such as RIC testing and beamforming testing. The current assessment is that the demand does not exist.

***Notable Characteristics***

- Indoor footprint – UNH-IOL hosts 20,000 square feet of open lab space, with part of the area used for physical layer measurements, part for plugfests and other events, and part dedicated to free-standing walk-in RF isolation chambers. The facility also includes a 3,000-square-foot data center.

- Mobile core – The lab maintains multiple open-source mobile cores. Companies bring their own commercial cores for use as needed.

- Network testing – UNH-IOL works with nearly all large test vendors such as Viavi and Keysight, and these vendors contribute equipment to the lab. Traffic generation is based on services from IXIA, Spirent, and Xena Networks, as well as open-source tools.

- Compute – The lab maintains compute capacity within one optical hop and provides connectivity to public cloud computing services.

***Capacity to Offer Services to External Users for Testing and Development***

- Personnel – UNH-IOL has 30 full-time professional staff members as well as around 100 paid undergraduate and 10-15 paid graduate student interns acting as part-time staff.
- Remote Access – Companies typically ship equipment to the IOL facility for testing, which can then be remotely configured through a VPN system. The lab offers support via bare metal and containers for installing software.
- Security and IP Protection – The lab signs non-disclosure agreements with companies as needed and maintains both digital and physical access controls to protect equipment and intellectual property.
- O-RAN Alliance – UNH-IOL is a contributor.

**Verizon Boston Innovation Lab**

Operator Research Facilities

Verizon operates multiple labs and research facilities across the US, with the Verizon Boston Innovation Lab, located in Boston, MA, notable for its potential to support Open RAN research. The mobile network technology testing lab is targeted at testing of infrastructure, specific features, and mobile devices for commercial deployment or supplier proof of concept in a Verizon technology landscape. Primary lab users today are internal to Verizon. Some external entities have also conducted testing in this lab.

The team and limited resources of the Verizon Boston lab are geared toward research and development of new/advanced equipment or capabilities required for the national Verizon wireless network.

The on-premise 5G base stations (gNodeBs) are purpose built by the three dominant OEMs serving the US market (Ericsson, Nokia, and Samsung). No Open RAN architecture (CU, DU, RU, and RIC) systems have been established in the facility. However, Verizon plans to add Open RAN resources in 2023.

***Notable Characteristics***

- Outdoor network deployment – All the Verizon spectrum currently licensed (from low-band to mmWave) and CBRS with SAS access are available. They have gNodeBs, radios, and antennas available that support their bands to conduct new software, features, and UE research/testing.
- Indoor network deployment – There are multiple Faraday cages available indoors.
- Mobile core, gNodeB, and user endpoints (UEs) – The Verizon Boston lab offers access to Ericsson 5G-NSA mobile core and gNodeBs from Ericsson, Nokia, and Samsung.
- Network testing equipment – RF signal meters, load emulators, drive test simulators, and handoff testing systems are available.
- RIC, CU, and DU – Not yet established. Planned for 2023.
- Multi-dimensional test capabilities – Can conduct R&D, Compliance (3GPP, ETSI, etc.), Interoperability, Security, and Performance/stress testing.
- Compute – Verizon maintains access to compute capacity within one optical hop.

***Capacity to Offer Services to External Users for Testing and Development***

- Engagement – Internal process by RAN engineering or the business that commissions testing on behalf of a customer.
- Present cost structure for testing is $10,000 per week, but the model for Open RAN products has not yet been defined.
- Personnel – One network engineer, one RF engineer, and two associate network engineers. Resources from other Verizon labs around the nation can be pulled in as needed.
- Remote Access – Resources and services are remotely accessible.
- Security – Security testing is only performed on specific applications when requested through program management.
- IP Protection – NDAs are supported and all vendors in the lab are under NDA.
- O-RAN Alliance – Alliance member.

**Virginia Tech Commonwealth Cyber Initiative (CCI) xG Testbed**

Advanced Feature Research and potential for Interoperability and Performance Parity Testing

The Commonwealth Cyber Initiative (CCI) xG Testbed based out of Virginia Tech supports academic researchers across the state of Virginia and researchers from the commercial wireless industry.

Academic research is supported by funding from the state of Virginia and by grant dollars. Industry projects are funded either by the companies involved, or by federal agencies such as the Department of Defense, DARPA, and the National Science Foundation.

The team and available resources at the xG Testbed are geared toward research and development of advanced features supported by Open RAN technologies. This includes the development of network applications that tie into the non-real-time and the near-real-time RAN Intelligent Controller (RIC), and specifically to the use of artificial intelligence (AI) and machine learning (ML) in RAN optimization.

With additional funding, the testbed could expand into interoperability testing by: dedicating software development time to becoming fully compliant with O-RAN specifications, purchasing more network testing hardware, and hiring additional personnel.

***Notable Characteristics***

- Outdoor network deployment – The xG Testbed is building out three network nodes across a 1.5-mile corridor in Blacksburg, Virginia, with construction set to begin in January 2023. Each node will include commercial radios and software defined radios (SDRs), supporting both a production CBRS network and an experimental research network. The CCI xG team has access to priority access licenses (PALs) for use in the CBRS band, plus spectrum in ISM bands and via experimental program licenses. Additional outdoor facilities available through Virginia Tech include a drone park, farm site, and a smart road designed for testing automated vehicles.

- Indoor network deployment – The indoor footprint of the xG Testbed covers around 2,100 square feet, including a small 300 square-foot lab, and a ceiling deployment of 72 SDRs.

- Mobile core, gNodeB, and user endpoints (UEs) – The xG testbed offers access to virtual mobile cores, the simulated control plane of a gNodeB, and simulated UEs. Most assets are open source, but the testbed also includes a commercial core for rapid prototyping of 5G standalone and non-standalone solutions. The testbed also maintains a handful of COTS UEs (smartphones).

- Network testing equipment – The testbed includes basic network testing equipment from Keysight and Rohde & Schwarz.

- RIC, CU, and DU – The CCI xG team is currently configuring a dedicated AL/ML platform to act as the brain for indoor deployment. The indoor testbed will be integrated directly with ONAP to a non-real-time RIC sitting in the service management and orchestration (SMO) layer to support testing of rApps. The testbed also maintains implementations of an open-source near-real-time RIC to support testing of xApps.

- AI/ML Capabilities – The CCI xG team is currently configuring a dedicated AL/ML platform to act as the brain for indoor deployment. This will allow researchers to do data training, create data models, and test xApps and rApps. The team collaborates with partners to collect datasets and could collect more for data model training.

- Compute – The xG testbed maintains compute capacity within one optical hop and provides edge compute capacity.

***Capacity to Offer Services to External Users for Testing and Development***

- Personnel – The CCI xG team is led by a full-time faculty member and includes roughly seven masters and PhD students, as well as one dedicated engineer for operational support.

- Remote Access – Researchers can connect to the testbed remotely via VPN and SSH, and can directly access bare metal resources, virtual machines, and containers. Researchers can deploy any software stacks they like and can access COTS UEs attached to the network as needed.

- Security and IP Protection – The testbed team uses Virginia Tech's lawyers to support non-disclosure agreements, offer intellectual property protection, and support classified projects. All systems are password-protected, and there is no open access to the physical infrastructure. Individual projects are isolated from each other with resource slices allocated as needed.

- O-RAN Alliance – Virginia Tech is a contributor.