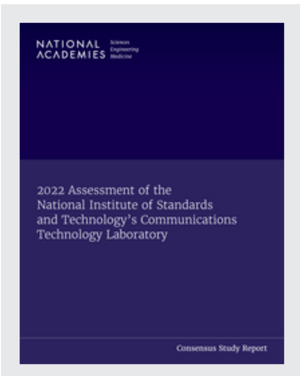

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2022 Panel on Review of the National Institute of Standards and Technology's Communications Technology Laboratory

Laboratory Assessments Board

Division on Engineering and Physical Sciences

National Academies of Sciences, Engineering, and Medicine

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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Edward Frank (NAE), Brilliant Lime, Inc., and Neil Siegel (NAE), Northrup Grumman. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Preface

Radio spectrum continues to be important to our nation from economic, public safety, and national security perspectives. It is a finite, and therefore extremely valuable, natural resource, and the "nearly insatiable demand for spectrum access"[1] poses an ongoing challenge in allocating spectrum to the wide variety of stakeholders, each of whom need it for some vital purpose. The management and allocation of the nation's spectrum falls to the Federal Communications Commission and the National Telecommunications and Information Administration. In 2014, the National Institute of Standards and Technology's (NIST's) Communications Technology Laboratory (CTL) was established to unite wireless communications efforts and address this challenge through research and technology. CTL built on NIST's long history of radio science and measurement with research and development capabilities centered around spectrum.

The National Academies of Sciences, Engineering, and Medicine's 2019 assessment of CTL[2] called for a reorganization for it to better meet its mission. In 2021, CTL, after significant strategic planning, completed this reorganization, expanding its organizational structure and the breadth of its research. Although wireless communications and spectrum remain central to CTL's mission, other advanced communications technologies—quantum communication and applications such as Internet of Things and smart manufacturing—are now part of CTL's purview. CTL is currently organized into five divisions that work on projects in the following six research focus areas: Core Network Technologies, Fundamental Electromagnetic Technologies and Standards, Next-Generation Wireless Systems, Public Safety Communications, Smart Infrastructure and Manufacturing, and Spectrum Sharing and Sensing. Researchers from multiple divisions work in each focus area. CTL's expanded scope and cross-functional approach provide the foundation for innovative connections and research explorations. In addition, CTL's recent efforts to identify workplace equity issues and take steps toward recruiting and retaining a more diverse workforce have the potential to enrich the research environment and productivity. Taken together, these initiatives could have a significant positive impact on CTL. By bringing in researchers with diverse backgrounds and perspectives and facilitating communication and collaboration across projects and divisions, CTL will be poised to further its mission in new and unique ways.

[1] Developing a Sustainable Spectrum Strategy for America's Future, Presidential Memorandum 54513, 83 Fed. Reg. 210 (October 25, 2018). Available at https://www.govinfo.gov/content/pkg/FR-2018-10-30/pdf/2018-23839.pdf, accessed October 24, 2022.

[2] National Academies of Sciences, Engineering, and Medicine, 2019, *An Assessment of the Communications Technology Laboratory at the National Institute of Standards and Technology: Fiscal Year 2019*, Washington, DC: The National Academies Press, https://doi.org/10.17226/25602.

This is a time of transition in CTL due to both the reorganization and the expiration of the Public Safety Trust Fund (PSTF). The PSTF was a one-time investment in the development of public safety communications technologies and standards that was included as part of The Middle Class Tax Relief and Job Creation Act of 2012 (P.L. 112-96). This act initiated the deployment of a nationwide First Responder Network (FirstNet) and established CTL as the research and development arm of FirstNet, thus providing both direction and funding for CTL's Public Safety Communication Research (PSCR) Division. With funding from the PSTF sunsetting in fiscal year 2022, CTL's leadership in the public safety community and continued research and development efforts to support evolving technology, infrastructure, and first responder needs are at risk. Although PSCR will continue high-priority projects on a scaled-down basis, the public safety community has seen the possibilities and outcomes when public safety communication research is prioritized and well funded, a situation that will no longer exist. This will be a big change for PSCR, and the impact on the public safety community is unknown.

The assessment of CTL by the 2022 Panel on Review of the National Institute of Standards and Technology's Communications Technology Laboratory, falling at the end of the COVID-19 pandemic when things were just beginning to open back up, was conducted entirely remotely; there were no in-person interactions. While this yielded some efficiencies, especially with there being no need for travel, it also presented challenges. The in-person meetings that are the norm for these assessments have included many opportunities for informal engagement with CTL's personnel—such as laboratory tours, breaks, lunches, and a working dinner—which provided panels with a broader exposure to CTL's researchers, programs, facilities, and equipment. Because there was no in-person visit to CTL, these informal interactions did not happen, and the panel was only able to make limited observations about the condition of CTL's facilities, equipment, and personnel. Also, as is true of many remote meetings, interactions were more structured and limited; the kind of dialog that can happen when people are sitting around a table happens much less frequently, if at all, in the remote setting. On the positive side, the remote-only format allowed the entire panel to hear, and comment on, all of the presentations from CTL, providing the opportunity for a richer assessment. Historically, panels split into teams so the entire panel did not get to see each presentation and was only exposed to a portion of the work at the laboratory they were assessing.

In spite of these challenges, CTL provided the panel with a robust set of read-ahead materials and planned a meeting packed with informational presentations, responding nimbly to requests for changes from the panel and National Academies staff. When it became clear that the remote-only meeting did not provide all of the panelists with the information that they wanted, CTL readily agreed to and quickly hosted a set of follow-on meetings with the panelists to dive deeper into specific questions. Finally, they responded quickly to a number of questions and information requests as the panel drafted the report. In all, including closed panel working meetings, the panel held eight meetings to conduct its information gathering and draft the report. The National Academies staff worked closely with the chair and panel members as the report was drafted. This is another benefit of working remotely; normally, there would only have been one in-person meeting.

This report reflects the panel's assessment based on what they learned during this study. The main source of information was provided by CTL in the course of this project. The factual material in this report was provided to CTL for a fact check. Of course, nothing reflecting panel assessments or judgments was provided to CTL in advance of the panel's briefing of the final report. Finally, a "ghost panel" of experts was engaged to conduct a review of this report and judge whether it addressed the statement of task and whether it went beyond the statement of task, whether the report's recommendations are supported by adequate arguments, whether the report is impartial, and whether it is clear and understandable.

The panel wants to thank Marla Dowell, the director of CTL, for facilitating this assessment and making her staff available to support the panel's requests. They are all very busy people, and supporting this assessment was an extra demand on their time. We also want to thank Anne Lane, the CTL chief of staff, for taking on the additional assigned duty of being main contact between the panel and National Academies staff and CTL. She responded quickly to panel requests when the main meeting in May 2022 was being planned and responded quickly to questions and requests following that meeting. We also want to thank the presenters and other CTL staff who took the time to make formal presentations to the panel and attend follow-up meetings.

Azeb Getachew, the administrative assistant for the Laboratory Assessments Board, provided excellent support to help to organize the panel and organize the meeting. Jayda Wade, a research associate, was hired late in project but jumped in with alacrity and quickly helped to make things better. Katie Bratlie, the director of the Laboratory Assessments Board, joined the National Academies well after this project was under way but quickly learned the ropes and provided strong support. James Myska, senior program officer and study director, who guided the study, provided outstanding support to the panel, kept us focused, and helped us navigate the challenges we encountered. We thank them all.

Finally, and most importantly, I'd like to thank the panel for all the time and energy they put into this report. Thank you for enduring the challenges of a remote review and staying engaged throughout the process. Your expertise and insights strengthened the review and are highly valued. It was a pleasure to work with each of you.

Cynthia S. Hood, *Chair*
2022 Panel on Review of the National Institute of Standards and Technology's Communications Technology Laboratory

Summary

At the request of the director of the National Institute of Standards and Technology (NIST) in 2021, the National Academies of Sciences, Engineering, and Medicine formed the 2022 Panel on Review of the National Institute of Standards and Technology's Communications Technology Laboratory (CTL). The panel met virtually with CTL management and staff to conduct its assessment of the laboratory's work, facilities, equipment, personnel, portfolios of scientific expertise, and effective dissemination of the results of CTL's work. The choice of projects to be reviewed was made by CTL. The panel applied a largely qualitative approach to the assessment applying the members' collective expertise and experience. The following is a summary of the assessment detailed in this report. The assessment relies primarily on information provided by CTL. Time constraints precluded more extensive information gathering and analysis, and these assessment reports are, by their design, at a high level and brief.

TECHNICAL QUALITY OF THE WORK

CTL has staff working in six research focus areas, each of which has achieved noteworthy accomplishments. These include millimeter-wave measurements and modeling; quantum channel metrology; the "campus as a testbed," which allows NIST to conduct smart grid research; and the delivery of programmable Josephson voltage standards reference instruments. The panel assesses that the technical quality of the work being performed at CTL is of a very high quality.

Work in the Core Network Technologies research focus area is directed toward developing timely and long-term essential aspects of computer networking, both wired and wireless, including resolving systemic vulnerabilities in existing and planned infrastructure and developing new architectures and protocols to improve trustworthiness. The staff working in this area have also worked to promote standards for 6G networks.

Work in the Fundamental Electromagnetic Technologies and Standards (FETS) research area is directed toward guided wave electromagnetics, electromagnetic fields, high-speed waveform metrology, and superconductor electronics. There is focus on crosscutting outcomes that provide solutions to other research focus areas in CTL, along with other laboratories throughout NIST. The work builds on the excellent prior work in metrology that the staff has conducted.

The Next-Generation Wireless research focus area includes a variety of interdisciplinary projects on millimeter-wave instrumentation, 5G New Radio direct mode communication, and spectrum sharing. This program enjoys a very strong reputation in the research community based on its millimeter-wave measurement and modeling work, its contributions to the NextG Channel Alliance, and its valuable contributions to the Citizens Broadband Radio Service standards.

Researchers engaged in the Public Safety Communications Research focus area have supported the deployment of a nationwide First Responder Network (FirstNet), which aims to improve communications for first responders by providing them with priority access to communications networks nationwide. Specific research areas include mission critical voice, location-based services, user interface/user experience, public safety analytics, security, and resilient systems. Many of these areas are crosscutting throughout NIST.

The Smart Infrastructure and Manufacturing research focus area addresses smart connected manufacturing systems, smart grid programs, the Internet of Things, smart cities and communities, security for operational technologies, and industrial wireless systems. Each of these research areas is fully engaged in the mission of CTL and is represented in relevant industry standards development organizations.

The Spectrum Sensing and Sharing research area addresses microwave noise metrology, radio frequency spectrum sensing, and atmospheric spectroscopy. As the focus areas imply, a wide range of frequencies is covered, and the applications are likewise broad. This program is forward-looking and researchers plan to address challenges in spectrum coexistence, receiver performance characterization, and measuring skyward emissions from 5G systems.

TECHNICAL EXPERTISE OF THE STAFF

The technical expertise of the staff in CTL is excellent, is well aligned to their work, and is widely respected by their peers in the field in all research areas discussed during the panel. Although the COVID pandemic presented several challenges to in-person work, CTL implemented multiple measures to minimize the disruptive impact of the pandemic by prioritizing setting up remote equipment so that employees could conduct work offsite.

NIST is an esteemed institution that has been able to attract strong talent based on its reputation alone. However, one of the major personnel challenges that CTL faces is its inability to compete with industry for highly educated technical researchers based on salary. CTL is working with the Office of Personnel Management to institute special pay rates for NIST researchers, as other agencies such as the Department of Defense have done, to increase its ability to attract and retain top talent. NIST also supports teleworking, allowing significant flexibility to its employees.

ADEQUACY OF RESOURCES

As noted in this report, the panel's assessment was entirely remote, diminishing its ability to meaningfully evaluate CTL's facilities. However, CTL was clear about the shortcomings of some of its laboratories and other facilities that prevent researchers from realizing their full potential (e.g., Building 24). Building 24 on the Boulder, Colorado, campus has a facilities condition rating of −8 on a scale where 72 out of 100 is considered unacceptable. The information technology (IT) infrastructure in the building is also insufficient; the network bandwidth for the entire building of 20 staff members and 12 research laboratories is only 1 Gb/s. Staff move data physically from one laboratory to another by carrying portable hard drives, which is inefficient. Several facilities have lost power and are unable to maintain stable temperatures within measurement chambers, which causes significant delays and is an inefficient use of the staff's time and resources. In some instances, researchers spend project money to rectify facility issues. Some buildings (e.g., Building 3) have been newly renovated and enable researchers to conduct high-quality work. It is clear that, in some instances, poor facility conditions are hampering CTL's ability to accomplish its mission.

EFFECTIVENESS OF DISSEMINATION OF OUTPUTS

The researchers working in the Core Network Technologies group have been very effective in disseminating their work. They publish in top-tier peer-reviewed journals and have presented a number of invited talks. The Named Data Networking forwarder developed by NIST has been adopted by at least one significant research project.

The researchers in the Fundamental Electromagnetic Technologies and Standards research focus area have delivered five direct current/alternating current quantum-based voltage standards. They have also published over 100 publications in top-tier journals, increasing the visibility of the Rydberg Atom-based Quantum Radio Frequency Field Probe, a technology that has the potential to fundamentally change communications.

The researchers working on Next-Generation Wireless Research have engaged in foreign and domestic collaborations, released code via GitHub, and published their works. They have over 35 publications in high-impact journals, have filed more than three patents, and have successfully commercialized that work.

The researchers in the Public Safety Communications Research focus area have a strong track record in disseminating their results through standards, publications, publicly available data sets, application programming interfaces, and open-source tools. Their yearly stakeholder meeting serves to showcase their results and get feedback from public safety stakeholders representing industry, academia, and federal, state, and local government.

The researchers in the Smart Infrastructure and Manufacturing research focus area have published many collaborative papers and delivered a number of keynote presentations. They also publish conference proceedings, as is typical in this research area.

The researchers in the Spectrum Sharing and Sensing research focus area also have a commendable publication record. As with all of the other research areas, they disseminate their work through high-impact journal publications, conference proceedings, and through conference presentations. They have also been able to translate their technology through NIST programs such as the Technology Maturation Accelerator Program and the NIST Science and Technology Entrepreneurship Program.

1

Introduction

What is now called the National Institute of Standards and Technology (NIST) was founded by Congress in 1901 as the National Bureau of Standards. The founding charge was to establish a measurement infrastructure to enhance U.S. industrial competitiveness. NIST is now part of the Department of Commerce with a stated mission "to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life."[1] The Communications Technology Laboratory (CTL) was established in 2014 as a research and development organization to unite NIST's ongoing wireless communications efforts. CTL builds on NIST's long history of radio science and measurement.

Since 1959, the National Academies of Science, Engineering, and Medicine have been contracted to provide assessments of NIST's laboratory programs. The National Academies' assessments are conducted by panels of experts from industry, academia, and other scientific and engineering communities of practice, and each addresses a statement of task provided by NIST.[2] In 2022, at the request of the director of NIST, the National Academies formed the 2022 Panel on Review of the National Institute of Standards and Technology's Communications Technology Laboratory with the following statement of task.

STATEMENT OF TASK

The National Academies shall form a panel of experts who shall perform an independent technical assessment of the quality of NIST's CTL. The panel shall hold a virtual site visit to the CTL in Boulder, Colorado, to conduct an in-depth technical assessment of CTL's work. The panel will then use any materials provided by NIST before the remote site visit, and the results of that site visit, to draft a report that reflects the expert consensus of the panel. The assessment will address the following factors at the request of the NIST Director:

[1] National Institute of Standards and Technology, 2022, "About NIST," https://www.nist.gov/about-nist, accessed September 16, 2022.

[2] A list with links to past assessments can be found at https://www.nist.gov/director/national-academies-national-research-council.

1. Assess the organization’s technical programs.
   - How does the quality of the research compare to similar world-class research in the technical program areas?
   - Is the quality of the technical programs adequate for the organization to reach its technical objectives? How could it be improved?
2. Assess the portfolio of scientific expertise within the organization.
   - Does the organization have world-class scientific expertise in the areas of the organization’s mission and program objectives? If not, in what areas should it be improved?
   - How well does the organization’s scientific expertise support the organization’s technical programs and the organization’s ability to achieve its stated objectives?
3. Assess the adequacy of the organization’s facilities, equipment, and human resources.
   - How well do the facilities, equipment, and human resources support the organization’s technical programs and its ability to achieve its stated objectives? How could they be improved?
4. Assess the effectiveness by which the organization disseminates its program outputs.
   - How well are the organization’s research programs driven by stakeholder needs?
   - How effective are the dissemination methods and technology transfer mechanisms used by the organization? Are these mechanisms sufficiently comprehensive?
   - How well is this organization monitoring stakeholder use and impact of program outputs? How could this be improved?

The CTL director asked the panel to review work in six research focus areas: (1) Core Network Technologies, (2) Fundamental Electromagnetic Technologies and Standards, (3) Next-Generation Wireless Systems, (4) Public Safety Communications Research, (5) Smart Infrastructure and Manufacturing, and (6) Spectrum Sharing and Sensing.

CONDUCT OF THE REVIEW

This assessment is the third National Academies review of CTL, with the previous reviews taking place in 2015 and 2019.[3] In contrast to the two previous reviews that involved visits to the main CTL site in Boulder, Colorado, the information gathering for the 2022 report was done solely remotely due to the ongoing COVID-19 pandemic. This changed the nature of the panel’s information-gathering process in key ways. For example, during the 2019 review, the panelists spent 2.5 days on site at CTL in Boulder, Colorado, providing, in addition to the formal sessions, many opportunities to interact with CTL personnel informally during breaks, lunches, and a dinner arranged specifically to provide additional interaction opportunities. In addition, the onsite review meeting enabled the panelists to tour the Boulder facilities and see demonstrations of some of the laboratory capabilities. This facilitated the evaluation of the facilities, equipment, and capabilities. The lack of these opportunities during this review limited the information that this panel could collect to conduct its work.

The information gathering done by this panel formally began with a review meeting consisting of 2.5 days of online sessions with CTL. The first 2 days largely consisted of CTL presentations with limited time for questions after each presentation. On the third day, there was a question and answer session with time allocated to each focus area. After the initial meeting, the panel provided lists of additional questions to CTL in each of the focus areas. CTL provided written responses to the questions, and there were 1.5-hour online follow-up meetings in five of the six research focus areas to discuss the responses and any other questions the panelists had.[4]

[3] Ibid.
[4] The panelists in one of the research focus areas felt that a follow-up meeting was not necessary.

The panel used the information that CTL provided before and during the online sessions to conduct the assessment using a largely qualitative approach. Time constraints limited the amount of information gathering possible, so the panel focused on the research that the leadership of CTL chose to present. The panel members assessed the factors detailed in the statement of task, to the extent they could, using their professional judgment, their collective knowledge, and experience. Also, this report assesses only the work that CTL is currently doing and any opportunities and challenges related to that work. Questions of what work CTL or any other NIST laboratory should be doing fall under the purview of a separate independent NIST-sponsored body, the Visiting Committee on Advanced Technology. As such, opining on whether CTL is doing the right kinds of research is outside the purview of the panel.

A REMOTE-ONLY REVIEW

Overall, the online format impeded this review and had the following impacts:

- It limited the interactions between the panelists and CTL personnel at the meetings. During the meetings, most of the information was conveyed by area group leaders. Although the leaders were best positioned to summarize the content, especially given the limited time, the panel missed out on interacting with those doing the work.
- In addition, the large group setting of the meetings with various levels of personnel may have further limited the panel's ability to gather information from the researchers working most directly in the research.
- The online format also severely impacted the panel's ability to assess the facilities and equipment, and personnel. The panel members did their best to extract facility information where they could, with varying success.
- It also impacted how well the panelists could process the information being received. The information-gathering process required very long days in front of the computer, working across several time zones.
- It also limited the panelists' interactions with each other and the networking that is often the best part of this kind of volunteering.

On the positive side, the online format enabled the recording of the presentations along with the sidebar conversations and questions in the chat. This allowed for an enduring record of the meetings and was helpful in drafting the report.

Recommendation 1-1: If at all possible, the leadership of NIST's laboratories should ensure that all future assessments have an in-person component to allow the panels to see the facilities and equipment and to interact directly—both formally and informally—with the researchers.

THIS REPORT

This report is structured as follows:

- Chapter 1, Introduction
- Chapter 2, Overview of the Communications Technology Laboratory
- Chapter 3, Core Network Technologies
- Chapter 4, Fundamental Electromagnetic Technologies and Standards
- Chapter 5, Next-Generation Wireless
- Chapter 6, Public Safety Communications Research

- Chapter 7, Smart Infrastructure and Manufacturing
- Chapter 8, Spectrum Sensing and Sharing
- Chapter 9, Facilities, Equipment, and Personnel
- Chapter 10, Assessment of Communications Technology Laboratory Responses to the Key Recommendations of the 2019 Assessment
- Chapter 11, Key Recommendations

This report includes panel recommendations that specify "who should do what" to address any areas that the panel believes warrant action. The panel underpins the recommendations with salient examples of programs and projects that are intended collectively to portray an overall impression of the laboratory, while preserving useful suggestions specific to projects and programs. Key recommendations are those that the panel considers especially worthy of attention.

Each chapter was led by designated chapter teams. While the panel attempted to apply a uniform organization to each chapter, not every chapter team felt that this was possible. Different teams felt that they received different levels of information and wrote their chapters accordingly.

2

Overview of the Communications Technology Laboratory

The Communications Technology Laboratory (CTL) is one of the six laboratories operated by the National Institute of Standards and Technology (NIST).[1] It was established in 2014 to bring NIST's distributed work on wireless communication under the unified leadership of one laboratory. CTL

> Serves as an independent, unbiased arbiter of trusted measurements and standards to government and industry. We focus on developing precision instrumentation and creating test protocols, models and simulation tools to enable a range of emerging wireless technologies.[2]

COMMUNICATIONS TECHNOLOGY LABORATORY REORGANIZATION

In 2021, CTL underwent a reorganization, expanding to include the following five divisions:

1. Core Network Technologies (lead: Abdella Battou, Smart Connected Systems Division chief), comprising
    a. Emerging Network Technologies Program,
        i. Information-Centric Networks,
        ii. 5G/6G Core Networks, and
        iii. Quantum Optical Networking, including metrology, network architectures, and protocols;
    b. Trustworthy Networks Research Program,
        i. Robust Inter-Domain Routing,
        ii. Trustworthy Intelligent Networks,
        iii. Software Defined and Virtualized Networks,
        iv. Trustworthy Network of Things,

[1] The other National Institute of Standards and Technology (NIST) laboratories are the Engineering Laboratory, Information Technology Laboratory, Material Measurement Laboratory, NIST Center for Neutron Research, and Physical Measurement Laboratory.

[2] NIST, 2022, "About CTL," updated May 5, https://www.nist.gov/ctl/about-ctl.

   v. High Assurance Domains, and
   vi. U.S. Government IPv6 Program;
2. Fundamental Electromagnetic Technologies and Standards (lead: Paul Hale, Radio Frequency Technologies Division chief), comprising
   a. Electromagnetic Traceability,
   b. Microwave Measurements for Materials and Electronics,
   c. Over-the-Air Testing, and
   d. Quantum Traceability for Communications;
3. Next-Generation Wireless Systems (lead: Nada Golmie, former Wireless Networks Division chief and current NIST fellow), comprising
   a. Antenna measurements,
   b. Channel sounding and modeling,
   c. Signal models,
   d. Spectrum sharing and metrology, and
   e. Worldwide NextG;
4. Public Safety Communications (lead: Dereck Orr, Public Safety Communications Research Division chief), comprising
   a. Mission Critical Voice,
   b. Location-Based Services, and
   c. User Interface/User Experience;
5. Smart Infrastructure and Manufacturing (lead: David Wollman, Smart Connected Systems Division deputy chief), comprising
   a. Smart Connected Manufacturing,
   b. Smart Grid,
   c. Internet of Things and Infrastructure,
   d. Smart Cities and Communities; and
6. Spectrum Sharing and Sensing (lead: Melissa Midzor, Spectrum Technology and Research Division chief), comprising
   a. Spectrum Sharing, and
   b. Spectrum Sensing.

As part of the reorganization process, CTL undertook an extensive strategic planning exercise. The CTL Strategic Plan[3] describes the planning process, results, and an action plan. The following six research focus areas were identified:

- Core Network Technologies,
- Fundamental Electromagnetic Technologies and Standards,
- Next-Generation Wireless Systems,
- Public Safety Communications,
- Smart Infrastructure and Manufacturing, and
- Spectrum Sharing and Sensing.

The mapping of these focus areas to divisions is shown in Table 2.1. The reorganized CTL leverages existing strengths in research and development, metrology, and standards coordination with an expanded scope, including "wired and wireless communications, spectrum sharing, photonics and quantum communications, as well as other next generation communications

[3] NIST, "CTL Strategic Plan, 2021-2025," https://drive.google.com/file/d/1OcslPrGwdk1l-F8HrqxfdBBFJNw3iBMZ/view, accessed September 21, 2022.

TABLE 2.1 Mapping of the Communications Technology Laboratory (CTL) Research Focus Areas to Its Divisions

	Core Network Technologies	Fundamental Electromagnetic Technologies and Standards	Next-Generation Wireless Systems	Public Safety Communications	Smart Infrastructure and Manufacturing	Spectrum Sharing and Sensing
Public Safety Communications Research Division			x	x	x	
Radio Frequency Technologies Division	x	x	x	x		x
Smart Connected Systems Division	x				x	
Spectrum Technology and Research Division	x		x			x
Wireless Networks Division	x	x	x	x	x	x

SOURCE: National Institute of Standards and Technology Communications Technology Laboratory, 2022, "2022 NASEM Review Materials," Boulder, CO.

modalities, such as Internet of Things (IoT) and smart grid technologies, industrial networking and communications."[4]

For the work in each research focus area CTL draws on multi-disciplinary teams of researchers from across the laboratory, bringing to bear the most relevant expertise to provide standards, tools, and commercialization resources to U.S. industry. This structure is similar to that in NIST's five laboratories performing research to further NIST's six critical and emerging technology areas.

The leaders in each research focus area are responsible for collaborating with their peers and the laboratory office to guide the research direction for the focus area. Project plans are crafted each year to further the capabilities in each focus area or address an industry need. Project plans have defined milestones, staff, and budget and are crafted in collaboration between the division chiefs and research focus area leads. Project Plans are approved by the CTL director. Division chiefs manage staff development, staff hiring, safety, operations, budget, and project implementation.

Given the recent nature of the CTL reorganization, this assessment reflects the fact that there has been limited time for the projects and organizations to make the connections envisioned in the reorganization. The panel believes that as CTL finds new ways to connect various efforts within the organization, opportunities and impact will grow.

Table 2.1 maps CTL's divisions to the six research focus areas. While the table shows that the Radio Frequency Technologies Division and the Wireless Networks Division perform work in the Public Safety Communications research focus area, this is a case of their normal work having public safety communications applications. They are not doing significant work funded by the Public Safety Trust Fund and its expiration is not expected to affect them.

BUDGET

The CTL budget for fiscal year (FY) 2022 is approximately $117 million. The dollar amounts and percentages of the total budget for each focus area are shown in Figure 2.1. The funding trends for each focus area since 2019 are shown in Figure 2.2. Note that prior to the reorganization in 2021, CTL had four research focus areas—Public Safety, Spectrum Testing, Fundamental Metrology, and Next Generation Wireless.

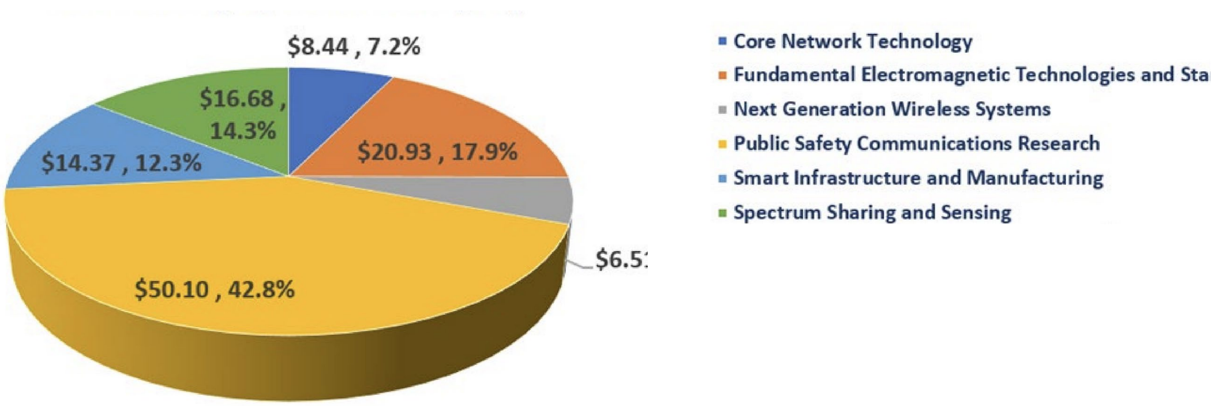

FIGURE 2.1 Communications Technology Laboratory (CTL) fiscal year 2022 budget for each research focus area in millions of dollars. SOURCE: National Institute of Standards and Technology Communications Technology Laboratory, 2022, "2022 NASEM Review Materials," Boulder, CO.

[4] NIST Communications Technology Laboratory (CTL), 2022, "2022 NASEM Review Materials," Boulder, CO.

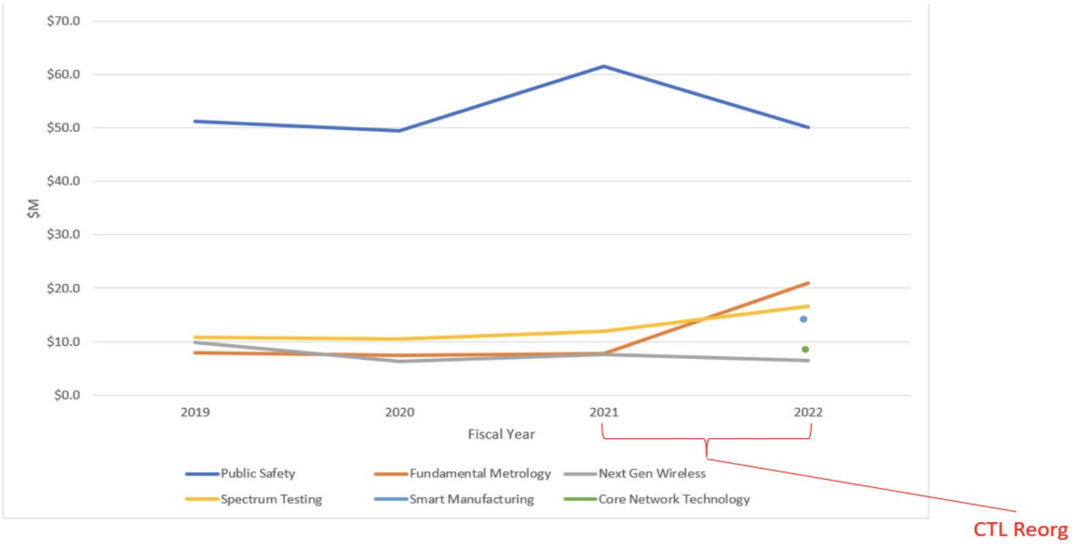

FIGURE 2.2 Communications Technology Laboratory (CTL) spending by research focus area in millions of dollars. SOURCE: National Institute of Standards and Technology Communications Technology Laboratory, 2022, "2022 NASEM Review Materials," Boulder, CO.

TABLE 2.2 Sources of Funding for Fiscal Year 2022 Communications Technology Laboratory (CTL) Budget (in Thousands of Dollars)

	Scientific and Technical Research and Services Base	Non-Base to Date	Other Agencies to Date	Expected Calibrations and Other	Public Safety Communications Research (PSCR)	Total
Current CTL Funding	$23,466.2	$8,594.2	$4,466.4	$300.0	—	$36,826.8
Additions from Reorganization	$26,500.8	$2,030.3	$1,012.5	$561.4	—	$30,105.0
PSCR	$3,250.0	—	—	—	$46,850.7	$50,100.7

SOURCE: National Institute of Standards and Technology Communications Technology Laboratory, 2022, "2022 NASEM Review Materials," Boulder, CO.

CTL funding comes from—largest to smallest— the Public Safety Trust Fund, congressional appropriations, contracted work from other agencies, and calibrations. The amounts of funding from various sources for FY 2022 are shown in Table 2.2. Note that the reorganization more than doubled the amount of the CTL budget coming from congressional appropriations.

Expiration of the Public Safety Trust Fund

FY 2022 is the final year of PSCR funding from the Public Safety Trust Fund. This will result in approximately $50 million less in PSCR spending per year. This fund was always temporary, and the expiration was known all along. As discussed in Chapter 6, the PSCR Division has planned for this and is already working on how to adjust its activities in light of the expiration. It should be noted that most of these funds were not spent internally on CTL research but were directed to outside activities like prize challenges and research grants and contracts. While the change in funding appears to be dramatic, the panel does not believe that it affects any of the non-PSCR parts of CTL.

IMPACTS OF THE CHIPS AND SCIENCE ACT OF 2022

The Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act of 2022 (P.L. 117-167), was signed into law during the preparation of this report. Although this development is too recent for this panel to be able to assess its impact and CTL's response, CTL reports that it has several programs that are well positioned to support the goals of this act. CTL staff have been involved in high-level planning activities to ensure that their project plans are aligned with industry and administration goals. CTL sees the following opportunities in its research focus areas:

- **Fundamental Electromagnetic Metrology and Standards.** This research focus area includes research, development, testing, and evaluation of materials, devices, and circuit design. It also includes the validation and verification work that will support the growth of the U.S. semiconductor value chain. CTL is leveraging partnerships with the International Electronics Manufacturing Initiative (iNEMI), Semiconductor Research Corporation (SRC), and test equipment manufacturers to help with prioritizing research programs in this space.
- **Next Generation Wireless.** Semiconductors are at the core of the wireless communications industry. Understanding complex antenna designs and wireless propagation are key to both the design and testing of wireless chips. CTL will leverage its partnerships through the NextG Channel Model Alliance and the National Science Foundation's Resilient and Intelligent NextG Systems program to provide data, models, and measurement methods to support the design and testing of wireless chips.
- **Smart Infrastructure and Manufacturing.** CTL programs in smart manufacturing, hardware security, and operational technologies support the advanced manufacturing goals of the CHIPS and Science Act of 2022.[5]

STAFF

CTL operates from the NIST campuses in Boulder, Colorado, and Gaithersburg, Maryland. As of May 2022, there are 345 CTL staff. Table 2.3 shows the distribution of the staff type in each division.

Figure 2.3 shows the academic credentials held by CTL federal staff in various career paths. The career paths are defined in the figure caption.

Figure 2.4 shows the distribution of years of service for CTL federal staff, showing that CTL has been successful in hiring and retaining federal staff. Sixty-seven percent of the staff has been at CTL for at least 5 years, and 28 percent has been there for at least 10 years.

[5] Email correspondence between Marla Dowell, director, CTL, and Jim Myska, study director, August 10, 2022.

TABLE 2.3 Communications Technology Laboratory Staff Type in Each Division

	Federal Employees			NIST Associates[a]		
Division	Permanent	Term-Limited	Intermittent	Domestic	Foreign	Total
Headquarters	16	1	0	2	1	20
PSCR	15	19	0	19	0	53
Radio Frequency Technology	27	15	0	39	11	92
Wireless Networks	24	2	2	2	20	50
Smart Connected Systems	30	0	5	9	29	73
Spectrum Technology and Research	17	6	0	26	8	57
Total	129	43	7	97	69	
Grand Totals		179			166	345

[a] NIST associates include guest researchers, research associates, contractors, and other non-NIST employees that require access to the NIST campuses or NIST resources.
SOURCE: National Institute of Standards and Technology Communications Technology Laboratory, 2022, "2022 NASEM Review Materials," Boulder, CO.

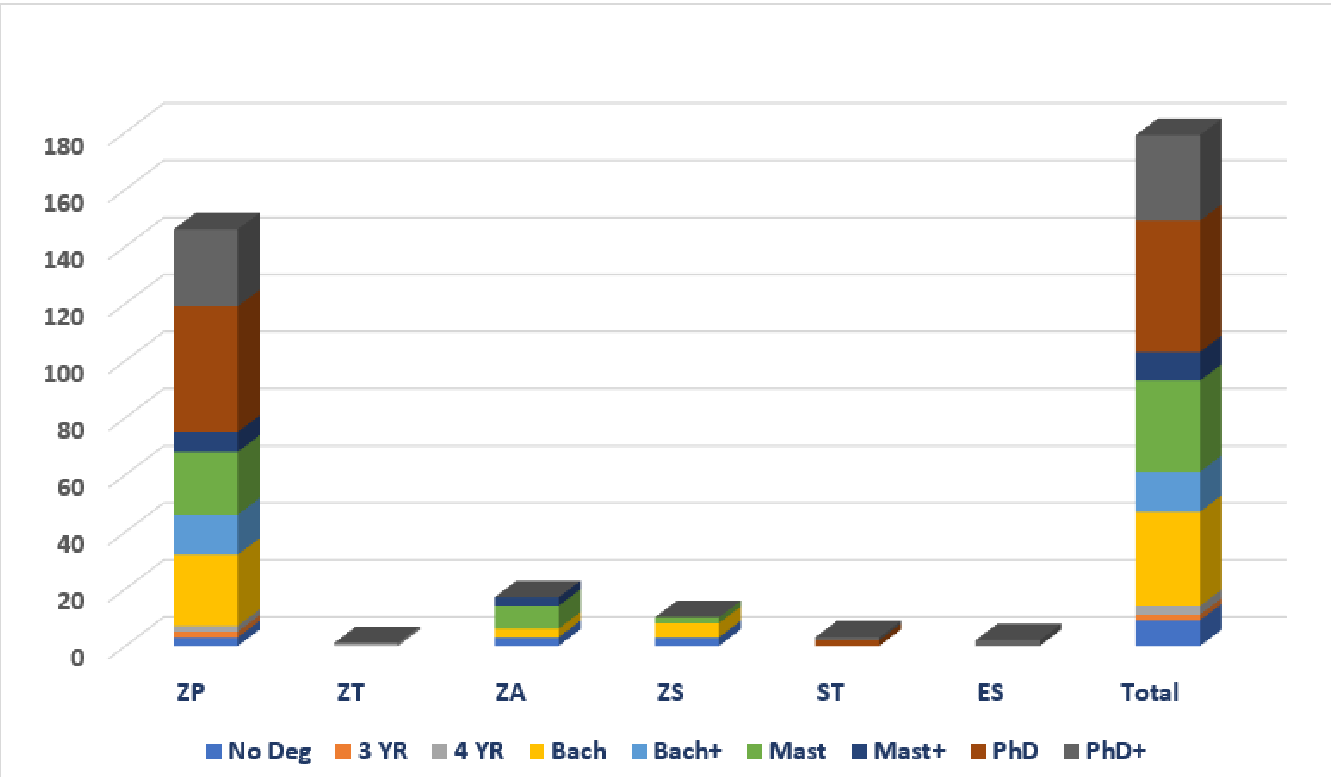

FIGURE 2.3 Federal staff degree by career path. NOTES: No Deg, no degree; 3 YR, 3 years post-high school; 4 YR, 4 years post-high school; Bach, bachelor's degree; Bach+, bachelor's degree plus some graduate education; Mast, master's degree; Mast+, master's degree plus some post-graduate education; PhD, doctoral degree; PhD+ doctoral degree plus some post-graduate education; ZP, scientific and engineering staff; ZT, scientific and engineering technician; ZA, administrative staff; ZS, administrative support staff; ST, NIST fellows and senior research scientists; ES, senior executive. SOURCE: National Institute of Standards and Technology Communications Technology Laboratory, 2022, "2022 NASEM Review Materials," Boulder, CO.

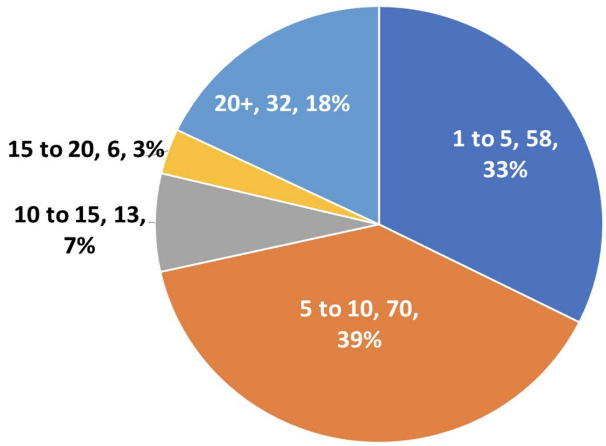

FIGURE 2.4 Communications Technology Laboratory (CTL) federal staff years of service. The numbers in each section of the pie chart give the range of years of service, the number of staff who fall into that category, and the percentage of the total staff that number of staff represents. SOURCE: National Institute of Standards and Technology Communications Technology Laboratory, 2022, "2022 NASEM Review Materials," Boulder, CO.

3

Core Network Technologies

The Core Network Technologies group at the Communications Technology Laboratory (CTL) has two major thrusts, each of which addresses both timely and long-term critical aspects of computer networking. The Emerging Network Technologies program develops metrology, test, and measurement techniques to support new disruptive network technologies, including 5G/6G core networks, quantum networking, and information-centric networks. The Trustworthy Networks Research program concentrates on technologies necessary to increase the security, resilience, and performance of the protocols underpinning the Internet. This includes resolving systemic vulnerabilities in existing and emerging critical network infrastructures and developing new architectures and protocols to improve the trustworthiness of future networks.

OVERALL DISCUSSION

The quantum networking programs have continued to produce notable results through their transition into CTL from other areas of the National Institute of Standards and Technology (NIST). Over the past 2 years, the team has made substantial advances in quantum channel measurement and performance. It has also taken the initial steps toward establishing a testbed for experimentation with optical networking of superconducting quantum nodes together with transduction devices. Having a single infrastructure where various devices and optical channels can be connected and measured in concert will allow both direct comparisons of devices under controlled conditions and enable measurement of more realistic topologies involving repeaters, transducers, and optical channels.

The 5G/6G core network work started in 2021 as part of the Advanced Network Technologies division in the Information Technology Laboratory and was transferred to CTL in the same year. The technical objectives of this program are to advance networking and measurement sciences and promote standards for 6G networks, focusing on core network and end-to-end network services. The current technical focus areas are artificial intelligence (AI), native architectures for 6G core networks, selected foundational technologies (end-to-end service quality assurance, edge AI, automation for network security and resilience, and metrology), and building a testbed.

The trustworthy networks group has two areas of focus: improvements in the robustness and security of Internet protocols (IPs) and initial investigations into a disruptive networking technology—information-centric networking—which has the potential to be the basis for applications that would be difficult to develop using the existing IP suite and could someday replace Transmission Control Protocol (TCP)/IP as the global protocol stack of the Internet.

Area-Wide Challenges and Opportunities

The Quantum Networking program spans a number of groups across NIST, while the quantum channel, quantum transducer, and quantum networking projects were made part of CTL when CTL was reorganized. The participants in this arena have a long track record of productive collaboration that has produced many successes, including some substantial breakthroughs and improvements in the state of the art.

> **Key Recommendation 1:** NIST should ensure there is adequate coordination of work across the multiple laboratories engaged in quantum networking efforts to make sure that synergies and efficiencies are realized and different laboratories do not work at cross purposes, especially across the various NIST laboratories involved in quantum computing and metrology research.

Two notable technical areas in which CTL has shown consistent leadership are the specifications for Border Gateway Protocol (BGP) Route Origin Authorization and its supporting Resource Public Key Infrastructure. BGP is a dynamic routing protocol that automatically learns routes between sites that are connected by using site-to-site VPN connections. This reduces the need for manual route configuration on routers. (Microsoft 2021) This work on BGP is expected to continue for the foreseeable future, as ossification of the IPs and infrastructure makes substantial incremental improvement difficult. One recent potential area of opportunity is the possible adoption of BGPSec (BGP security) in addition to BGP origin authentication. In the past, BGPSec was considered infeasible on core Internet routers due to the heavy computational load, but recent large improvements in the computational capabilities of modern routers allow the community to reassess this.

> **Recommendation 3-1:** CTL should extend the existing NIST-developed metrology to assess the operation and effectiveness of Route Origin Authorization to be able to measure performance and assess the feasibility of BGPSec (BGP security) deployment.

ASSESSMENT OF TECHNICAL PROGRAMS

Accomplishments

Quantum Network Architecture, Protocols, and Metrology

NIST continues to hold a leadership role in the field of quantum channel metrology. A few results are particularly important and worth calling out:

- A world-record for quantum channel efficiency (at 41 percent),
- The achievement of practical remote entanglement, and
- Substantial progress in the creation of practical transducers for the conversion between the radio frequency and optical domains.

5G/6G Core Networks

Because the 5G/6G core network program is new, the focus has been on research, in collaboration with academia and industry, to develop selected networking and measurement technologies to establish the technical foundation that will enable the team to contribute to 6G standardization. It is believed that these will lay the foundation to shift to a user-centric architecture required in 6G. There is not much collaboration with the Next Generation Wireless group currently, but this will be developed in the coming months and years. There are essentially two projects, the Edge AI and Edge Learning Project, and the End-to-End Service Quality Assurance Project.

The goal is to develop edge-enabled learning architectures using machine learning (ML) and algorithms that can address edge-learning challenges. The key challenges are that access nodes and core networks manage their data independently. Establishing some cross-domain work between access nodes and core networks is essential for this project. These are areas that are being explored:

- Resource constraints,
- Non-independent and identically distributed data,
- Data privacy, and
- Security vulnerabilities.

The goal of this project is to develop architectures and algorithms for autonomously managed subsystems to collectively ensure end-to-end service quality. As a result, the researchers have developed a new distributed architecture and algorithm that can enable access nodes and core networks to autonomously "cooperate" with each other to dynamically negotiate their local quality of service budgets and to collectively meet end-to-end quality of service goals by sharing only their estimates of the global constraint functions, without disclosing their local decision variables. They demonstrate that this new distributed algorithm converges to an optimal solution with high probability, and present numerical results to demonstrate that the convergence occurs quickly, even with measurement noise.

The next step will be to limit the amount of information needed to achieve maximal accuracy and rapid convergence without increasing the risk that the algorithm converges too slowly, or converges to a local minimum. This would address the resource constraint, data privacy, and security vulnerabilities objectives listed above.

The goals of the two projects described above aim to advance algorithms for autonomously managed systems, including vehicles, which is relevant to vehicle teleoperation. NIST convened a vehicle teleoperation forum that brought together industry, academic, and government stakeholders to discuss the state of the art, challenges, opportunities, and future directions for research. Examples of thee include performance and safety measurements under resource constraints, and architectural elements that ensure data security and privacy. An industry consortium was created, the Teleoperation Consortium, and NIST is serving on its advisory board. The consortium enables collaboration between the companies, organizations, and governmental bodies engaged in developing bidirectional vehicle communications and standardization needs.

Trustworthy Networks

IP security is a long-standing program (15+ years) with an impressive track record and high ongoing relevance to the broad networking community. The various CTL projects on BGP security continue to hold a leadership role in the networking community. The work on Domain Name System (DNS) security, while somewhat plateauing, continues to be valuable. Notable activities on network protocol security include

- Co-authorship and technical input to BGP protocol security standards;
- Rapid prototyping of proposed standards specifications;
- Measurement and monitoring tools for assessing BGP security, detecting breaches in a timely fashion, and performing forensics after disruptive events; and
- Publication of deployment and best practices guides.

Equally strong to this area has been work on DNS security, particularly the definition and deployment of DNSSEC (DNS Security Extensions) protocols. NIST has been a universally recognized international expert in DNSSEC and has been key to its widespread (albeit slow) deployment after a long gestation period. This is winding down and ought to be credited as a major success for the team. There are, however, opportunities for further engagement, particularly in the privacy arena.

Providing DNS privacy deeply affects the interests of users, DNS operators, and cloud application providers. The proposals under current standardization efforts need to reflect the give-and-take that exists among these parties and strike a good balance of their various interests.

One set of work that CTL has had, tasks associated with the Office of Management and Budget mandate to assist in transitioning government networks to IPv6, is drawing to a close, reaching planned completion in 2025. As a result, resources are being moved incrementally off this effort and will be available for other work.

More recently, the Core Network Technologies group has taken a leading role in industry and standards organizations to define both the processes and technology for the new area of Zero Trust Networking. This effort aims to shift the overall approach to securing networks and their associated applications from one where the level of trust in performing actions is undefined and arbitrary, to one in which actions are by default not allowed and explicit authorization is required for establishing the necessary trust to allow them to take place. CTL's role has been one of

- Defining the essential elements of a zero trust architecture,
- Enumerating general deployment models,
- Providing insight into use cases, and
- Articulating a high-level roadmap for adopting Zero Trust in Enterprise settings.

These elements have been formalized through the publication of a Zero Trust Architecture document (SP 800-207) and a joint demonstration project with a number of industry partners. This work is expected to continue with revisions of the architecture document as more is learned and deployment experience gained, and further formalization of the appropriate elements through standardization in the Internet Engineering Task Force and elsewhere.

The second area of focus on disruptive networking technologies is relatively new. One strong focus of the team is in the creation, enhancement, and maintenance of the NIST high-speed Named Data Networking (NDN) forwarder, which has had a positive reception in the Information Centric Networking (ICN) research community. The high-speed NDN forwarder has been adopted by at least two high-profile research projects in large-scale scientific data—the N-DISE (Named Data Networking for Data Intensive Science Experiments) project using data from the European Organization for Nuclear Research's (CERN's) Large Hadron Collider, and applications to genomics data. This project is quite small (four to five staff), so it is not resourced to be a major influence on the field.

The zero trust networks group has had notable accomplishments in the publication of the Zero Trust Architecture in SP 800-207 and in orchestrating a wide variety and a large number of industry partners to come together to bring coherence to a rapidly evolving arena with a mix of technologies and strong competitive pressures.

Likewise, notable accomplishments in the area of IP Security are the clear ability to declare success for the longstanding work on DNSSEC and playing a key role in the deployment of BGP origin authentication through the Resource Public Key Infrastructure.

CTL has had notable accomplishments in the area of ICN in which it was able to create the NIST high-speed NDN forwarder and its adoption by two high-profile research projects to host and manage the NDN community, which brings together a set of active researchers using the NDN protocol suite for research into ICN. This semi-formal organization hosts workshops for the presentation of in-progress research, the coordination of the NDN testbed network run by the University of California, Los Angeles, and other institutions outside of NIST, and provides email lists for collaboration on an ongoing basis. They also published at least one paper in metrology for ICN networks.

Challenges and Opportunities

Quantum Network Architecture, Protocols, and Metrology

As the field matures, work on actual quantum networking beyond communication over a single quantum channel will gain importance. Emerging areas of research and commercialization of quantum network technology include

- Quantum repeater implementation and metrology,
- Network-wide measurement techniques (going beyond measuring single channels), and
- More complex entanglement schemes that can enable multicast, among other useful capabilities.

There are significant opportunities for NIST to provide leadership in a number of emerging areas, such as quantum repeater implementation and metrology, network-wide measurement techniques (going beyond measuring single channels), and more complex entanglement schemes. The management of quantum channels using protocols running over paired classical channels is a rapidly evolving area for which CTL expertise (in the robust networking group) for secure and performant protocol design is important to exploit.

5G/6G Core Networks

The 5G/6G core networks program has developed a state-of-the-art federated learning algorithm, an AI/ML technology, for non-independent and identically distributed data simulation with proven convergence. The next steps are algorithms that can address all four challenges: 5G and 6G networks, energy efficiencies, data management, and digital twins.

Key Recommendation 2: CTL should establish an artificial intelligence (AI)/machine learning (ML) 5-year roadmap. This roadmap should include the application of AI and ML to 5G and 6G core networks, energy efficiencies, data management, and digital twins.

CTL needs to be very selective in determining which areas to focus on because the 5G/6G core networks program is only about 1 year old and has barely started. This area is very broad and complex. CTL appears to be making progress in all areas where resources have been allocated (i.e., resource constraints, non-independent and identically distributed data, data privacy, and security vulnerabilities) and it hopes to expand the program moving forward.

CTL has recognized that building a 5G testbed would be a great research asset and it is working toward that goal. CTL wants to develop an open-source 5G testbed that could also be used in the context of beyond 5G and 6G core networks. This core network would support radio access networks and applications across NIST and various government agencies. This would hopefully be used to establish internationally federated testbeds to support global research collaboration and explore new federated networking capabilities.

So far, the software and hardware acquisition for the testbed are in progress, but no details on the status of those acquisitions were provided. CTL has established a global collaboration team to develop federated 5G testbeds. They are leveraging the Institute of Electrical and Electronics Engineers (IEEE) 2302 Standard that the group led to developing federated 5G testbeds with a number of partners such as the Electronics and Telecommunications Research Institute, Mobigen, INSoft, Katech, Kiat-USA, the University of Arizona, and the University of Missouri-Kansas City. They had a kick-off meeting on May 16-18, 2022, at NIST.

One of the key challenges will be to secure funding and add resources to maintain the momentum gathered in the first year. Surely a case could be made that 5G/6G core networks is worthy of attracting some funding from the CHIPS and Science Act of 2022 (P.L. 117-167), but a solid 5-year roadmap needs to be in place in the near future.

> **Key Recommendation 3:** CTL should accelerate the development of a testbed with the Next-Generation Wireless team to enable a system that can fully test 5G/6G systems. CTL should foster collaboration between the Core Networks and Next-Generation Wireless teams to find and leverage synergies.

Trustworthy Networks

In the trustworthy networks group, aside from the BGPSec possibilities noted above, more disruptive activities are in progress (mostly in Europe) on finally replacing BGP with a protocol that has much better security characteristics while enabling more flexible and higher performance path selection. NIST could take a role in helping to evaluate the potential benefits of such approaches, particularly the SCION protocol family and other protocols being considered by the Path Aware Networking Research Group (part of the Internet Research Task Force). NIST could also help determine the feasibility and the various trade-offs needed to consider such a transition.

> **Recommendation 3-2:** CTL should increase its involvement in new routing technologies for global Internet routing through experimentation and analysis of initial deployments of SCION and other protocols under consideration by the Path Aware Networking Research Group.

As the deployment of DNSSEC has become essentially routine, the focus of DNS security has pivoted to the privacy aspects. NIST could take a more active role in developing measurement and evaluation tools for DNS privacy; help balance the interests of large cloud providers, DNS service providers, and users; and help determine which protocols (e.g., DNS over TLS, DNS over HTTP, oblivious DNS) get deployed and how the protocols are managed.

> **Recommendation 3-3:** CTL should take a more active role in the development and dissemination of measurement and evaluation tools for DNS privacy; help to balance the interests of large cloud providers, DNS service providers, and users; and help determine which protocols (e.g., DNS over TLS, DNS over HTTP, Oblivious DNS) get deployed and how they are managed.

For Zero Trust Networks, keeping up with this rapidly evolving arena will require resources of multiple types, including architecture, tools development, and some novel metrology to both assess effectiveness and to perform forensics when failures of the various protocols, algorithms, and code are discovered. There is also some danger that the current enthusiasm goes through a “trough of disillusionment” when the inevitable limitations of the approach become more generally recognized. Zero trust networking research and metrology require resources of multiple types, as noted above. It is important to match the skill portfolio to the emerging tasks in this area.

For ICNs, there is an opportunity to expand adoption of the NIST high-speed NDN forwarder and make it either a co-reference or a replacement reference for the now quite old and messy Network Forwarding Daemon. However, doing so will require a significant expansion of support capability, and of the tooling needed to rapidly incorporate new functionality introduced by researchers. Further along, making this forwarder the focus of an expanded NDN testbed that covers Internet scale could enhance both the adoption and rapid evolution of ICN in both the research community and industry.

The adoption of ICN beyond a small research community has been slow and does not appear to be on the verge of a breakout with significant industrial and commercial participation. Even in certain niches, like industrial control, vehicular networking, or ad hoc wireless networks, interest has been spotty. There is a non-trivial risk that interest in ICN will wane.

Given NIST's expertise in metrology, placing more focus and resources on measurement tools, synthetic and real traffic trace generation and maintenance, and publications to provide apples-to-apples comparisons of various ICN protocols and architectures would be a major contribution to the field.

Recommendation 3-4: There is a non-trivial risk that interest in Information Centric Networking (ICN) will wane. CTL should reassess its ICN projects in 1 to 2 years to see if they still represent a good use of NIST's limited resources.

Advanced Distributed Denial of Service Attack Mitigation Techniques

CTL was actively looking into the distributed denial of service attack mitigation techniques before its re-organization. The security of the 5G/next-generation networks needs to be measured and assessed for deployment in national laboratories and public safety research centers more than ever before, because the commoditization of 5G core allows for amplification attacks from a single Radio Access Network to infiltrate multi-vendor core networks, thereby increasing security risks.[1]

Recommendation 3-5: CTL should continue its distributed denial of service attack mitigation work as it applies to 5G Radio Access Network security.

PORTFOLIO OF SCIENTIFIC EXPERTISE

Accomplishments

The staff working on IPs is strong and has maintained impressive continuity over many years, while successfully integrating new personnel as needed. Through its history as part of the security focus in the Information Technology Laboratory, this group has a good reputation and can recruit top talent.

The staff on the NDN project is new and partially drawn from finishing students from universities working in this area. They have done a considerable amount of work, and, in the creation of the high-speed NDN forwarder, have accomplished quite a bit for a small group.

For the Quantum Network Architecture, Protocols, and Metrology group, the movement to CTL has not slowed progress in this emerging area, and the scientific team has been well absorbed into CTL's overall program of work. This group has authored numerous publications at the cutting edge of quantum metrology, channel efficiency, transducers, and remote entanglement generation. The work has been picked up by various teams working in the same area, such as the groups at Keio University in Japan and Delft University in the Netherlands. As this is a rapidly evolving and growing area of research and

[1] Amplification attacks allow and attacker to dramatically increase the power of an attack, yielding significant consequences from a relatively small amount of attack resources. For more information see https://www.radware.com/security/ddos-knowledge-center/ddospedia/amplification-attack.

eventual standardization, expanding staffing levels on these projects will enable NIST to remain a leader in quantum metrology, quantum channel design, and the architecture of quantum networks.

The 5G/6G Core Networks group has been active and influential. In only its first year of existence, this group has submitted over 20 papers and has given over 30 presentations and invited talks. In addition, they helped establish the Teleoperation Consortium.

Challenges and Opportunities

In the area of Internet protocol work with BGP, continued efforts are seeing less reward as this work has been widely adopted and is in near-universal use by Internet service providers. Hence, either moving on to new areas or finding additional challenges in privacy and security to tackle would allow CTL to continue and potentially enhance its leadership in trustworthy networks.

For the disruptive networking, and especially the ICN work, this needs to be expanded with more staff to increase progress on the forwarder work and to undertake additional metrology projects, such as the creation of synthetic traces and the tools to measure ICN networks.

Core networks is a wide area to investigate and there are numerous opportunities; one of the main challenges is to identify where to invest very limited resources. New network and service orchestration solutions exploiting AI and ML will result in significant network automation that will reduce operating costs. This is an area that CTL chose to address with their limited staff, but other areas, such as Service Base Architecture,[2] which could be an enabler to a network that continuously adapts to communication conditions, could be an interesting area of focus in the future.

EFFECTIVE DISSEMINATION OF OUTPUTS

Accomplishments

Much has been achieved with a limited staff of 6-8 members with the 5G/6G Core Networks group. As mentioned previously, in only its first year of existence, this group has submitted or published over 20 significant papers and has given over 30 presentations and invited talks. In addition, they helped establish the Teleoperation Consortium.

The work on IPs protocols continues to produce a variety of extremely valuable outputs, from standards publications in the Internet Engineering Task Force, to various guides, to implementers and network operators that serve as "go-to" references for a large fraction of the Internet community.

The ICN work has produced a few meaningful publications that are well regarded and were presented at the top research conference in the field (the Association for Computing Machinery's Information-centric Networking Conference). The NIST NDN forwarder has been adopted by at least one significant research project (N-DISE) and is a critical part of that project's needed infrastructure. In addition, NIST's role as host/organizer of the NDN community meetings helps the NDN part of the ICN research community to have a forum for sharing ideas and intermediate results. The panel was not able to discern any challenges or opportunities in this area.

[2] "Service-Based Architectures provide a modular framework from which common applications can be deployed using components of varying sources and suppliers. The 3GPP defines a Service-Based Architecture (SBA), whereby the control plane functionality and common data repositories of a 5G network are delivered by way of a set of interconnected Network Functions (NFs), each with authorization to access each other's services." What is the 5G Service-Based Architecture (SBA)?, https://www.metaswitch.com/knowledge-center/reference/what-is-the-5g-service-based-architecture-sba, accessed November 7, 2022.

4

Fundamental Electromagnetic Technologies and Standards

This chapter addresses the Fundamental Electromagnetic Technologies and Standards (FETS) research focus area. FETS is supported by the Radio Frequency Technology Division, which provides solutions by capitalizing on and leveraging its expertise in the following four research groups: (1) Guided Wave Electromagnetics, (2) Electromagnetic Fields, (3) High-Speed Waveform Metrology, and (4) Superconductor Electronics. The last group was added during the recent reorganization. Outcomes of the FETS focus area address specific high-impact fundamental problems and provide solutions that support the five other research focus areas in the Communications Technology Laboratory (CTL).

To ensure future impact and keep advances in CTL technologies and standards relevant, CTL collaborates with four other National Institute of Standards and Technology (NIST) laboratories—the Physical Measurement Laboratory, the Information Technology Laboratory, the Material Management Laboratory (MML), and the Engineering Laboratory. The work with the MML is on the Material Measurement Laboratory mega-qubit Innovations in Measurement Science (IMS) project, which CTL leads, and the electric-acoustic spectroscopy project, which the MML leads. The aim is to address grand challenge–like problems of key interest to industry and the nation through the IMS program as either lead or support.

OVERALL DISCUSSION

To perform its research mission on metrology, CTL's funding is adequate and stable. The Radio Frequency Technology Division does, however, need to continue to seek support to upgrade facilities that are currently lacking. The current state of these facilities hinders its ability to provide services related to standards testing. The team of scientists and technologists is excellent, highly productive, and actively engaged across CTL divisions and NIST laboratories, which provides enhanced productivity and a strong interdisciplinary technical culture.

CTL staff have identified important metrology projects to support current and future communications needs. It has a strong foundation in solving fundamental problems and good strategies for near-term measurement challenges. Since the reorganization, it also has a clearer strategy for establishing emerging measurement methods (e.g., over-the-air testing) and is actively pursuing beta testing of such ideas in projects associated with its inter-laboratory IMS collaborations. Because of the number of projects and the high level of integration with other projects, the effort from the Radio Frequency Technology Division with different focus areas and laboratories needs to show the depth and breadth of connectivity. Due to the fundamental nature of the work, it was difficult to see the full impact until after all other presentations were given. In addition, it was unclear how to determine which projects are emerging, active, sunsetting, or required for legacy purposes. Clarification of these would better convey the relevance, value, and impact of the FETS focus area by this division within CTL.

The importance of the work within the Radio Frequency Technology Division is evident, and a highly trained workforce is necessary to maintain such high-quality work. CTL's commitment to hiring excellent people is clear, and its understanding of the need to diversify its future workforce more urgently was evident by the staff and programs being developed at the management and leadership level. Specific strategies at the division level to support the diversification of its technical workforce were less clear. Developing these strategies in collaboration with divisions would allow for a more synergistic approach for implementation. Efforts to make select versions of the work accessible to lay audiences and youth could help with NIST branding nationwide and support CTL's goals for diversifying its workforce, especially in locations where demographics are less diverse. CTL's goals to diversify the future workforce are embedded into the highest leadership level.

The CTL metrology staff are experts with years of experience in providing consistent and diligent dissemination of their scientific and technical findings to the broader community of technical professionals and stakeholders.

The FETS focus area is important and it has the capacity to grow, especially if the facility's challenges are addressed regarding the emerging needs of new technology and application areas. Its growth will play an important role in serving the nation's needs and expansions in communication technology. It was clearly communicated that equipment upgrades are needed. With the pandemic constraints, the Radio Frequency Technology Division made significant efforts to move forward by developing alternative solutions for in-person and remote access to work in response to the pandemic. Some conventional measurement and standard services were impacted by equipment limitations due to building upgrade delays. Equipment and facilities are discussed in Chapter 9.

The CTL physical infrastructure was mostly sufficient for its previous programs. Since the pandemic began in early 2020, however, delays in facilities access have made such upgrades even more important for the Radio Frequency Technology Division. Despite these delays, CTL has been extremely productive in its FETS focus area, and the outcomes of this effort could be observed in the other focus area projects and IMS projects presented.

CTL's work in electromagnetics and quantum science for communications are outstanding and important for next-generation advancements. Over-the-air testing standards development has emerged over several years, and CTL is leading in that effort, which is revitalizing the measurement space for antenna research related to communications and the advanced systems and standards developed over the past two decades. Finally, the strength of CTL's microwave measurements for materials and electronics by the Radio Frequency Technology Division for many decades has provided and continues to provide important test and measurement methods, standards, and data. These efforts help industry establish protocols, especially for integrated circuit chips, for determining acceptable performance metrics and standards for high-speed communication circuits and devices used frequently in consumer electronics and scientific government applications. CTL's development of quantum-based technologies advances FETS standards and traceability into a new generation of accuracy.

The FETS research area stakeholders comprise diverse community members (i.e., industry, government, academia, and research communities). Moreover, the FETS research focus area stakeholders have a wide range of needs from basic science and engineering to applied research and technology that can benefit from the development of different test and measurement capabilities, research facilities, and experts who can address the different stakeholder projects. The IMS projects may have similar needs and requirements for unique test and measurement capabilities, facilities, and experts. While performance metrics for the different technologies are easier to quantify at the fundamental level, clarification of how uniquely designed integrated systems platforms are evaluated needs to be included.

CTL has diverse technical expertise in its world-class staff. CTL's restructured research focus areas makes it easier to see the collaborations between the laboratories of divisions and inter-laboratory collaborations between IMS projects (e.g., with the Physical Measurement Laboratory, Information Technology Laboratory, and Engineering Laboratory). The reorganization created tremendous strength in CTL.

Area-Wide Challenges and Opportunities

The collaboration between the superconducting and electromagnetic research groups within the Radio Frequency Technology Division offers even greater potential for advancement by applying these technologies to support the other research focus areas. Continued investigation in enabling quantum computing and sensing can revolutionize communication, networking, and other related industries through high-performance and energy-efficient components. CTL's fundamental research and development can serve as an incubator and seedling for further government, academic, and industry innovation as components evolve and systems are integrated. CTL's creation of precise measurement equipment based on quantum and superconducting electromagnetic concepts also has the potential to provide independent test and measurement evaluation of candidate systems from other research organizations—an ideal testbed.

> **Recommendation 4-1:** CTL should continue to advance its work in quantum information science and engineering and leverage the strengths of the superconductor group, recently added to the Radio Frequency Technology Division. It should also continue to find ways to co-integrate different technological systems (e.g., electrical, optical, and quantum) effectively to support the direction of industry and government.

Integration of CTL projects with the work of other NIST laboratories, both as lead and collaborator, was strong and needs to be continued to ensure that the efforts within CTL are tracking with new directions and emerging fields.

> **Key Recommendation 4:** Given the fundamental nature of FETS, the Radio Frequency Technology Division should create a system or database that tags key projects and links them to other work within or between different CTL focus areas, divisions, or NIST laboratory projects. Such a system would provide tracking of the work throughout CTL and allow others to better understand the connections, impacts, uses, evolution, and sunsetting of the work.

ASSESSMENT OF TECHNICAL PROGRAMS

The Radio Frequency Technology Division executes various projects within the four major program areas of

- Electromagnetic traceability,
- Microwave measurements for materials and electronics,
- Over-the-air testing, and
- Quantum traceability for communications.

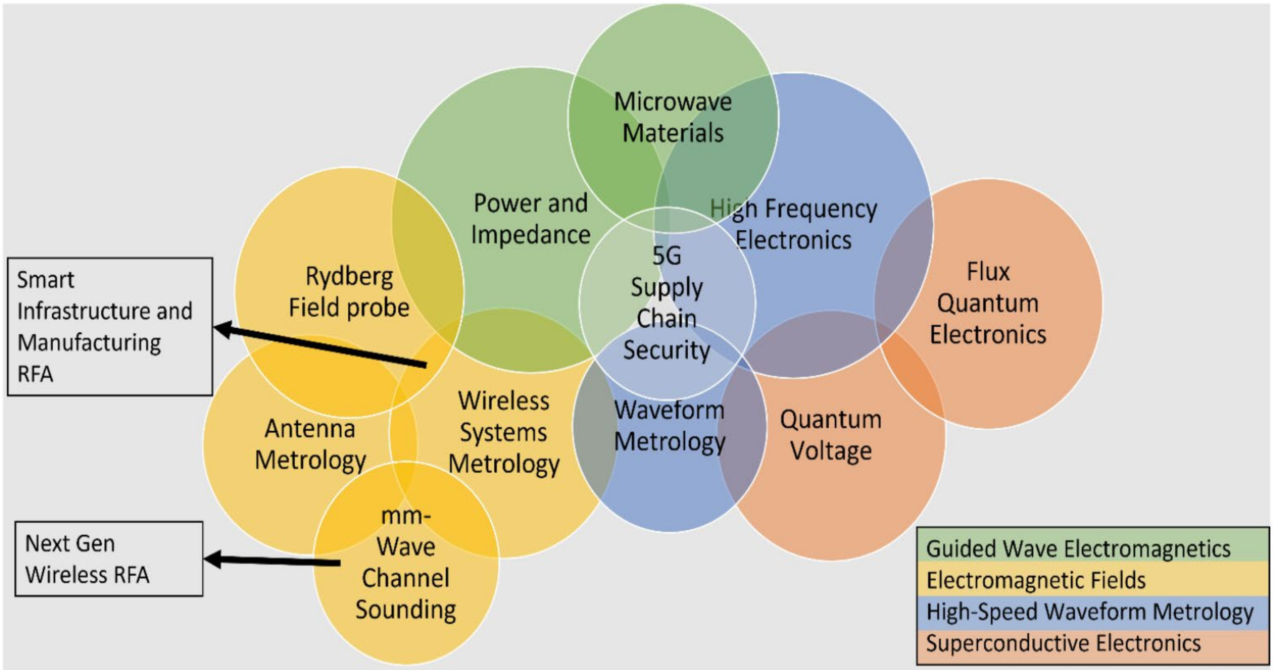

FIGURE 4.1 Venn diagram showing cross-fertilization between Radio Frequency Technology Division research groups and their interdisciplinary projects. SOURCE: National Institute of Standards and Technology Communications Technology Laboratory, 2022, "2022 NASEM Review Materials," Boulder, CO.

These major program areas can be further broken down into interdisciplinary projects requiring the contribution of multiple research groups within the Radio Frequency Technology Division. Figure 4.1 provides a Venn diagram depicting the relationships of those projects with the four Radio Frequency Technology Division research groups and their connection to other research focus areas.

These projects cover a wide range of fundamental radio frequency measurement problems for both classical and quantum radio frequency metrology. CTL continues to pave the way in developing and delivering better measurement technologies. The world-class quality of its research in fundamental metrology is proven through successful international intercomparisons and dissemination of intrinsically accurate quantum artifact standards. Due to its standing, CTL's Radio Frequency Technology Division provides various measurement services and is working on future measurements and standards identified as industry needs. Projects focused on characterizing uncertainty of radio frequency quantities, extending the frequency range coverage of measurement technology, and addressing emerging new applications are appropriately chosen to ensure that the Radio Frequency Technology Division can reach its technical objectives for stakeholders in academia, government, and industry.

Accomplishments

Projects chosen within the FETS research focus area simultaneously focus on enhancing existing classical radio frequency metrology and developing new quantum-based metrology to address industry trends and needs. CTL's Radio Frequency Technology Division maintains the U.S. national standards for various radio frequency measurements and has deep expertise in International System of Units (SI)-

traceable radio frequency measurement technology.[1] The division has continually focused on increasing the frequency range in which that expertise and standards exist. With the interest in higher and higher communication operating frequencies, both fundamental and harmonic frequencies within the microwave and millimeter-wave bands need to be characterized for all communication components. This has led CTL to execute multiple projects focused on

1. Extending the NIST microwave uncertainty framework to include traceability for uncertainty above 100 GHz under dynamic conditions (change in time, position, or angle of arrival), and/or using correlative analysis;
2. SI-traceable measurements, models, and tools for authenticity, design, security, characterization, and verification of hardware and materials to include semiconductors, on-wafer integrated circuits, optoelectronics and photonics, three-dimensional microelectronics, and microfluidic chips; and
3. Over-the-air testing for high-frequency and complex radio frequency channels using synthetic aperture measurements under the SAMURAI project[2] and developing test environments and performance tools for the design and verification of millimeter-wave, industrial Internet of Things applications.

In addition to its growth in classical radio frequency metrology, CTL has developed and delivered multiple innovations in quantum standards. One such accomplishment is the delivery of Programmable Josephson Voltage Standards Reference Instruments that are intrinsically accurate and based on quantum effects as a new SI traceable reference for the volt. The Programmable Josephson Voltage Standards Reference direct current-to-direct current comparison agreement is 3×10^{-11} V/V, an order of magnitude better than previous electrochemical battery artifacts. In addition, this technology has been leveraged to develop the Josephson Arbitrary Waveform synthesis at radio frequencies with statistical uncertainty below 1×10^{-7}, which is more than two orders of magnitude better than current alternating current calibrators. These developments not only improve the accuracy of standards and measurements worldwide, but the technology opens doors to more promising applications of quantum-based sources for future radio frequency communication, computing, and qubit control. CTL is currently engaged in several projects to focus on these future applications.

The development, demonstration, and dissemination of the Rydberg atom-based sensors is another CTL achievement with significant potential to revolutionize communications. CTL continues to enhance the technology by working on the development of arrays of Rydberg sensors for direction finding and beamforming, the evolution of the original Rydberg atom-based radio receiver, and exploring other measurement and calibration possibilities. CTL recently demonstrated the ability to measure phase at different locations within a cell to determine the angle of arrival of an incoming radio signal. The continued evolution of such an environment-independent and electromagnetically sensitive sensor directly aligns with the need for extreme bandwidth, miniaturized, radio frequency sensor technology for all applications currently using antennas. The progression in Rydberg atom projects shows an intentional technical plan to continue to add capability that could lead to the replacement of conventional antennas for a number of communication-related applications.

In response to the 2019 assessment by the National Academies of Sciences, Engineering, and Medicine,[3] CTL has participated in several IMS projects in collaboration with other NIST laboratories. These projects cover a range of topics by leveraging the Radio Frequency Technology Division's

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[1] When something is SI-traceable, it means that it can be traced back to established SI standards. The SI is the International System of Units.

[2] For more information see https://www.nist.gov/publications/welcome-samurais-software.

[3] National Academies of Sciences, Engineering, and Medicine (NASEM), 2019, *An Assessment of the Communications Technology Laboratory at the National Institute of Standards and Technology: Fiscal Year 2019*, Washington, DC: The National Academies Press, https://doi.org/10.17226/25602.

expertise in measurement, uncertainty improvement, and electromagnetics. CTL has done well to ensure that each project supports the further expansion of its capability into higher frequencies (sometimes even leaving the radio frequency spectrum) and quantum technology (or at least investigating electromagnetics at a molecular level). These activities have contributed to capital investments in facilities for CTL as new ranges and laboratories are created in support of them.

Lastly, critical to the Radio Frequency Technology Division's core function of providing accurate measurements, CTL completed a 5-year quality assessment of the division's measurement services in 2020. In 2021, the Radio Frequency Technology Division also received re-approval from the Inter-American Metrology System and had the first quality management system that NIST accredited to the full requirements of the new ISO/IEC standard 7025:2017. This speaks well of CTL and the quality of its people and processes by reaching this milestone during the pandemic.

Challenges and Opportunities

The extension of traceability to include more complex factors to uncertainty becomes not only a challenge in the method of collection, but also in data recording. The scale of data required to characterize a measurement not only spectrally, but now temporally, spatially, and directionally, could be a significant big data problem. CTL currently develops and distributes various software packages for managing NIST traceability, uncertainty, and measurement data. Examples are the NIST Microwave Uncertainty Framework, classical and quantum calibration software modules, and software products from the NextG Channel Model Alliance.

> **Recommendation 4-2:** CTL should continue to provide NIST software updates and additions to the broader community that evolve along with the growing complexity of its metrology data sets as one way of avoiding a future big data problem.

The Rydberg atom arrays are a prime opportunity for CTL to lead the way and warrant maximum effort, because more system-level analysis, design, and development are needed to mature the technology. There are a number of challenges in terms of realizable instantaneous bandwidth and system size, weight, and power. This could be done in partnership with external organizations, such as the Defense Advanced Research Projects Agency (DARPA), the Intelligence Advanced Research Projects Activity, the National Aeronautics and Space Administration, and military research laboratories, which have focus and experience in transitioning technologies from research into operational deployment. However, CTL's experience would be critical to ensuring that performance gains are not lost.

> **Recommendation 4-3:** CTL should continue to seek more Rydberg atom sensor-focused external partnerships with organizations like the Defense Advanced Research Projects Agency, the Intelligence Advanced Research Projects Activity, the National Aeronautics and Space Administration, and military research laboratories, which have focus and experience in transitioning technologies from research into operational deployment. Collaboration with other NIST laboratories to address size, weight, and power improvement and system-level issues through other advanced technology being developed in those laboratories would further advance the evolution of Rydberg atom-based capabilities.

Authenticity verification for communication hardware and microelectronics is of national concern. CTL has engaged stakeholders through workshops and reports. Although there are currently discussions on developing use cases, a primary enabler for this is the ability to perform the required measurements at different facilities with different equipment; this requires calibrated measurements traceable to NIST. The derived uncertainty of those measurements needs to be well below the tolerance of the authentication parameter to be measured. Given the current supply-chain issues in a post-pandemic economy, this is an urgent problem. As materials and products become scarcer, the need to diversify sourcing becomes greater, which results in a growing reliance on foreign suppliers or multiple suppliers for the same component to avoid catastrophic delays. This reliance accelerates accepting the increased risk of acquiring suspect counterfeit or malicious components. This acceleration needs to be met by an equally accelerated effort to triage the potential counterfeit part epidemic.

Recommendation 4-4: CTL should begin developing an authentication demonstrator based on existing measurement capabilities to provide a testbed to help develop and experiment with possible use cases; identify needed technology enablers; and quantify current performance gaps. The demonstrator would include selecting a component that can be acquired from multiple diverse suppliers, including known counterfeit versions, and quantifying variability across units in every parameter that CTL can currently measure. If external funding is not available at this time, an IMS project could be the best vehicle for such an investigation.

Calibrations—Ebbs and Flows

The Radio Frequency Technology Division quality assessment conducted in 2020 provided the number of calibrations performed each year from 2016 to 2020. The trend showed the number at nearly 4,000 in 2016, falling to 1,200 in 2018, and having a large increase to over 6,000 in 2019. It was not clear if this 500 percent increase in a single year was a result of the National Academies' 2019 assessment.[4] However, 2020 had less than 2,300 calibrations, which could be a result of multiple issues, including the pandemic or could just indicate that the number of calibrations in 2019 was an anomaly. Given that NIST is known for its calibration work and CTL is heavily investing in developing advanced calibration methods and tools, the amount of calibration work conducted by CTL may be an indicator of, or a contributor to, CTL's accomplishments or issues.

Key Recommendation 5: CTL should investigate the reasons behind the trend in the number of calibrations performed annually. Specifically, CTL should understand (1) the significant drop in 2018, (2) the surge in 2019, and (3) the trend during the pandemic. The results of this investigation should inform a strategic plan for determining if there needs to be a goal for achieving the desired amount of CTL calibration work and what that amount might be.

PORTFOLIO OF SCIENTIFIC EXPERTISE

Accomplishments

The Radio Frequency Technology Division has four research groups, led by a group leader, with team members in either the technical staff or associate category.

1. Radio Frequency Electronics has 9 staff and 11 associates.
2. Radio Frequency Fields has 7 staff and 19 associates.
3. High-Speed Measurements has 7 staff and 10 associates.
4. Superconductivity has 11 staff and 6 associates.

The division headquarters has four staff and one associate. In total, there are 37 staff members and 46 associates. The Superconductivity group joined the division in fiscal year 2022.

[4] Ibid.

Due to the virtual format of the 2022 assessment, there was limited interaction with the Radio Frequency Technology Division staff. The interaction was limited to the division leaders and presentations from select team leads. However, the high-performing work product of the division demonstrates the expertise of the staff. The division team continues to lead SI-traceable measurements and has been focusing on improving the infrastructure capability to ensure that its constituents—other laboratories, industry, and government—receive the precision of measurements needed. This places CTL as a leader in the field. In addition, the Rydberg Atom-based Quantum Radio-Frequency Field Probe[5] work is a highly productive effort that provides high visibility for CTL, increases its interagency collaboration within and outside of NIST, and positions it to play a key role in the upcoming NIST-on-a-chip funding effort.[6] Other high-performing areas include leading efforts for precision materials measurements as well as quantum voltage measurements that are both essential for emerging topics of high priority to industry in heterogeneous integration and advanced devices as well as in computing.

Challenges and Opportunities

Since the National Academies' 2019 assessment,[7] the Radio Frequency Technology Division experienced several leadership changes resulting in acting personnel for division chief and three group leader roles. Currently, all roles are filled, starting with division chief in 2020 and various group leader roles in 2021. The new structure allows divisions to work on focus area projects as well as collaborative projects with other groups. It appears to be a good, and timely, fit and provides the organization with interconnections between the strong disciplinary nature of divisions to advance fundamentals while supporting and advancing the goals and objectives of the interdisciplinary nature of IMS projects.

As the complexity of collaborative and interdisciplinary projects grows, it may be necessary to consider hiring personnel who can cross the vertical and horizontal layers between fundamentals and applications, especially as materials, devices, and hardware systems become more integrated with software and software technologies like artificial intelligence and machine learning.

Recommendation 4-5: CTL should continue to evaluate the needs for testing between technologies—wired and wireless, electronic, optical, and quantum for communication and computing—and collaborate with other laboratories within NIST to help determine planning and funding needs.

EFFECTIVE DISSEMINATION OF OUTPUTS

Publications and patents were a consistent mechanism for the delivery of outcomes and showcased the high quality, significance, and visibility of research such as the Rydberg Atom-based Quantum Radio Frequency Field Probe and quantum voltage efforts.

Accomplishments

The Radio Frequency Technology Division has had the following accomplishments:

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[5] For more information see https://www.nist.gov/programs-projects/rydberg-atom-based-quantum-rf-field-probes.

[6] For more information about NIST-on-a-chip, see https://www.nist.gov/noac.

[7] NASEM, 2019, *An Assessment of the Communications Technology Laboratory at the National Institute of Standards and Technology: Fiscal Year 2019*, Washington, DC: The National Academies Press, https://doi.org/10.17226/25602.

- Five direct current/alternating current quantum-based voltage standards, with four more planned for 2022;
- Continued maintenance of U.S. national standards for S-parameters, radio frequency power, inter-frequency phase, antenna gain, thermal noise, field strength, and Josephson volt work; and
- Research outcomes in top-tier journals in the following projects with high productivity (over 100 publications), high visibility, and inter-agency support for CTL across the four research groups:
    1. Rydberg Atom-based Quantum Radio Frequency Field Probe: five programs at other agencies, 47 publications, 6 patents (3 granted, 2 filed, 1 with NIST legal), 2 related IMS programs, NIST-on-a-chip funding, and 1 Cooperative Research and Development Agreement (CRADA);
    2. Microwave Materials: 2 DARPA programs, 20 publications, 2 patent applications, 1 CRADA, 2 related IMS programs, and related NIST-on-a-chip funding;
    3. Quantum Voltage: 1 Intelligence Advanced Research Projects Activity program, 25 publications, 2 patents granted, 1 patent filed, 2 related IMS programs, and NIST-on-a-chip funding; and
    4. High-Frequency Electronics: 2 DARPA programs, 11 publications, patent application, 1 CRADA, and 2 related IMS programs.

Challenges and Opportunities

Technically, as communication systems continue to evolve in complexity and diversity to accommodate the broad range of applications, users (i.e., people and things), and system requirements, supporting the development of the next generation of innovations and personnel needs to continue to be a priority. CTL has established a very strong organizational structure that should position it to continue to make significant contributions to emerging applications in the communications field. The strong interactions between CTL and other NIST laboratories, industry, as well as with other government agencies, are catalyzed by its mission and role in establishing and influencing the formation of precision standards and measurement methods for the field. The development of advanced concepts around probe technologies and measurement techniques for over-the-air transmission and voltages for quantum computing is both forward-thinking and influential to industry and other government agencies.

Diversity is one of NIST's core values.[8] CTL has put in place a very forward-thinking strategy to support its current workforce more holistically and to diversify its workforce in terms of race, ethnicity, and gender. It was developed with input from many stakeholders and is striving to create a better outward facing NIST that is learning from the past. Their past effort, when the organization was structured differently, did not seem to work as well. While those efforts didn't work as well as intended, diversity goals seem to be better integrated into the new CTL structure. One challenge specific to this division is that electrical engineering students are on the decline, these students in the electromagnetic and radio frequency subfields relevant to the Radio Frequency Technology Division have been on a steeper decline, and those students that are U.S. citizens of diverse ethnicities are particularly difficult to find due to their rarity. This calls for particular attention when attempting to build a more diverse workforce for the Radio Frequency Technology Division.

Recommendation 4-6: When recruiting its future workforce, CTL should (1) define specific strategies that integrate diversity goals into the Radio Frequency Technology Division's workforce generation strategies to account for its unique challenges in recruiting diverse researchers in this field, and (2) use select projects from the FETS focus area that will impact the broader lay community to

[8] See https://www.nist.gov/about-nist.

support national awareness of CTL's research, offer technical access, and expose the broader community to science, technology, engineering, and mathematics work opportunities.

5

Next-Generation Wireless

The NextG Wireless Research program within the Communications Technology Laboratory (CTL) is comprised of 31 experienced and highly skilled radio frequency engineers, physicists, software engineers, and computer scientists based in Gaithersburg, Maryland, and Boulder, Colorado. The team is involved in a variety of inter-disciplinary wireless research projects, including, but not limited to, millimeter-wave wireless propagation modeling and performance evaluation of next-generation waveforms and communication protocols. Publicly sharing the models and disseminating data sets to the research community are some of the key highlights of the group's accomplishments, along with their high-impact conference and journal publications. The collaboration extends beyond U.S. academic institutions to include foreign research partners, who have been doing mid-band work for use with 5G that the United States is just beginning to take up, as part of their cutting-edge, next-generation research and Channel Model Alliance work.

ASSESSMENT OF TECHNICAL PROGRAMS

The following discussion focuses on three major projects that the Next-Generation Wireless research group is currently involved in, and two collaborative support projects to highlight their key accomplishments, new opportunities, and this panel's recommendations. We discuss the projects in the bottom-up order of open systems interconnect layers starting with the physical layer work, then protocols (medium access and networking), and then the application layer work.

Millimeter Wave Instrumentation (Physical Layer)

Metrology for Next-Generation Wireless Networks

This project includes (1) precision channel propagation measurements and modeling, (2) wireless system performance, and (3) communications for Internet of Things (IoT) applications. The channel measurement work relies on three successive generations of CTL radio frequency channel sounders, the first two covering 28, 60, and 83 GHz and the third covering 140 GHz. The group has developed a comprehensive measurement-based modeling and analysis tools suite. Device-to-device communication is being investigated under Long-Term Evolution (LTE) and New Radio protocols via link-level simulations and system-level evaluations. The work is of the highest quality, reflecting the NIST tradition of performing high-precision, reproducible, and traceable measurements.

The group indicated that the sub-6 GHz bands are increasingly important and agreed that the United States is somewhat behind the rest of the world in this regime. While the United States focused on millimeter-wave technology with regards to 5G research, the rest of the world, including but not limited to Europe and Asia, focused on sub-6GHz band research.[1] Now that the United States has started to use the sub-6 GHz band for deploying 5G networks, it is important that CTL expands its research to include the sub-6 GHz band. The CTL group noted, however, that the inclusion of sub-6 GHz into their channel measurement work would be dependent on the availability of increased resources.

Recommendation 5-1: CTL should partner with foreign researchers on sub-6 GHz work as a way to get a quick jump-start on the research by leveraging existing work on the topic, then work to identify gaps and focus their research on those topics with respect to the future sub-6 GHz research work.

Next-Generation (NextG) Channel Model Alliance

The group has actively participated in the Next-Generation (NextG) Channel Model Alliance since 2015, providing data sets and models to the open research community, including making them publicly available via MATLAB toolbox. The focus and the energy spent are apparent and contribute to the success of the effort. But there are new frontiers beyond the NextG Channel Model Alliance work, including, but not limited to, power management and dynamic spectrum sharing at the edge that will need a concerted effort from the larger community, including CTL from the measurement perspective with respect to next-generation wireless deployment.

Key Recommendation 6: CTL should create a roadmap of what the next 5 years of NextG Channel Model Alliance's work will look like. The group should use this roadmap to determine where they can leverage CTL's unique capabilities to focus on the key gaps and make the biggest impacts on next-generation wireless technology and its deployment in the next 5 years.

5G New Radio Direct Mode Communication (Protocol)

The Next-Generation Wireless group conducted a study on 5G New Radio direct mode communication in collaboration with the public safety research group since direct mode—also called device-to-device in 4G LTE and side link in 5G—is a key functional capability for public safety communications. The study focused on resource management, physical layer capacity, quality of service, and LTE/New Radio coexistence. If feasible and successfully deployed, the device-to-device mode will keep first responders connected in situations where there is no cellular infrastructure to provide a 4G/5G network service. Moreover, unlike the 5G non-standalone mode, which focuses on the 4G/5G network coexistence, the 5G standalone mode side link deployment is more likely to happen as large-scale IoT and vehicle-to-everything applications demands are only met by the 5G New Radio standard. The Office of the Under Secretary of Defense for Research and Engineering (OUSD (R&E)) recently funded a 5G

[1] For more information see https://media.defense.gov/2019/Apr/03/2002109302/-1/-1/0/DIB_5G_STUDY_04.03.19.pdf.

standalone side link study that could be leveraged to get a head-start on a standalone mode side link study.[2]

> **Recommendation 5-2:** CTL should develop a partnership with OUSD (R&E) and collaborate on OUSD (R&E)-funded projects, like the 5G side link study. CTL should also leverage the ongoing work to update their 4G/5G non-standalone mode study with the relevant findings from the OUSD (R&E) study, especially regarding the public safety use case.

Spectrum Sharing for Citizens Broadband Radio Service (Application)

The Next-Generation Wireless group has contributed significantly to Citizens Broadband Radio Service band spectrum sharing by creating tools, models, and data sets, along with developing standard techniques to achieve dynamic and efficient spectrum sharing between commercial and federal users in the 3.5 GHz frequency range. The team developed synthetic waveform generation tools and contributed to the test harnesses that were essential for the testing of industry-developed environmental sensing capability sensors. These sensors are widely used by industry and academia today and enable shared use of the CBRS band. Their work on this topic, including the reference implementation and publications, has been recognized with a major award within NIST and by the community at large. Given the increasing demand for the more shared spectrum between federal and commercial users, it is important that CTL extend their spectrum sharing application work to include the multi-band spectrum sharing between federal users and commercial users in what was traditionally Department of Defense bands. The National Science Foundation has started a set of Spectrum Innovation Initiative projects that creates dynamic radio access zones for spectrum sharing between federal and commercial users at the edge instead of using centralized databases.

> **Recommendation 5-3:** CTL should create a roadmap for the application-related work as applied to multi-band spectrum sharing deployment at the user device. CTL should also collaborate on National Science Foundation–funded Spectrum Innovation Initiative projects to align with the ongoing work on this topic and identify gaps that can be included in the roadmap.

Collaborative Project

Open Radio Access Network (RAN) Research

The Next-Generation Wireless research group, in collaboration with the Core Network research group, is looking into acquiring an Open Radio Access Network (RAN) 5G testbed to use for their future 5G/6G research work. The testbed would be key to combining the Next-Generation Wireless research group's ongoing physical layer, protocol layer, and application layer work described above so that a cross-layer, full-stack analysis of next-generation wireless network systems can be done and the impact with respect to full-stack 5G/6G performance can be understood. Many testbeds are available and in use today across industry, open-source communities, and national laboratories. The selection process of the right 5G testbed for CTL's use will need to be well documented so that other laboratories can apply similar thought processes and criteria to acquire 5G testbeds for their use in the near future.

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[2] 3GPP TR 23.700-33 V0.3.0 (2022-05). 3GPP TR 23.700-33 V0.3.0 (2022-05) 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Study on system enhancement for Proximity based Services (ProSe) in the 5G System (5GS); Phase 2 (Release 18).

Key Recommendation 7: The Next-Generation Wireless group should be actively involved in the Open RAN testbed selection process in collaboration with the Core Networks group. The selection process and criteria of the Open RAN testbed process should be well documented and disseminated to the other national laboratories that are also looking to acquire similar testbeds in the near term.

ACCOMPLISHMENTS, CHALLENGES, AND OPPORTUNITIES

Collaboration with International Researchers

Because NIST performs a variety of work that touches on national security and export control, foreign nationals cannot work as permanent employees at NIST. This is a challenge because there is a lot of international graduate student talent that NIST cannot engage with as a part of their permanent workforce. However, 6-month visiting appointments for international researchers can be arranged. Despite the challenges in engaging with international researchers, CTL has used this visiting appointment authority effectively to engage in international collaboration. This is commendable. Further expanding ongoing international collaborations is a great opportunity to advance the Next-Generation Wireless group's future sub-6GHz work.

Millimeter Wave Work

Millimeter wave measurements and modeling are the most significant activity of the group. CTL's millimeter-wave and terahertz channel sounder are recognized by the research community as the best of breed. CTL's open-source millimeter-wave Raytracer and measurement data are used by commercial industries as means of evaluating their product's performance. The combined work of radio frequency, LIDAR (light detection and ranging), and camera systems to tell where radiation emanates from a body, for precision channel modeling, has proliferated applications in the area of human presence detection, human activity tracking, and augmented reality/virtual reality.

The challenges with millimeter-wave operations remain, however. The blockage problem with millimeter-wave communication—due to the frequency range and its high attenuation due to mobile blockers and the user's own body—has not been solved. The perennially suggested solution of network densification and small-cells to scale millimeter-wave deployment has not been shown to make business sense except in niche applications. In March 2020, the Federal Communications Commission auctioned millimeter-wave spectrum for $2.24/Hz; in January 2021 mid-band spectrum (e.g., C-band) was auctioned for $290/Hz. Innovation in the sub-6 GHz band is likely to be much more profitable, and thus more relevant than innovation in the millimeter-wave band in the near term. There is also ever-increasing demand to share more spectrum between the federal and commercial users in the sub-6 GHz band. Therefore, instead of focusing on millimeter wave for 5G deployment, the sub-6GHz band deployment makes more sense both technically and economically. A shift to sub-6 GHz 5G deployment brings with it the need to accurately study the impact of this mid-band spectrum sharing on military and existing federal system operations. The Next-Generation Wireless researchers at CTL have a vital role to play in using high-fidelity experiments to quantify the technical impacts of sub-6 GHz deployment in the near future.

Recommendation 5-4: CTL should extend its next-generation wireless systems propagation measurement program to include the sub-6 GHz bands because they are technically and economically appealing and are being adopted in the United States. CTL should conduct high-fidelity experiments to quantify the technical impacts of sub-6 GHz 5G deployment in the near future.

NextG Channel Alliance

The Next-Generation Wireless research program is a key contributor to the NextG Channel Alliance, an established user community for wireless signal propagation measurements and modeling. The group helps maintain the signal propagation modeling data repository as part of the alliance's working group members. CTL's active participation in Alliance activities and the quality of seminars and workshops held by the Alliance are evident in the yearly increase in industry participation and the collaborative work published by the Next-Generation Wireless group in collaboration with the larger industry groups and stakeholders. Furthermore, the attendance of researchers from CTL's Next-Generation Wireless group at different Institute of Electrical and Electronics Engineers (IEEE) conferences and events—such as the IEEE Conference on Vehicular Technology, the International Conference on Communications, and the Global Communications Conference—have benefited the Alliance meetings and vice versa.

There are newer and harder pressing problems beyond channel modeling that relate to the scalability and feasibility of deploying 5G/6G networks in near future. For example, power management, and intelligent surface reflectors that jointly adjust and reconfigure wireless signals for longer-range transmission are some of the areas that need measurement study, modeling, and characterization. There is an opportunity for CTL to consider what beyond the NextG Channel Alliance work could benefit from their attention to make an equally significant impact on 5G/6G network deployment as the Alliance work had on 4G/5G deployment via their millimeter-wave study that has been ongoing for over 6 years.

Recommendation 5-5: CTL should build a roadmap for what is next beyond the NextG Channel Alliance work and align the roadmap with the emerging 6G network problems that will be critical to mitigate before making any large-scale deployment of 6G in any type of setting.

5G New Radio Side Link

5G New Radio Side Link enables direct communication between devices without packets going through the network. While this direct communication can occur both in network and out of network (i.e., out of coverage or off network), CTL has mainly focused its research on the out of coverage scenario to address critical communication for first responders in areas where there is no network or where the network has been damaged. A study report published in 2021 by CTL evaluated the state of New Radio Side Link based on 3GPP Release 16, which was developed to support V2X (i.e., vehicle-to-everything) communications. The report covered issues or gaps within the protocols to support New Radio Proximity Services, direct device discovery, direct communication, and user equipment-based relays. The report further recommended enhancements to the New Radio Side Link power efficiency, reliability, and latency. CTL has also been developing link-level and system-level simulation capabilities to evaluate the performance of New Radio Side Link, including capacity and range. The challenge is that the community and the efforts funded by the Office of the Under Secretary of Defense for Research and Engineering (OUSD (R&E)) have already released Proximity Services architectural advancements based on Release 18. Release 18 highlights Non-standalone mode of user equipment to 5G Radio Access Network interface and support for user equipment-to- user equipment Unicast, user equipment-to-Network Relay, and path switching between user equipment-to-RAN and user equipment-to-user equipment communication paths for relay and non-relay use cases, which provide significant resiliency to networking capability for first responders.

Recommendation 5-6: CTL should review the 5G New Radio device-to-device side link instantiation recommended by the Release 18 study as it pertains to public safety application use case and confirm that their output from their 2021 study, which is based on Release 16, agrees with the more recent OUSD (R&E) work based on Release 18.

Spectrum Sharing

The dynamic spectrum sharing application is a great use case study of the group's combined full-stack performance and modeling work. As successful as this group has been in the deployment of database-based Citizens Broadband Radio Service spectrum sharing tools and techniques, dynamic radio access zone research is a great opportunity for the group to make spectrum sharing using machine learning algorithms between federal and commercial users more dynamic and edge-based. Furthermore, commercial off-the-shelf lightweight hardware and software components make deploying these machine learning algorithms possible at the user edge. The Open RAN has made it easy to deploy such artificial intelligence and machine learning orchestration algorithms at the edge by defining a standard real-time and near-real-time application (called xAPP and rAPP) and application programming interface via their specification. Furthermore, there is an opportunity to delve into the security of these interfaces and how original equipment manufacturers adopt the Open RAN standard for commercial deployment.

Recommendation 5-7: The CTL Next-Generation Wireless group should collaborate with the Spectrum Sharing group and continue the study of dynamic spectrum sharing as the key application performance study of their full-stack 5G physical layer and network (protocol) layer work.

Resources

Overall, given the inherent importance of next-generation wireless research and development, it is somewhat surprising that the Next-Generation Wireless program has the smallest budget of any of the other groups within the Wireless Networks Division ($6.51 million, 5.6 percent of the overall budget). Out of necessity, this group has had to limit its scope and research focus. It is good to hear that a $12 million budget increase has been requested for the advanced communications research (including the next-generation waveform and the spectrum sharing work).

PORTFOLIO OF SCIENTIFIC EXPERTISE

The Next-Generation Wireless group has the world-class expertise that it needs to accomplish its current missions and to develop its work in different directions as future circumstances dictate. Their multi-disciplinary team of radio frequency electrical and computer engineers, physicists, and computer scientists covers the full range of expertise needed to do hands-on hardware and software development and mathematical modeling to achieve the organization's mission and program objectives. One improvement would be to hire a telecommunications engineer with expertise in 5G RAN after CTL acquires its Open RAN testbed.

EFFECTIVE DISSEMINATION OF OUTPUTS

CTL has been highly effective in disseminating its research findings via publications, foreign and domestic academic collaborations, the release of design documents, data sharing, and reference implementation code releases via GitHub. Over the last 3 to 5 years, they have published in over 35 combined journals and high-impact conference papers, over three patents, and a follow-on entrepreneurial pursuit to commercialize some of the Internet protocol, machine learning models, and data shared via Matlab toolbox and reference implementation code published out in CTL's GitHub account.

6

Public Safety Communications Research

The Communications Technology Laboratory's (CTL's) Public Safety Communications Research (PSCR) research focus area is facing a budgetary challenge distinct from the other research focus areas—the Public Safety Trust Fund (hereafter referred to as the Trust Fund) funding that has supported much of the research is expiring.

The Middle Class Tax Relief and Job Creation Act of 2012 (P.L. 112-96) initiated the deployment of a nationwide First Responder Network (FirstNet) and established CTL as the research and development arm of FirstNet. This act appropriated $300 million from spectrum auction proceeds to the National Institute of Standards and Technology (NIST) to be used as specified in 47 U.S.C. § 1443 (2016), "Public Safety Wireless Communications Research and Development" (see Box 6.1). The spectrum auction funds became available to CTL in fiscal year (FY) 2016, and the Act specifies that at the end of FY 2022, all appropriated funds that are unused are to be returned to the U.S. Department of the Treasury. Approximately $50 million of this fund were spent each year.

The CTL PCSR Division was tasked with the research and development to support the use of FirstNet, while the National Telecommunications and Information Administration (NTIA) was given the charge of constructing and managing FirstNet. FirstNet is now serving approximately 3.5 million first responders nationwide. CTL and FirstNet work together collaboratively: CTL has expertise in requirements determination, whereas public safety organizations typically do not have the technical capabilities to determine requirements on their own. The PCSR Division's role was to create a roadmap for reliable public safety technologies, conduct a needs assessment to determine priorities, and research new technology as needed to extend the capabilities of FirstNet. This required engaging in user-centered design with the distinctive first responder community. FirstNet can then invest in the innovations developed through PSCR programs to facilitate deployment.

BOX 6.1
47 U.S.C. § 1443 (2016)
Public Safety Wireless Communications Research and Development

(a) NIST directed research and development program
From amounts made available from the Public Safety Trust Fund, the Director of NIST, in consultation with the Commission, the Secretary of Homeland Security, and the National Institute of Justice of the Department of Justice, as appropriate, shall conduct research and assist with the development of standards, technologies, and applications to advance wireless public safety communications.

(b) Required activities
In carrying out the requirement under subsection (a), the Director of NIST, in consultation with the First Responder Network Authority and the public safety advisory committee established under section 1425(a) of this title, shall—

(1) Document public safety wireless communications technical requirements;
(2) Accelerate the development of the capability for communications between currently deployed public safety narrowband systems and the nationwide public safety broadband network;
(3) Establish a research plan, and direct research, that addresses the wireless communications needs of public safety entities beyond what can be provided by the current generation of broadband technology;
(4) Accelerate the development of mission critical voice, including device-to-device "talkaround" capability over broadband networks, public safety prioritization, authentication capabilities, and standard application programing interfaces for the nationwide public safety broadband network, if necessary and practical;
(5) Accelerate the development of communications technology and equipment that can facilitate the eventual migration of public safety narrowband communications to the nationwide public safety broadband network; and
(6) Convene working groups of relevant government and commercial parties to achieve the requirements in paragraphs (1) through (5).

CTL's PSCR research areas are as follows:

- Mission Critical Voice, which focuses on communications for first responders including direct mode communications, mission-critical push to talk, Land Mobile Radio-to-cellular (i.e., Long-Term evolution [LTE]) communications, and public safety user quality of experience;
- Location-Based Services, which focuses on indoor mapping, tracking, and navigation for the public safety community;
- User Interface/User Experience, which facilitates the provision of tools to first responders that are designed around their specific context, tasks, and requirements, based on user-centered design and feedback; and
- Public Safety Analytics, which includes research on algorithms, data sets, and open-source tools that can be leveraged by public safety organizations to analyze emergency events.

There are also two crosscutting research areas that focus on use cases that were identified as being important to PSCR stakeholders:

- Security use cases that involve developing and enhancing security solutions to current and future public safety communications, and
- Resilient systems use cases that involve ensuring technology works in situations where first responders have limited or no network connectivity.

To fulfill the Trust Fund mandate between 2016 and 2022, CTL had to develop research teams to enable critical contributions to be made in a short timeframe. To do this, CTL conducted PSCR work using a number of methods such as

- Research within CTL and in collaboration with other groups in NIST,
- External research using grants and cooperative research agreements, and
- Prize challenges that provided innovative ways to interact with non-traditional stakeholders.

The looming expiration of the Trust Fund necessitates a scaling down of PSCR activities. The Mission Critical Voice, Location-Based Services, and User Interface/User Experience research areas have been identified as the highest priorities for continued PSCR funding in FY 2023.

GENERAL DISCUSSION

CTL's PSCR Division is a unique national resource for the public safety community. The Trust Fund funded a wide range of activities to support the research and development of advanced communication technologies that are specific to public safety. This one-time investment enabled the public safety community to make systematic progress toward using commercial wireless communication innovations and developing the technologies and features needed for public safety. The Trust Fund enabled public safety to effectively use commercial broadband technologies, but maintaining currency with the national infrastructure requires continued significant investment. Given that both technology and the nation's infrastructure are evolving, new and different approaches to public safety are needed.

In the time since the last review in 2019,[1] PSCR had adequate funding to carry out its mission. The current review is occurring in the midst of the transition from having the Trust Fund as the main source of funding to relying primarily on traditional appropriated funds as part of the NIST-wide annual budget requests. FY 2023 will be the first time since 2005 that PSCR has not received any funding from the Department of Homeland Security Science and Technology Directorate.

CTL has prioritized continued support in three core areas: Mission Critical Voice, Location-Based Services, and User Interface/User Experience. Mission Critical Voice is central to public safety. The ability of first responders to obtain clear timely voice communications in an emergency situation is necessary for them to effectively perform their missions. Location-Based Services have been narrowly defined to address the needs of first responders. User Interface/User Experience research is cross-cutting, and the expertise in that domain needs to be sustained in the public safety community.

A request from NIST for sustaining funding that aligns with these priorities was announced during the review of CTL. NIST's continued funding request for 12 core researchers and their work in the PSCR Division meets the minimal requirements for the core research team to be sustained. Although the management of the sunset of the Trust Fund has been effective in terms of continuity of strategic priorities, the mission and funding of PSCR moving forward are less clear.

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[1] National Academies of Sciences, Engineering, and Medicine, 2019, *An Assessment of the Communications Technology Laboratory at the National Institute of Standards and Technology: Fiscal Year 2019*, Washington, DC: The National Academies Press, https://doi.org/10.17226/25602.

Key Recommendation 8: The PSCR Division should define its mission beyond the mandates of the Public Safety Trust Fund. Changes to the nation's infrastructure and technology need to be taken into consideration for PSCR to position itself to stay ahead of the evolving needs of the first responder community and effectively support public safety communication in a changing world. Working with stakeholders to understand the impact of changes and prepare for them requires collaboration with other divisions in CTL, such as with the teams working on smart connected systems and next-generation networking.

The PSCR Division has done an outstanding job of bringing together the public safety community. The formation of a community that includes researchers, vendors, and practitioners is a significant achievement. The PSCR Division has created a unique interdisciplinary nexus of scientific expertise, networks of collaboration, and cutting-edge laboratories around public safety communications. Annual stakeholder meetings have created and serve to maintain a network of relationships that span the public safety communications domain. These meetings also provide an opportunity for the PCSR Division to connect with stakeholders to create cross-sector teams and potentially provide diverse sources of funding to ensure that the research, and the meetings, continue. The PSCR Division has also engaged in a process to facilitate the commercialization of public safety technology to ensure that research gains are brought to the public safety marketplace. It has facilitated the creation of a first responders purchasing guide that lists communications equipment that meets established standards. Any break in this work risks a loss of momentum and jeopardizes the progress made to date.

The PSCR Division has met the stated goals of creating a set of research portfolios and capabilities specific to public safety. In doing so, the division has built a large, active stakeholder community in which both individuals and the organization have critical leadership roles. The PSCR Division's leadership and role as a community convener are central to the stakeholder ecosystem and needs to be maintained. Investments to maintain the annual meetings, the laboratory, the purchasing guide, and other forms of stakeholder engagement are critical. Investments to maintain the community and communication that guides the development and refinement of both short- and long-term strategic research priorities are also necessary.

Key Recommendation 9: The PSCR Division should take a leadership role in developing a sustainable model for bringing together stakeholders to research, develop, and commercialize public safety innovations. CTL should ensure the continuation of the PSCR Division's community leadership role and its functions in convening meetings of stakeholders and PSCR community groups.

ASSESSMENT OF TECHNICAL PROGRAMS

The assessment of PSCR technical programs is complicated by the expiration of the Public Safety Trust Fund in FY 2022 and the necessity of aligning any recommendations with the future funding situation. The PSCR Division's technical programs focus on developing, expanding, or influencing research capacity, disruptive approaches and technology, standards, products, and public safety methods. These activities directly support transforming public safety operational capabilities. Due to the PSCR Division's success influencing early-stage research and development, it has expanded its efforts to help drive projects to the commercialization stage.

The research programs presented by CTL were Mission Critical Voice, Location-Based Services, and User Interface/User Experience. These areas have been prioritized for support beyond the expiration of the Trust Fund funds. The subsections below focus on these areas.

Accomplishments

PSCR research and development activities include both projects internal to CTL and in collaboration with external partners. The internal projects have developed measurement methods and metrics, driven participation in standards resulting in 483 public safety specific contributions, and developed unique laboratory facilities. PSCR external projects include extramural grants and prize challenges.

More than $79 million in extramural grants have been awarded to 207 recipients. These grants have resulted in 1 patent, 3 pending patents, more than 20 open-source tools and data sets, and 114 publications to date.

The PSCR Division has run 18 prize challenges to date, with four of those under way at the time of the presentation to the panel. It has awarded more than $4.5 million in 524 prizes to winning submissions from 27 different states and 7 countries. The prize challenges have engaged a diverse population of participants ranging from students to experienced industry professionals.

Mission Critical Voice

The Mission Critical Voice team has the following active research areas:

- Mission critical push-to-talk,
- Quality of experience,
- Test equipment, and
- Direct mode.

The research in these areas includes four extramural grant programs. More than $26 million has been awarded to 17 recipients.

In 2020, the PSCR team held a virtual roundtable to gather stakeholder input on Mission Critical Voice strategic priorities. Prior to this, the land mobile radio-to-LTE transition—involving the transfer of traditional land mobile radio, where local push to talk radio is available to all responders, to the broadband cellular LTE environment—had been a significant priority of the Mission Critical Voice portfolio. The development of standards and a listing of devices compliant with these standards required extensive research to develop the metrics for the standards. Completing and meeting that goal is a noteworthy accomplishment that directly addresses the purpose of the Trust Fund. The success of the land mobile radio-to-LTE transition effort enabled a shift in priorities and resources that increased the focus on research and development of quality of experience measurement. A roundtable was used to collect input on the approach to collecting Mission Critical Voice measurements and to identify new methods, variables, and parameters for the PSCR Division to consider in future research.

A core contribution in Mission Critical Voice is the development of standards to support mission-critical services on current and next-generation technologies. Public safety communication requirements are different from traditional voice communication. The PSCR team coordinated with FirstNet to introduce public safety use cases and critical communication technologies to the 3rd Generation Partnership Project (3GPP) international standards body. The specific measurable components for evaluation of the quality of experience for Mission Critical Voice are mouth-to-ear latency, end-to-end access time, voice quality and speech intelligibility, and probability of successful transmission. The process is modeled as a mouth-to-ear user measure with evaluations grounded in quality of experience—availability, intelligibility, and total time of transmission.

The PSCR Division has created a unique interdisciplinary nexus of user-centered computing, working with first responders as its users and providing communications expertise to evaluate and enable the systematic migration of Mission Critical Push-to-Talk communications from traditional handsets using land mobile radio to a complex broadband environment. This nexus was enabled by the leadership shown by the CTL PSCR researchers in the creation of the Public Safety Communication Innovation Laboratory. Testing in this laboratory is important for doing research and developing the standards for mission critical services.

To deploy the standardized services in FirstNet and to facilitate new features that can be built on the standardized services, testing needs be done to certify compliance of the commercial devices, applications, and radio access networks (RANs) with the standards. This requires the availability of test equipment. Test equipment is used throughout the telecommunications development life cycle for each of the components (network, device, application). To address the need for test equipment, PSCR has funded three external research grants for developing test equipment. This equipment will be made available to the Global Certification Forum and PCS Type Certification Review Board certification laboratories. One grantee has created a test platform that is facilitating certification and as of November 2021, the Global Certification Forum is allowing certification laboratories to perform Mission Critical Push-to-Talk certification testing.

Direct-mode communication is considered a required feature by first responders to fully transition from land mobile radio to LTE. The PSCR Division contributed to the 3GPP standards support for LTE direct mode through device-to-device communication and off-network Mission Critical Push-to-Talk, but LTE direct mode has performance limitations and is not widely available. To overcome these issues, the PSCR team is working with the Wireless Networks Division on 5G direct mode communication (i.e., New Radio Side Link communication). It did a capacity study that showed that New Radio Side Link improves capacity over LTE while allowing flexible configurations to adapt to different public safety deployment scenarios and service requirements.[2] The major features that improve New Radio Side Link capacity include configurable hybrid automatic repeat request, support of higher modulation and coding, and spatial multiplexing. Ongoing research topics include LTE and New Radio coexistence, quality of service, resource management, and relay capabilities.

Location-Based Services

The ability to locate, track, and provide information to first responders while indoors under difficult conditions remains a critical capability sought by the public safety community. The Location-Based Services team has the following active research areas:

- Mapping,
- Tracking,
- Navigation, and
- Ground truth.

The research in these areas includes five extramural grant programs with more than $18 million awarded to 15 recipients.

Accurate mapping of indoor environments provides the basis for first responder navigation and tracking. The PSCR Division's Point Cloud City program funded three external grants that have produced publicly available, annotated, three-dimensional, indoor point clouds for 29 public and private buildings in three cities covering more than 4.5 million square feet.[3] These data can be used to advance research and development in mapping, localization, and navigation for public safety. Light Detection and Ranging (i.e., LIDAR) technology, cameras, and custom sensors were used to create the point clouds of indoor environments. The annotation includes the identification of approximately 30 items of interest to first

[2] National Institute of Standards and Technology (NIST), 2021, *Study of 5G New Radio (NR) Support for Direct Mode Communications*, NISTIR 8372, May, https://nvlpubs.nist.gov/nistpubs/ir/2021/NIST.IR.8372.pdf.

[3] For more information see https://www.nist.gov/ctl/pscr/funding-opportunities/past-funding-opportunities/psiap-point-cloud-city.

responders in the point cloud data (e.g., walls, doors, windows, and gas shutoffs). The point cloud data are also georeferenced to provide the real-world coordinates of the building features.

The PSCR Division designed this program to pair researchers with public safety organizations. This enabled the researchers to more fully understand the challenges that first responders face and focus the division's efforts accordingly. The partnership also enabled the public safety organizations to participate in the design and implementation of the project, thereby providing input on and envisioning how the technology could be used in real-world situations. The PSCR Division is to be commended for facilitating this type of partnership that is critical to developing technology that is relevant and useful to first responders.

Through workshops with government, public safety, and industry stakeholders, the PSCR Division identified an inability to track first responders indoors when there is no pre-existing communications infrastructure as a key technology gap. To address this gap, the PSCR Division has awarded $8 million to the Crisis Technologies Innovation Lab at Indiana University to implement the First Responder Smart Tracking prize competition. This is a five-phase competition with a goal of developing and demonstrating the indoor localization and tracking of first responders within one-meter accuracy in a variety of buildings without pre-deployed infrastructure such as Wi-Fi access points or Bluetooth beacons. The phases go from concept and initial design all the way through live field-testing at the Muscatatuck Urban Training Center. Phase 1 concept and initial design submissions were due on March 21, 2022, and the competition will wrap up with advanced live field testing at the Muscatatuck Urban Training Center from October 23-27, 2023. A total of $5.6 million in prizes will be awarded. Twenty-five prizes were awarded for Phase 1.

One of the PSCR Division's funded external projects is the Ultimate Navigation Chip, a chip-scale personal navigation system. Researchers at the University of California, Irvine, were awarded $1.96 million to design, build, and develop the Ultimate Navigation Chip. Their design uses a variety of sensors and fuses deterministic, probabilistic, and cooperative approaches. It uses foot-based sensors, signals from cellular networks, digital TV and Wi-Fi, and cooperation from mobile agents equipped with computation and communication capabilities. In addition to the research grant, University of California, Irvine, was awarded a separate grant for a demonstration project with Orange County Fire Authority at the Authority's Regional Fire Operations Training Center and fire stations. This project focused on their system's tracking, localization, visualization, and data collection capabilities.

The Location-Based Services team has been working to establish an indoor localization system evaluation facility at the Public Safety Immersive Test Center (PSITC). PSITC is located in Boulder, Colorado, and is a collaborative effort between the PSCR Division and FirstNet. It provides the opportunity to perform immersive public safety standards and measurement testing in a wide variety of settings. PSITC is equipped to enable the generation of ground truth data. This allows for localization system evaluation in accordance with the International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) standard 18305.

User Interface/User Experience

The User Interface/User Experience portfolio is a critical element for facilitating the deployment of new public safety technologies. There are active research projects in the following areas:

- User experience research and testing methodologies,
- Usability requirements,
- Virtual reality, and
- Augmented reality.

Virtual reality and augmented reality have been identified as priorities by stakeholders. The PSCR Division leverages staff from the NTIA Institute for Telecommunication Services for expertise in video and image quality and the NIST Information Technology Laboratory for expertise in usability research. The User Interface/User Experience portfolio includes partnerships outside of NIST with four extramural grant programs resulting in 20 award recipients as well as four prize challenges, with $1.1 million awarded to 24 contestants.

The focus on public safety technology User Interface/User Experience has been productive in the past and is worthy of continued support in the future. User Interface/User Experience has been successfully integrated into the research and development of new public safety technologies. Research for next-generation communication includes research on advanced modes of interaction with communications systems based on biometrics, tactile communication, eye tracking, and even brain activity. The User Interface/User Experience team has developed and published the report *Augmented Reality (AR) Usability Evaluation Framework: The Case of Public Safety Communications Research*,[4] which provides guidance on planning user-based usability evaluations throughout the augmented reality development cycle.

The User Interface/User Experience team has leveraged the building of the public safety community and stakeholder engagement to improve the interaction of public safety personnel with technology. The PSCR Usability team conducted an exploratory, sequential, mixed-methods study to gather insights into the experiences and needs of first responders. The initial phase of the study included in-depth interviews with around 200 first responders. This was followed by a nationwide survey of more than 7,000 first responders. The survey results have been analyzed and published in a series of "Voices of First Responders" reports that are intended for designers, developers, vendors, researchers, and public safety administrators of public safety communication technology. To date, there are nine reports in this series, each covering a unique aspect or portion of the survey data. These reports are an important contribution.

It is critical for first responders to be able to interact in a more natural manner in emergency situations. Emergencies and disasters—both human-made and natural—create unique requirements for responders when using communications technology. The context, including both the cognitive load and physical environment, alters how humans will interact with technology. The PSCR Division is responding to this by exploring the use of augmented reality and virtual reality to start prototyping and testing possible technology interfaces. A variety of virtual reality environments across public safety disciplines are available as open source on GitHub. The User Interface/User Experience team has also administered extramural grant programs focused on both virtual reality and augmented reality. The virtual reality program focused on leveraging virtual reality for training, testing, and the prototyping of new systems for first responders. The augmented reality program focuses on transitioning augmented reality prototypes and research concepts from a laboratory setting, commercializing them, and making augmented reality technologies operational in the field.

PSITC was designed to help answer key research questions around the future of user interfaces for public safety training and operations. PSITC is a unique resource that allows the emulation of a wide variety of virtual environments. It comprises a modular layout, a motion capture system capable of centimeter accuracy, a variety of augmented reality and virtual reality headsets, a mobile staircase and other equipment for z-axis motion, and physical furniture and gear to add a tactile component to simulations.

Commercialization

The PSCR Division's commercialization efforts target the technology development and life-cycle gaps that can occur when transitioning from successful results in research laboratories and prototypes to publicly available technologies. The PSCR Division has three programs to address these gaps. The first program is Follow-on Funding for Technical and Business Assistance and Demonstration Projects with Public Safety Agencies. This program provides funding opportunities to entities that have won previous

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[4] See https://www.nist.gov/publications/augmented-reality-ar-usability-evaluation-framework-case-public-safety-communications.

PSCR Division awards in order to provide needed technical and business assistance to either advance prototypes into commercialization or create a demonstration project with a partnering public safety agency. The goal is to speed the projects toward deployment, providing first responders with needed improvements. There have been seven awards made through this program. The University of California, Irvine, demonstration project with the Orange County Fire Authority described in the Location-Based Services section above is an example of one of these projects.

The second program is the PULSE Accelerator, which seeks to accelerate communications innovations in support of public safety communities. The PULSE Accelerator provides companies that are working in a PSCR focus area a free 12-week virtual program along with over 50 hours of strategic consulting and market research to help companies develop a better understanding of the public safety market. This opportunity has been offered in three rounds between March 2021 and May 2022, with 8 to 10 companies participating each time.

The third program is the R2 Network, a nationwide public safety network that connects first responders and technology innovators. The R2 Network is a public–private partnership formed with a goal of developing a free, sustainable platform to enable the connections that will facilitate innovative solutions to disaster response and resiliency (i.e., R2) challenges. The R2 Network was created with support from the PSCR Division, the FirstNet Authority, and the Economic Development Administration (all three are part of the Department of Commerce), along with industry, nonprofits, and other public safety stakeholders.

Challenges and Opportunities

The primary challenge faced by the PSCR Division is obtaining the funding necessary to maintain leadership and continuity in key research and development areas with the expiration of the Public Safety Trust Fund. Funding from the Trust Fund has enabled the PSCR Division to broaden and invigorate the public safety research and development community through internal research and grants, engage with a broad technical community through prize challenges, and help innovators learn how to bring public safety innovations from the laboratory to the market through commercialization efforts. Perhaps most importantly, all of these efforts have brought together teams of innovators and first responders to work together on building technology to support first responders. The PSCR Division has developed significant expertise in the entire technology life cycle along with the organizational aspects of bringing diverse stakeholders together to solve complex real-world problems. It is important to share this expertise so it can be used to help determine where and how investments are needed to meet the special research and development needs of the public safety community. This may also be valuable to other communities that are interested in applying research to solve real-world problems.

Recommendation 6-1: The PSCR Division should write a report on the lessons learned from the large-scale investment in public safety research, development, and commercialization that the Public Safety Trust Fund enabled. The report should make use of feedback from outside participants in PSCR projects and outside stakeholders and include technological, organizational, and human aspects, including successful commercialization efforts.

FY 2023 will be a significant transition for the PSCR Division. As the remaining research and development efforts scale down or stop completely due to the expiration of the Public Safety Trust Fund, the PSCR Division will have to reimagine its role in the public safety community. Moving forward, it will be critical for the PSCR Division to develop and leverage collaboration opportunities within CTL, NIST more broadly, other government agencies (some of which already contract with NIST to do research), and industry. For example, there are no current research issues that integrate the Smart Grid with PSCR. The safety of first responders when interacting with possibly live systems (e.g., microgrids) needs to be evaluated. For instance, safety reviews of interactions with the grid control could be integrated with existing utility safety reviews to bring PSCR expertise to the challenges and opportunities created by independent interoperable microgrids.

Mission Critical Voice

Although significant progress has been made in the transition from land mobile radio to LTE/broadband devices, ongoing attention is required. The continuing development of protocols, hardware, and above all the changes in the threat environment require sustained investment. The PSCR Division will continue to play a role in research and development of new Mission Critical Voice technologies along with developing the measurement capabilities necessary to deploy new features and applications in FirstNet.

As FirstNet continues to grow in adoption and deployment, it may be appropriate to shift the focus from building basic capabilities to gaining insight into deployments and traffic patterns. Data from FirstNet would be valuable for Mission Critical Voice research, and it would also be of interest to many in the broader public safety community. There currently is no agreement for FirstNet to make data available to the PSCR Division and the public safety community.

> **Recommendation 6-2:** The PSCR Division should facilitate the establishment of a data pipeline from FirstNet to the broader public safety community. These data can be used to identify and study issues that are specific to public safety communications and may not be prioritized by the FirstNet operators given that public safety is a relatively small part of their business.

Location-Based Services

The Location-Based Services portfolio has had admirable successes but lacks a clear argument for prioritization in the long-term. Of the three priority research areas, the distinct need for a PSCR research team within CTL is more clearly illustrated by the strengths and accomplishments in Mission Critical Voice and User Interface/User Experience research. Although public safety does have unique requirements for location-based services, as infrastructure becomes more connected (e.g., the Internet of Things) and indoor localization and tracking become more mainstream, there may be opportunities to leverage the mainstream location-based service research, development, and commercial efforts of industry and academia.

Location-based services, mapping of buildings, and other data compilations create individual and systematic privacy risks. Citizen privacy is a necessary component of interacting with first responders. Risk analysis of data collection, storing, and sharing is necessary. For example, there is a need to engage in substantive risk analysis about information sharing before publishing the layout of elementary schools. NIST has a tradition of excellence in risk analysis in other domains, including the management of risks from ransomware and risks in supply chains. This expertise can be used in the context of data privacy; for example, integrating the NIST Privacy Framework into evaluations of PSCR.[5] Effective privacy rubrics include data minimization, but risk minimization also requires privacy by design and actionable risk-based standards and practices.

> **Recommendation 6-3:** The PSCR Division should create a roadmap for incorporating individual and systemic privacy risk analysis in Location-Based Services and other portfolios as appropriate.

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[5] For information about the NIST privacy framework see https://www.nist.gov/privacy-framework/privacy-framework.

User Interface/User Experience

The PSCR Division has done an excellent job integrating User Interface/User Experience into research projects and prize challenges. The integration of User Interface/User Experience and involvement of the public safety community in these activities enables the technologists to understand and design for the unique challenges and requirements of first responders. This is especially important in light of the challenges in the adoption of new technologies by the public safety community. Maintaining this integrative approach throughout the research and development life cycle may be a challenge, particularly as limited funding becomes a factor.

Recommendation 6-4: The PSCR Division should continue this integrative approach to User Interface/User Experience, involving participants from the broad range of the public safety community, in ongoing and future projects.

Commercialization

Due to the expiration of the Public Safety Trust fund, the future of the PSCR commercialization programs is not clear. These programs were initiated to address the challenges of moving innovation from the laboratory and demonstration stage into a viable product. They also help those interested in commercializing innovations to better understand the public safety market and provide ongoing support. The commercialization programs are a natural follow-on to the prize challenges where early-stage technology is developed in response to various public safety critical needs. The prize challenges cultivate interest and expertise in public safety technology and the commercialization programs build on this to help facilitate entrepreneurship and create a public safety marketplace. Since the mission of the PSCR Division includes getting advanced public safety technologies deployed, the commercialization programs are important.

Recommendation 6-5: CTL should investigate partnerships to continue its commercialization programs. The collaboration between the PSCR Division, FirstNet Authority, and the Economic Development Administration to create the R2 Network is a good example of a partnership for commercialization and expansion of this can be explored.

In addition to commercialization programs, funding for public safety entrepreneurs is necessary. The Small Business Innovation Research program has proven effective for encouraging high-tech innovation.

Recommendation 6-6: The PSCR Division should investigate using the Small Business Innovation Research program to fund innovation and entrepreneurship in public safety. This may require partnering with other government agencies.

PORTFOLIO OF SCIENTIFIC EXPERTISE

To fulfill the Public Safety Trust Fund mission between 2016 and 2022, the PSCR Division had to build a team with expertise that aligned with the Trust Fund mission and public safety needs to enable critical contributions to be made in a short timeframe. The PSCR team included staff from the CTL PSCR, Radio Frequency Technologies, and Wireless Networks divisions; the NIST Information Technology Laboratory; NTIA; and the Department of Homeland Security, along with external experts from academia, industry, and the public safety community. External experts from around the world participated through research grants, cooperative agreements, and prize challenges. Recruitment of personnel on temporary assignment from multiple agencies enabled the PSCR Division to expand effectively during the expenditure of funds from the Trust Fund, and that organizational foresight is enabling the current scaling down and focus on the three specific areas noted in the introduction. This approach resulted in fulfilling the mission of the Trust Fund and significant accomplishments in each of research portfolios. The PSCR Division currently has 15 full-time staff who are aligned with the three research portfolios that have been identified by CTL as having the highest priority: Mission Critical Voice, Location-Based Services, and User Interface/User Experience. The PSCR Division has been able to successfully accomplish its mission with the current 23 full time federal staff, together with the temporary personnel and leveraging of outside collaborators. The expiration of the Public Safety Trust Fund could present challenges to staffing.

EFFECTIVE DISSEMINATION OF OUTPUTS

The PSCR Division has a particularly strong requirement for disseminating the results of its work, as its audience is quite broad and includes the security community, the networking community, the usability community, and the extremely diverse and distributed population of first responders. The PSCR communities of interest include both research and commercial partners. The scope of dissemination can be seen in the FirstNet Push-to-Talk Land Mobile Radio Interoperability capability project. The results of this project were disseminated through research publications, usability evaluations, creation of testing standards for operators and vendors, and the integration of these results to first responders in an acceptable, accessible format. Where feasible, the PSCR Division has required deliverables from those conducting external research or participating in prize challenges such as data sets, application programming interfaces, and open-source tools that can be used by the community and facilitate further engagement.

The PSCR stakeholder meetings have been extremely valuable, bringing together a wide range of stakeholders, showcasing their results, and obtaining feedback about future directions. The annual meetings have created and serve to maintain a network of relationships that span the public safety communications domain. The meetings give the PSCR Division an opportunity to report out on research projects and get community input. Stakeholders from the public safety community, industry, academia, and federal, state, and local government attend the meetings. In 2020 and 2021, due to the COVID-19 pandemic, the stakeholder meeting was online and free to attend. This enabled a wider audience but also limited interactions as all-remote meetings preclude the informal interactions that occur when people gather in person. In 2022, the stakeholder meeting returned to an in-person format but included virtual content as well. The content from the stakeholder meetings is on the PSCR website.[6]

[6] See https://www.nist.gov/ctl/pscr/annual-stakeholder-meeting.

7

Smart Infrastructure and Manufacturing

INTRODUCTION

The following six program areas were presented to the panel as comprising the Communications Technology Laboratory's (CTL's) Smart Infrastructure and Manufacturing research focus area:

- **Smart Connected Manufacturing Systems.** The mission is to develop standards, guidelines, and tools to enable the United States manufacturing industry to improve the quality, reliability, interoperability, and efficiency of their manufacturing systems using data and advanced communications technologies.
- **Smart Grid Program.** The mission is to improve the efficiency, sustainability, economics, and resilience of the nation's electric grids by developing and demonstrating advances in measurement science, control theory, and communications to enhance grid interoperability and facilitate the use of electrical grids as enabling platforms for modern energy technologies and services, including flexible, trustworthy, distributed energy resources.
- **Internet of Things (IoT) Devices and Infrastructure.** The mission is to develop advances in measurement science, including conceptual frameworks, testing and testbed methodologies, co-simulation software platform, tools, and best practices to enable the development and assurance of scalable, interoperable, and trustworthy IoT devices and infrastructures, including autonomous systems such as those for automated driving system safety.
- **Smart Cities and Communities.** The mission is to demonstrate replicable, scalable, and sustainable models for collaborative incubation and deployment of interoperable, standards-based IoT solutions, including, through the National Institute of Standards and Technology (NIST) Global City Teams Challenge, and to develop best practices to capture tangible and measurable benefits to the quality of life in communities and cities.
- **Security for Operational Technologies.** The mission is to develop cybersecurity methodologies, measurement science, standards, guidelines, and tools for securing operational technology systems including advanced control systems for connected IoT systems and critical infrastructure applications; consistency of NIST guidance is maintained through close coordination with the NIST cybersecurity program.

- **Industrial Wireless Systems.** The mission is to develop robust system requirements, system models, recommended architectures, metrology approaches for industrial wireless systems, test methods standardization, and guidelines for establishing trustworthy wireless systems for operational systems such as smart manufacturing and industrial control systems.

Of these, Smart Connected Manufacturing Systems, Smart Grid, and Industrial Wireless Systems were presented to the panel.

The Smart Infrastructure and Manufacturing research focus area is a relatively new one for CTL. The current budget in this area is $14.37 million (12.3 percent of the overall CTL budget). The groups were brought into CTL from other laboratories within NIST as part of the reorganization effort following the National Academies of Sciences, Engineering, and Medicine 2019 assessment.[1] While these groups are now in CTL, their technical focus is broader than communications. Opportunities to better connect with and leverage the communications expertise within the rest of CTL are still developing.

Not all of the above research areas were presented to the panel to the same depth. The Smart Connected Manufacturing Systems and Smart Grid team leads presented to the panel, along with the lead for a millimeter-wave channel characterization project, which is being executed within another laboratory in collaboration with the Industrial Wireless Systems research area within Smart Infrastructure and Manufacturing.

As a new research focus area within CTL, those working in Smart Infrastructure and Manufacturing have more work ahead of them to develop cohesion across the focus area's program areas and CTL more broadly. While the process of integration into the core mission of CTL as well as between the six different research areas within Smart Infrastructure and Manufacturing has begun, more work is needed. Each individual research area is very strong, but there is a lack of coherence among them. The stated unifying theme of "Trustworthy Interoperable Infrastructures" puts up an umbrella much larger than the work beneath it. This umbrella spans a great many topics, including many that CTL is not actively researching. As such, this umbrella has little value by way of helping to bring the various research topics together or to identify cross-cutting themes that would impact CTL's research in a meaningful way. The presentations did not demonstrate any linkages between the Smart Grid and Smart Connected Manufacturing programs, for example. The challenge is to maintain the obvious lead that these research areas have in their individual spheres while exploring new directions, especially those that incorporate communications into their research goals in a more organic way.

One potential integrating theme for Smart Infrastructure and Manufacturing that would incorporate well with CTL and the needs of industry is 5G and the broader NextG/6G trajectory. Intelligent, industrial applications are a driving use case for emerging wireless standards and systems. Manufacturing, smart grid, IoT, smart cities, and industrial and operational technologies all can take advantage of 5G's Ultra-Reliable Low Latency Communications mode and perhaps for the first time have interconnectivity at scale to bring coherent autonomy to bear. Current efforts seem more piecemeal. Leveraging some unique technical capabilities and expertise like millimeter-wave propagation would be useful.

A final broad observation is that the technical diversity of projects presented seemed scattered across fundamental research, experimentation and testbeds, metrology, and standardization. While all of these are within CTL's remit, emerging technologies generally follow an arc of development across those bins of activity, and the Smart Infrastructure and Manufacturing projects presented were unevenly distributed across the activity bins listed. For example, the smart manufacturing work focused primarily on standards and testbeds but lacked an apparent pipeline of research. Similarly, the millimeter-wave work seemed focused on testbeds and metrology, without a path to standards.

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[1] National Academies of Sciences, Engineering, and Medicine, 2019, *An Assessment of the Communications Technology Laboratory at the National Institute of Standards and Technology: Fiscal Year 2019*, Washington, DC: The National Academies Press, https://doi.org/10.17226/25602.

Recommendation 7-1: CTL should prioritize, over the next 3 years, the integration of Smart Infrastructure and Manufacturing across its various focus areas and between Smart Infrastructure and Manufacturing and the broader CTL mission set to reduce stovepipes between disciplines and enable more transdisciplinary discovery.

Recommendation 7-2: CTL should identify one or more Smart Infrastructure and Manufacturing integrating cross-cutting topics in research, experimentation, metrology, and standards that can serve to foster collaboration across the Smart Infrastructure and Manufacturing focus areas and CTL more broadly.

Recommendation 7-3: CTL should better map the Smart Infrastructure and Manufacturing activities in each of its focus areas into a strategic framework that connects technology maturity with research, testing, metrology, and standardization, and ensure a balanced portfolio leading to a sustainable research agenda.

ASSESSMENT OF TECHNICAL PROGRAMS

The panel commends CTL for taking bold action to reorganize its program areas and establish the Smart Infrastructure and Manufacturing research focus area. Establishing this area is important to bringing strategic focus to infrastructure and manufacturing, both of which are critical to maintaining a strong, competitive technology base for the nation.

Each of the six groups that comprise the Smart Infrastructure and Manufacturing research focus area is fully engaged in the breadth of CTL's mission and has established core research programs and testbeds infrastructure. They are represented in relevant industry standards development organizations, where the staff hold multiple leadership roles and have contributed to several different standards. It is clear that the expertise and contributions of the various project areas in Smart Infrastructure and Manufacturing are important and valued by standards groups and the larger community.

Standards and NIST Guidance Documents

The work in the Smart Infrastructure and Manufacturing research focus area in developing common frameworks for cyber-physical systems and the IoT are critical to future research, standardization, and efforts to engineer security. Standards generated include ISO 10303-242:2020, "Managed Model-Based 3D Engineering, Edition 2"; ISO 10303-242:2022 (Edition 3 to be published); and IEEE 1547.1-2020, "Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interface." NIST-generated Special Publications (SP) that are foundational to the industry include the following: NIST SP 1109R4 (NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 4.0); NIST SP 1500-201, -202, and -203 (Framework for Cyber-Physical Systems vol. 1, 2, and 3); NIST SP 1900-202 (Cyber-Physical Systems and IoT); NIST SP 800-82 (Guide to Industrial Control Systems Security); Guide to Industrial Wireless Systems Deployments, and NIST Advanced Manufacturing Series (AMS) 300-4.

Smart Grid

The Smart Grid focus area within Smart Infrastructure and Manufacturing is part of a larger Smart Grid Program that includes personnel from other laboratories and divisions within NIST. According to the information provided by the Smart Infrastructure and Manufacturing research focus area, the Smart Grid Program has 2.8 federal staff and 4.2 associate staff (indicating a mix of dedicated and shared staff), and there is a larger team of 15 additional contributors to the broader program. The broader Smart Grid Program objectives include (1) development of precision timing requirements for electric grid systems; (2) measurements, observation, and communications for grid management to ensure interoperability; (3) cybersecurity for grid systems; (4) power conditioning systems and control strategies to develop requirements for emerging distributed grid systems; and (5) standards development for all aspects of device and system functionality. Following the 2021 publication of the NIST Framework and Roadmap of Smart Grid Interoperability Standards—Release 4,[2] the objectives for Smart Grid Program standards work have evolved to focus on the development of interoperability profiles, rather than developing new standards to address emerging technologies.

Activities in the Smart Grid group tend to be more applied than fundamental because the focus is on ensuring communications security and interoperability among the various energy sources that contribute to the nation's existing grid system and the development of standards. Within this constraint, the Smart Grid group has authored or delivered co-authorship of 43 publications, including 15 NIST publications, 1 NIST Management of Institutional Data Assets (MIDAS) Object, 7 journal publications, and 13 conference publications, 3 industry guidance documents, 1 Department of Energy report, and 3 technical standards since 2019. Smart Grid Program contributors from other NIST groups have authored or co-authored an additional 6 NIST publications, 2 MIDAS Objects, 8 journal publications, 5 conference publications, 6 industry guidance documents, and 11 technical standards. Twelve staff members, including the group leader and members of the broader Smart Grid Program, participate in 716 standards activities, along with members from the broader Smart Grid Program.

One of the major accomplishments of the Smart Grid group over the past 3 years was the development of the "Campus as a Testbed," conceived to enable NIST smart grid research to leverage the real-world energy infrastructure installations and operational conditions present around the NIST campus as a resource to enhance the industry relevance of program metrology activities and enhance the realism of complementary laboratory (testbed) based research activities. These facilities include the 5 MW photovoltaic array, wireless communications networks, the NetZero Energy Research Test Facility, and other facilities. Experiments and infrastructure were developed to measure and characterize technical parameters. This allowed the team to gain insights, for example, into the propagation of harmonic distortions through deployed distribution systems. Interestingly, this testbed produced more research results than a purpose-built smart grid testbed because the campus experienced things like non-compliant design, repeated flooding from both natural causes and infrastructure failures, and project management challenges, thus representing a real operating environment and not an idealized model. The leadership of this testbed project has changed due to normal turnover, and the testbed is being redesigned for future experimentation.

Manufacturing Standards (Smart Connected Manufacturing Systems)

The manufacturing standards presentation covered work from the Smart Connected Manufacturing Systems Group within CTL and detailed CTL's role in system modeling standards and manufacturing digital thread standards. The overall approach is to identify commonalities in system models and analytical methods, and use those as points of leverage to drive the development of new abstractions that result in extensions to standard modeling languages—in particular, the systems modeling language (SysML).

Notably, CTL has played a prominent role in advancing systems engineering standards and, in particular, the widely used SysML. In addition to developing behavioral models for the current version of SysML, CTL played a central role in working jointly with stakeholders and the Jet Propulsion Laboratory

[2] National Institute of Standards and Technology. 2022. Smart Grid Framework: NIST Framework and Roadmap of Smart Grid Interoperability Standards, Release 4.0. https://www.nist.gov/ctl/smart-connected-systems-division/smart-grid-group/smart-grid-framework.

on the formulation of SysML 2. The Object Management Group, the standards organization behind SysML, adopted the NIST-Jet Propulsion Laboratory approach as the core to SysML 2.

For manufacturing digital thread standards, CTL is focused on filling gaps in the current standards ecosystem to help unlock the economic potential of advanced manufacturing. CTL has played a significant role in the development of the standards for the exchange of product model data (known as STEP) over the past few decades and has been engaged in a variety of related manufacturing standards. Particularly for standards for the exchange of product model data, CTL has led the interoperability and conformance ecosystem to help drive coherence among a diverse and complex ecosystem. The next frontier of their research is focused on adding supply chain cybersecurity to manufacturing standards.

Additionally, CTL has leveraged its existing machine shop, and with some modest upgrades, has turned it into a testbed for experimentation and prototyping.

Industrial Wireless Environment (Industrial Wireless Systems)

The Industrial Wireless Environment group has several project goals, including developing testbeds, researching technologies for the Industrial Internet of Things (IIoT), developing conceptual frameworks for the inclusion of impairments in performance modeling, developing spectral activity measurement capability, and developing channel exemplars for millimeter-wave and microwave operational environments. However, the only activity that was presented in detail was the millimeter-wave channel characterization effort, which is not a core Smart Infrastructure and Manufacturing activity and is carried out in collaboration with Innovations in Measurement Science and other centers within NIST. Other activities, such as time-sensitive networking using Wi-Fi, the development of a 5G testbed, and applications of machine learning in industrial wireless were briefly mentioned. However, in written answers to questions, CTL stated that one of the most impactful projects was the time-sensitive networking over Wi-Fi project, which resulted in multiple publications and one best paper award. The Industrial Wireless Environment group publishes about two to four papers and delivers three to five presentations per year.

The millimeter-wave IIoT channel characterization effort will eventually allow users to evaluate millimeter-wave IIoT device performance under real-world channel conditions. Measured channels will be replicated in a repeatable, over-the-air test chamber with configurations automatically managed by machine learning. The results of this channel characterization effort are contributed to the open 5G Channel Model Alliance Data Repository.

CHALLENGES AND OPPORTUNITIES

Smart Grid Program

A challenge is that the Smart Grid Program needs to be better integrated with the connectivity theme of CTL. One way to accomplish this would be to address the question of how 5G fits into the smart grid connectivity needs. The 5G testbed being built in the Next-Generation Wireless group was mentioned in several discussions. However, it is very unclear what this testbed actually is and whether the goals of smart grid connectivity can be achieved using the proposed testbed, which appears to be built with Citizens Broadband Radio Service equipment that is not state of the art in terms of 5G functionality. 5G-based smart grid connectivity would rely specifically on the Ultra-Reliable Low Latency Communication feature of 5G and it did not seem that the proposed 5G testbed would focus on this aspect.

There is an opportunity for the Smart Grid Program to be more involved in the design of the proposed 5G testbed to ensure that the Ultra-Reliable Low Latency Communication features are present. To date, there are almost no performance data available on this aspect of 5G because most operators are focused on high-speed broadband. Building a program that focuses on this aspect could be very beneficial to the broader IoT community.

Manufacturing Standards

Challenges in this area include the breadth of standards activities and a prioritization approach that not only accounts for where NIST has engaged and networked with leaders in the standards space but also where the United States and the federal government have specific needs to advance the competitiveness of the United States and to provide for use cases such as public safety and military communications, which might otherwise not be represented in standards bodies. With much of the Industry 4.0 effort's energy being driven by the European Union, NIST participation is critical.

CTL has had a prominent role in the development of manufacturing standards for decades. A forward-looking opportunity is to lead the development of the next generation of use cases and standards for advanced manufacturing. Particularly as the Industry 4.0 effort seeks to use wireless technologies, Smart Infrastructure and Manufacturing could leverage the broader communications expertise within CTL to step forward and lead the development of advanced manufacturing communications standards for 5G, 6G, and NextG.

Another opportunity is increased collaboration between CTL and the NIST Manufacturing Extension Partnership in setting manufacturing standards. The network of university and industry partnerships represented within the Manufacturing Extension Partnership are a tremendous collaborative relationship that could help amplify CTL's standards agenda.

Industrial Wireless Environment

Several challenges are apparent. The focus on millimeter-wave technology for IIoT seems to have been adopted without enough evaluation of mid-band (sub-6 GHz) technologies and the inherent obstacles in implementing millimeter-wave technology in an industrial environment. It is also not clear how measurements made in a very specific propagation environment would scale across industries and environments. While the millimeter-wave effort is a good contribution to measurement science, it is not at all clear as to how the work that is being done will confirm that millimeter-wave technology will indeed meet the latency and other performance targets of this application. If the goal is measurement, then the current approach is fine. However, if the goal is to pick the best technology for IIoT to meet the target performance, more work needs to be done in fully evaluating mid-band technologies in comparison to millimeter-wave technology. The group seems to be guided by what industry wants and their past expertise in millimeter-wave channel modeling rather than performing in-depth comparisons of their own.

By way of opportunities, the group has expertise in testing IIoT using Wi-Fi. Combined with their expertise in millimeter-wave technology, there is a unique opportunity to provide industry with benchmark comparisons of IIoT in different bands and using different technologies on the same testbed.

This could be done using WiGig chipsets at 60 GHz alongside 5 GHz Wi-Fi. Wi-Fi 6E in 6 GHz is also available today and is being evaluated as a high-throughput, low-latency alternative to millimeter-wave technology. A testbed that tests these various technologies and presents recommendations based on use cases would be extremely valuable.

PORTFOLIO OF SCIENTIFIC EXPERTISE

Accomplishments

The groups working in the Smart Infrastructure and Manufacturing research focus area possess world-class expertise in most of the areas where they work. However, from the material presented, and given the mandate of focusing on applied research, the output is more in the form of contributions to standards than in scientific papers, especially in smart grid and smart manufacturing, though they do produce papers. Certainly, the expertise in creating standards in the core areas of their mission is very commendable and quite impressive, as demonstrated by their many publications, presentations, and best paper awards.

Challenges and Opportunities

Current expertise in the Smart Grid Program and Smart Infrastructure and Manufacturing group is in the core areas these research areas cover, which do not include connectivity research. Incorporating more connectivity research into all the research areas, especially the smart manufacturing and smart grid efforts, is a challenge. Most of the efforts seem very focused on developing standards documents, which is an important aspect of CTL and NIST, but more attention also needs to be paid to basic research.

Smart grid and smart manufacturing are application areas that will benefit from 5G connectivity in the future. However, most of the research focus in both academia and industry is on broadband needs. An opportunity exists for those working in the Smart Infrastructure and Manufacturing research focus area to leverage its leadership position in the smart grid, smart manufacturing, and the industrial wireless environment to help formulate a strategy that develops scientific expertise in the application of 5G to these new application areas.

EFFECTIVE DISSEMINATION OF OUTPUTS

Accomplishments

The groups in the Smart Infrastructure and Manufacturing research focus area disseminate their results in various ways: contributions to standards publications, NIST documents (reports and data outputs), external journal and conference publications, and presentations (including keynotes) at appropriate venues. Many publications are collaborative, with coauthors from other NIST divisions and external organizations. The smart grid and smart connected manufacturing systems research areas have the largest output in terms of publications, presentations, and contributions to standards.

Challenges and Opportunities

Academic publications, conference attendance, and in-person attendance at standards-setting meetings have been challenging through the COVID-19 pandemic. Undoubtedly, these macro-conditions impacted the ability of the groups working in the Smart Infrastructure and Manufacturing research focus area to disseminate the results of its research, experimentation, and standards contributions. The Industrial Wireless Environment group does not seem to publish in journals, preferring conference publications and presentations instead, which may impact the archival nature of their research in the long term. The Smart Grid Program has a commendable output but is more focused on NIST publications.

Since 5G appears to be a cross-cutting theme across several different groups working in the Smart Infrastructure and Manufacturing research focus area, focused participation in 5G-related conferences would be useful and appropriate.

8

Spectrum Sensing and Sharing

INTRODUCTION

Research into spectrum sensing and sharing is housed within the Spectrum Technology and Research Division of the Communications Technology Laboratory (CTL). Within the sensing realm, the primary research focus areas are microwave noise metrology, radio frequency spectrum sensing, and atmospheric spectroscopy. Within the sharing realm, the focus areas are wireless coexistence and "black box" spectrum sensing. This research spans a very wide range of frequencies from radio (including millimeter wave and terahertz) to infrared and optical. The application space is equally broad, ranging from spectrum sharing between federal and commercial wireless systems to femtosecond-level time transfer.

Current research programs include the following:

- Wireless coexistence;
- Monitoring changes in radio spectrum use during the COVID-19 pandemic;
- The use of Wi-Fi signal propagation changes to monitor patient breathing for medical applications;
- Test and measurement lead for the National Advanced Spectrum and Communications Test Network (NASCTN), including Advanced Wireless Services (AWS)-3 and Citizens Broadband Radio Service (CBRS) projects;
- Digital radiometry;
- Infrared spectroscopy using optical frequency comb for atmospheric sensing;
- Ultrahigh accuracy time transfer using optical frequency comb pulses; and
- Calibration of blackbody targets for use in remote sensing.

Research challenges include the following:

- Use of artificial intelligence and machine learning to generate waveforms simulating real-world signals, to be used for spectrum coexistence studies without complications related to off-air capture, such as personally identifiable information;
- Receiver performance characterization; and

- Measuring skyward emissions from 5G systems for use in compatibility studies with, for example, passive remote sensing satellites.

ASSESSMENT OF TECHNICAL PROGRAMS

Laser Combs

In response to the 2019 National Academies of Sciences, Engineering, and Medicine's assessment of CTL,[1] some components of CTL were reorganized. One result of this reorganization was the assimilation of the National Institute of Standards and Technology's (NIST's) Fiber Sources and Applications Group into CTL's Spectrum Technology and Research Division from its previous home in the Physical Measurement Laboratory. This group's principal research thrust in the spectrum sensing domain is related to the application of laser combs for precision spectroscopy, a technology whose development at NIST earned a share of the 2005 Nobel Prize in Physics.

Laser combs have multiple applications that are being developed. For example, the combs can be used for exceptionally precise time transfer and ranging over free space links. The group is working at expanding the distance over which such transfer can take place, up to hundreds of kilometers (while using eye-safe power levels).

The large number of laser frequencies across the comb can be used to create a hyperspectral atmospheric transmission sensor, which can be used to accurately detect and quantify molecular species in the atmosphere. The technology has been used to detect, for example, methane leaks across oil fields and abundances of molecular species relevant to climate change across a city-scale environment. The technology has also been used for in situ atmospheric measurements that can be used to calibrate or validate space-based atmospheric sounders.

NIST and CTL have been successful in developing and refining laser comb technology and helping to transfer the technology to commercial ventures. This is a valuable contribution both to the industrial community and to climate science at large. While CTL's work on laser combs is important and impressive, the panel notes that it is not clear that this work fits within the definition of communications.

Recommendation 8-1: CTL should continue its goal of refining the laser comb technology and helping to transfer the technology for both commercial and scientific purposes.

Wireless Coexistence

The Spectrum Technology and Research Division is actively involved in various studies related to coexistence of wireless systems, and spectrum sharing at large. The chances and actual occurrences of conflicts in spectrum use are also increasing, such as the example of the potential interference between 5G deployments and the nearby aeronautical radio altimeter systems in the 3 and 4 GHz ranges.

The wireless coexistence work is linked to the group's work on wireless signal characterization, as coexistence depends on the nature and strength of the interfering signals. The Spectrum Technology and Research Division cited several examples of past or current work in this domain, including the following:

- Wi-Fi and Bluetooth coexistence as a testbed for general coexistence studies;
- Characterization of user terminal emissions for predicting coexistence between Advanced Wireless Services (AWS) and Department of Defense (DoD) systems in the 1.7 GHz range;

[1] National Academies of Sciences, Engineering, and Medicine, 2019, *An Assessment of the Communications Technology Laboratory at the National Institute of Standards and Technology: Fiscal Year 2019*, Washington, DC: The National Academies Press, https://doi.org/10.17226/25602.

- Initial efforts at the use of artificial intelligence and machine learning for test waveform generation, so that realistic interfering signals can be generated without recording real radio signals off air, which can create privacy issues;
- 5G skyward emissions to measure the impact of 5G signals on aeronautical and satellite systems; and
- Issues of fairness among coexisting systems.

A Spectrum Technology and Research Division's research effort has applied machine learning to determine which transmission parameters are most impactful to coexistence between disparate systems (such as Wi-Fi and Bluetooth). It has shown that restricting attention to those parameters can significantly reduce (by as much as 30 percent) the number of measurements needed to parameterize coexistence criteria. One of the practical impacts is to speed up analyses of coexistence between two or more systems that may be under consideration to share spectrum.

The fair coexistence work done by the group aims to develop a framework to objectively answer the question of whether a given scenario achieves a desired level of fairness, where fairness is intended as an input to the model and measurement method being developed.

Overall, the wireless coexistence work is relevant, of high quality, and important to the management of spectrum.

Spectrum Sensing

The Spectrum Technology and Research Division made a pivot of resources to address the COVID-19 pandemic. The group used machine learning to infer a person's breathing from variations of the Wi-Fi received signal (the physical movement of respiration caused measurable changes in signal), which may have applications in other diseases or future pandemics.

The group also took advantage of the unique shift in home, school, and work arrangements during the pandemic to perform detailed studies of changing radio spectrum use during this time.

National Advanced Spectrum and Communications Test Network

The Spectrum Technology and Research Division in CTL hosts the program office for NASCTN. As part of this role, they are a government-wide resource for undertaking technical studies related to NASCTN projects. Examples include the past and ongoing work on understanding coexistence between AWS-3 systems and DoD's aeronautical telemetry system that operates in the same band, and a newly launched project to study CBRS. Specifically, the new study will provide data-driven insight into the CBRS-sharing ecosystem's effectiveness between commercial and DoD radar systems, track changes in the spectrum environment over time, and assess whether the CBRS industry's network of radar sensors is performing its job to detect and avoid DoD radar when in use, according to the Part 96 rules.

The division has moved beyond current coexistence issues between radar and 4G LTE communications systems, or incumbent and secondary communication systems, and plans to study 5G-and-beyond systems. Such future 5G, 6G, and beyond systems will operate at higher frequencies with narrow beams and large available bandwidth.

The division reported about the work done at the beginning of the pandemic to allow measurements to be run remotely—a capability that is expected to automate measurement campaigns, making them more efficient and more extensive in the future. It also voiced concerns about (1) the amount of time required for purchases above $10,000 and (2) the availability of advanced equipment for spectrum sharing and sensing research, some of which is not yet commercially available.

The Spectrum Technology and Research Division disseminates its work through presentations and publications in professional conference proceedings and journals. It contributes to standards-developing organizations such as the Institute of Electrical and Electronics Engineers (IEEE), the American National

Standards Institute (ANSI), the 3rd Generation Partnership Project, the Technology Innovation Program, and the International Electrotechnical Commission. It has ongoing collaborations with industry and other agencies, including joint publications and standard contributions. Technology transfer happens through NIST programs such as the Technology Maturation Accelerator Program and the NIST-Science and Technology Entrepreneurship Program. Technical notes, reports, and data sets are made available online through NIST repositories and through the NASCTN webpage.

The group has received NIST awards for service, including Presidential Rank Award, Distinguished Associate Award, various medals, etc.

The Spectrum Technology and Research Division collaborates with other groups and federal agencies (i.e., through NASCTN) to share lessons learned. It shares detailed reports and data, with specifications, rationales for decisions, and challenges. Testbeds are open to others.

NIST has participated in industry standards groups. For example, NIST helped guide the standards for CBRS within the Wireless Innovation Forum. From the adoption of CBRS rules by the Federal Communications Commission (FCC) in 2015, NIST representatives participated in Wireless Innovation Forum standards meetings and made contributions on a wide range of standards items, including propagation models, interference statistics, protocols, and certification test code.

CHALLENGES AND OPPORTUNITIES

The Spectrum Technology and Research Division has moved beyond current coexistence issues between radar and 4G LTE communications systems, or incumbent and secondary communication systems, and plans to study 5G-and-beyond systems. Such future 5G, 6G, and beyond systems will operate at higher frequencies, where coexistence issues among active systems may be not relevant because beams are narrow and the available bandwidth is large. Instead, there may be potential coexistence issues with passive, possibly non-terrestrial, systems. In addition, next-generation wireless systems will include mixed industrial Internet of Things (IoT) applications and smart grid applications. Issues of trustable measurements and coexistence in such environments are expected to be rather challenging, given that IoT devices are expected to be heterogeneous, power limited, computationally limited, and geographically distributed in areas difficult, if not impossible, to access. In addition, medical devices will also need to be secure and guarantee privacy. Advances in these challenging areas of outdoor, dynamic, and distributed sensing are expected to have great practical impact.

Recommendation 8-2: CTL should continue its work on spectrum coexistence.

The use of spectrum to monitor atmospheric emissions is very interesting and timely. Upward skyward measurements are an opportunity for collaboration with the channel-modeling group in the next-generation wireless research focus area.

Recommendation 8-3: CTL should reach out to and collaborate with industry partners to develop tools that employ technologies being researched at CTL, where appropriate, to address climate change challenges.

Key Recommendation 10: CTL should engage actively with industry, including wireless standards groups, to remain aware of upcoming and pressing spectrum coexistence issues. The Spectrum Technology and Research Division should develop a framework that allows fast pivoting of resources (and techniques) as new bands become available to be able to contribute timely, accurate, and unbiased assessments of coexistence among increasingly dense and disparate spectrum uses.

A concern shared by the panel members is that spectrum sharing and spectrum sensing activities are not integrated, and thus their synergies are not clear. This is understandable at this stage, as the group is very new and some of its members have not worked together before. An immediate and concentrated effort appears needed to identify common goals and projects going forward. The panel positively assessed the ongoing efforts of the researchers of this new division, aiming to identify common challenges in terrestrial-to-non terrestrial measurements, emissions at higher frequencies, and also applications for rural and agricultural uses of wireless systems.

The panel heard from another division within CTL working in the Core Networks research focus area about the very exciting ongoing work on the Rydberg Atom-based Radio Frequency Field Probe, a technology that, if possible to develop to its full commercial potential, could revolutionize radio communications and metrology.

Key Recommendation 11: The Spectrum Sharing and Sensing team should collaborate closely with the Rydberg Atom-based Radio Frequency Field Probe team to examine the probe's potential application to spectrum sensing and metrology and identify key technology opportunities in the space of spectrum metrology.

PORTFOLIO OF SCIENTIFIC EXPERTISE

Personnel Expertise

The Spectrum Technology and Research Division is well staffed with many of its team members recognized as experts in their field. There are only a couple of vacancies at the time of writing this report. The team has been able to attract amazing talent that matches well to its mission and work and appears to be on track to achieve its goals.

Challenges and Opportunities

The Spectrum Technology and Research Division competes with industry and academia for the best people. The CTL director reports that they have implemented many aspects of workplace flexibility (in terms of work from home, schedule flexibility, and split shifts) to compensate for what they may not be able to offer in terms of salary. The team members attested to a very respectful and team-oriented work environment.

EFFECTIVE DISSEMINATION OF OUTPUTS

Accomplishments

The Spectrum Technology and Research Division has a good publication record. The group disseminates its work through presentations and publications in professional conference proceedings and journals. It contributes to standards-developing organizations, such as IEEE, ANSI, the 3rd Generation Partnership Project, the Technology Innovation Program, and the International Electrotechnical Commission. It has ongoing collaborations with industry and other agencies, including joint publications and standard contributions. Technology transfer happens through NIST programs, such as the Technology Maturation Accelerator Program and the NIST-Science and Technology Entrepreneurship Program. Technical notes, reports, and data sets are made available online through NIST repositories and the NASCTN webpage.

The group has a track record of receiving NIST awards for service, including the Presidential Rank Award, the Distinguished Associate Award, and various medals.

The Spectrum Technology and Research Division collaborates with other groups and federal agencies (i.e., through NASCTN) to share lessons learned. They share detailed reports with specifications, rationales for decisions, and challenges. Testbeds are open to others. This knowledge is beneficial to those who plan to set up similar or related experiments, as it reduces the design time, allows them to readily identify key challenges, and focuses on improving performance.

Challenges and Opportunities

NIST has successfully participated in industry standards groups. For example, NIST helped guide the standards for CBRS within the Wireless Innovation Forum. Since the adoption of CBRS rules by FCC in 2015, NIST representatives participated in Wireless Innovation Forum standards meetings and made important contributions to a wide range of standards items, including propagation models, interference statistics, protocols, and certification test codes. Similar opportunities will present themselves in, for example, the 3.1 to 3.45 GHz band, which is currently under study for shared use.

> **Recommendation 8-4:** Where possible, the Spectrum Technology and Research Division should engage with industry standards groups to both understand the ongoing needs of the wireless industry and to offer CTL's expertise in specific areas.

9

Facilities, Equipment, and Personnel

Because this assessment was entirely remote, with no in-person components, the panel was not able to visit any of the Communications Technology Laboratory's (CTL's) facilities in person. This imposed limitations, despite CTL's willingness to engage, provide information, and answer questions. Something vital is missed when a panel cannot interact closely and informally with the researchers at a laboratory under assessment, walk the halls, and see things first-hand. This has made it a challenge to say much about the condition of CTL's facilities and equipment, as well as CTL's personnel situation. As a result, different panel members received differing levels of information on the topics of facilities, equipment, and personnel. To avoid having large differences in how each chapter addresses these topics, the panel believed that it is best to consolidate the material here in a stand-alone chapter.

FACILITIES

While the panel's ability to say anything meaningful about CTL's facilities is limited, CTL made it clear that some of its laboratories and other facilities are in buildings that prevent CTL researchers from reaching their full potential (e.g., Building 24), while the Public Safety Communications Research group is doing very good work in a newly renovated building (Building 3). The contrast between the two buildings is the contrast between researchers whose facilities hinder their work, and researchers whose facilities enable their work.

Building 24, on the Boulder, Colorado, campus, which houses several testbeds and laboratories used by the Radio Frequency Technology Division, reportedly has a facilities condition rating of −8 on a scale where 72 out of 100 is considered unacceptable. In addition, the network bandwidth of the entire building, which houses offices for approximately 20 staff members and 12 research laboratories, is only 1 Gb/s. The National Broadband Interoperability Testbed and the Antenna Communication and Metrology Laboratory, both in Building 24, produce data files ranging from 1-30 TB. This results in employees moving data from laboratories to the National Institute of Standards and Technology (NIST) network by walking hard drives to another building. This seems inefficient and imbalanced with the level of research being conducted. Furthermore, the various facility issues with loss of power and inability to keep stable temperatures within measurement chambers due to underlying utility infrastructure and various age-related facility issues have caused delays and reduced availability of services, as noted even by a random review of temporarily unavailable measurement services on CTL's website.

Key Recommendation 12: CTL should immediately prioritize its budget allocations to rectify the Building 24 issues by making improvements or relocating its work to an improved facility.

During the COVID-19 pandemic, CTL established some new facilities and capabilities. It created a new 5G Coexistence Testbed consisting of commercial-grade 5G New Radio millimeter-wave technology in Building 3, which reportedly is in good condition. In general, it appears that there are multiple testbeds and laboratories that work well. CTL's Spectrum Technology and Research Division reported about work done at the beginning of the pandemic to allow the remote conduct of measurements without needing to be onsite—a capability that is expected to automate measurement campaigns making them more efficient and extensive in the future. This capability also likely increases the ability to collaborate with a wider range of researchers, some of whom may not be able to travel to the CTL laboratories.

Based on the information provided during this remote assessment, it appears that Public Safety Communications Research (PSCR) laboratory facilities and equipment are adequate for their mission. The PSCR team moved into a new building with laboratory facilities in Boulder, Colorado, in 2018. Recently, the PSCR team partnered with FirstNet to establish the Public Safety Immersive Test Center. This facility is located in the FirstNet Authority's Boulder, Colorado, facilities. The Public Safety Immersive Test Center includes a high-end virtual reality system to test and measure potential advancements in user interfaces as well as location-based services. The PSCR team also has a partnership to use the National Guard's Muscatatuck Urban Training Center to field test technologies developed as part of the ongoing First Responder Smart Tracking prize challenge. The Muscatatuck Urban Training Center comprises about 1,000 acres and provides a realistic multi-domain urban and rural training environment. This training center provides the opportunity for first responders to coordinate their training with the National Guard, which conducts emergency response missions in disaster situations.

Recommendation 9-1: CTL should evaluate the partnership with the Muscatatuck Urban Training Center for long-term continuation, particularly because of the opportunity to coordinate first responder and National Guard training that is central to its mission.

While the panel does not have any details, the condition of CTL's facilities generally has budgetary implications. Unaddressed current facility needs cause scientific work efficiencies to suffer if researchers need to waste time and research money working around facility issues. Addressing new and unknown future challenges will require sufficient facilities funding to ensure that CTL's facilities are capable of meeting future needs. This need creates an interdependency between funding for technical work and funding for the maintenance, renewal, and construction of facilities even though they have separate funding sources to ensure that CTL's laboratories are capable of accomplishing the mission. The CHIPS and Science Act of 2022 (P.L. 117-167) appears to include funding for improving NIST's facilities.

The condition of the capital facilities on NIST's Boulder, Colorado, and Gaithersburg, Maryland, campuses is treated in detail in the National Academies of Sciences, Engineering, and Medicine report *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology*.[1]

EQUIPMENT

For the Radio Frequency Technology Division, focusing on efforts to upgrade laboratory equipment, which was slowed due to the pandemic, continues to be the highest priority. Efforts that were put in place during the pandemic will be essential to help CTL maintain its leadership position. The restructuring that includes the Innovations in Measurement Science project for inter-laboratory collaboration, which focuses on important emerging areas, will also provide a great opportunity for CTL to identify equipment needs that address both fundamental and interdisciplinary research more effectively. In 2020, the Radio

[1] National Academies of Sciences, Engineering, and Medicine, 2023, *Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology*, Washington, DC: The National Academies Press, https://doi.org/10.17226/26684.

Frequency Technology Division conducted a quality assessment that showed increased attention to using the quality management system, which manages the quality assurance of calibrated measurements.

Two major equipment challenges were reported to the panel. First, the time scale of purchases is reported to be painfully slow for items above $10,000. Second, the advanced nature of the spectrum sharing and sensing research often requires equipment that is not yet commercially available. The panel hopes that the process of acquiring necessary equipment can be sped up, but such considerations are outside the scope of recommendations to be made in this assessment

PERSONNEL

CTL has successfully completed a reorganization that brings together the diverse groups involved in smart infrastructure and manufacturing from across the organization to help bolster its research, experimentation, and standardization missions. These groups have common themes in the areas of cyber-physical systems that can benefit from organizational proximity and shared laboratory test infrastructure. This includes 71 staff across five different groups.

In the edge-to-edge quality assurance project under 5G/6G Core Networks, staffing restrictions could be a significant impediment to further progress. The groundwork seems to have been established for a strong foundation to build on, but the program has not yet been fully funded, which could be a serious challenge. They have been investigating several related topics, including machine learning-based software-defined network routing, end-to-end quality assurance when network slices use virtual network functions, and multi-tier task offloading, but, due to the limited personnel, progress has been modest. One opportunity would be for increased collaboration with the Next-Generation Wireless group. It is easy to conceive of projects that could involve close cooperation between the two teams to create an antenna-to-core networks span.

During the COVID-19 pandemic, CTL took multiple actions to minimize the impact of restrictions on in-person work. Particularly for the Radio Frequency Technology Division, which requires hands-on activity to support testing and characterization of radio frequency components, virtual work could be problematic. However, the use of technology and teamwork was commendable. First, CTL requested the ability to redistribute their employee limit between the two CTL campuses (Gaithersburg, Maryland, and Boulder, Colorado) to allow a higher percentage to be in person at Boulder where most of the hands-on work is done. Second, they prioritized setting up remote equipment so that employees working remotely could participate via cameras. This included an increase in automation as well, allowing for in-person staff to maximize their productivity.

The PSCR team is comprised of a mix of permanent and term employees. Currently less than 30 percent of the staff are permanent employees. Term employees generally come from other government organizations and universities. The large percentage of term employees is reflective of the short-term nature of the PSCR funding. It has also been challenging for PSCR to recruit top talent with the uncertain funding situation.

Like much of the scientific job market, the Smart Infrastructure and Manufacturing Division is experiencing challenges in recruiting and retaining key staff to support its work. Some research areas (e.g., smart connected manufacturing systems and the Industrial IoT) have had key senior personnel leave for other opportunities. Hence, even though the total number of staff may remain more or less level, departures can cause temporary setbacks in project implementations and outputs. In particular, it can take years to build the needed stature within standards communities to drive agendas and impact standards development.

NIST cannot compete with industry based on salary. However, the prestige of NIST and the favorable working environment have enabled the recruitment of very strong talent with a good record of accomplishment in the field. The Wireless Networks Division, which staffs the next-generation wireless program, has an even better retention record than the rest of NIST. This is a great accomplishment. NIST strongly supports the culture of teleworking, which allows for a distributed workforce and flexibility to remain anywhere in the country and still contribute strongly to NIST's core research and measurement work mission via telework. Furthermore, working with the Office of Personnel Management to get special pay rates for NIST researchers is another opportunity to help with the recruitment and retention of talent at NIST.

The geographic distribution of Smart Infrastructure and Manufacturing Division work across Maryland and Colorado may present a unique opportunity for recruiting and retention, providing two geographic regions within which to employ personnel. Additionally, further partnerships with national laboratories, Manufacturing USA Institutes, and other related organizations working in smart infrastructure and manufacturing can help them amplify their impact and catalyze a larger network of people and laboratories.

Cybersecurity is a common theme to advanced communications capabilities. Generally, recruiting and retaining science, technology, engineering, and mathematics (STEM) personnel is a problem common in both the government and industrial sectors. Scholarship for Service programs like the National Science Foundation's CyberCorps and the Department of Defense Cyber Scholarship Program are capacity-building programs with a focus on cybersecurity. These programs offer opportunities to recruit personnel with additional expertise in security, privacy, and usability in those domains. As cybersecurity becomes increasingly integrated with personal and public safety, this initiative has become more closely aligned with CTL's work. Scholarship for Service recipients in graduate programs are a potential source of interdisciplinary cybersecurity research personnel.

Recommendation 9-2: CTL should explore integration with the Scholarship for Service programs.

DEVELOPING A DIVERSE WORKFORCE

There are opportunities for CTL, and NIST more broadly, to reach out to underrepresented communities to generate interest in CTL's work and develop a more racially, ethnically, and gender-diverse workforce. Finding ways to identify and connect select projects to the broader community's needs can establish relevance and importance in diverse communities. Products could then be developed with accessible language using communications experts to share with the broader community in ways that offer insight into the future of communications. An example of how effective this could be is seen in decades of James Bond movies, with his communication spy watch preparing the public for today's Apple watch. In the same way, NIST could connect today's advanced communication technologies to future products that matter to younger generations. This would be exciting to the youth and college students who could consider working at NIST in this area. Lessons learned from the pandemic on remote access could be leveraged to provide remote demos to stimulate the imagination and demystify what happens at NIST in general, and CTL more specifically, by shedding insight into its structure, the things it does, and its importance to communications.

Key Recommendation 13: As its workforce continues to grow and mature, CTL should find ways to showcase select important technologies developed in the course of its work as part of its diversity strategy. These efforts should make use of popular culture and lay language to appeal to the broadest base possible.

Technical societies have been developing extensive young professional programs, which can serve as a resource to help CTL and NIST seek new talent. Some of these societies have also been developing diversity programs to support workforce development and broadening participation in undergraduate and graduate education that may be helpful. One example is Project Connect, which targets microwave engineering and has been hosted at the International Microwave Symposium for the past 9 years. Within academia, finding ways to expand or evolve NIST's current programs with minority-serving institutions, such as historically black colleges and universities (HBCUs) and Hispanic-serving institutions, could be used to connect students to graduate programs with research skills of high interest to CTL or form joint projects for undergraduate and graduate students. Lastly, HBCUs graduate a significant number of the minority undergraduate bachelor degrees in engineering. While some have reached R2 status over the past few decades, research has grown on those campuses in engineering, and reaching R1 status is a number-one priority for many of the schools with science and engineering programs. CTL could explore working directly with HBCU campuses in graduate education on research topics of mutual interest that would also allow CTL to be a part of developing the next generation of engineers and scientists who will broaden participation. In addition, NIST could partner with organizations like Project Connect and Advancing Minorities' Interest in Engineering, which includes the deans of 15 of the HBCUs with accredited engineering programs, to establish initiatives that develop a broad pipeline and student access across multiple campuses simultaneously.

> **Key Recommendation 14:** As part of the CTL diversification staff strategy, CTL should encourage and partner with technical staff to develop a strategic plan that leverages existing and potential opportunities available for growing and training the talent pool within the desired areas of expertise with the help of professional societies and minority-serving institutions campuses. Examples of these opportunities include partnering with historically black colleges and universities, Hispanic-serving institutions, Project Connect, and the Advancing Minorities' Interest in Engineering organization.

10

Assessment of Communications Technology Laboratory Responses to the Key Recommendations of the 2019 Assessment

This chapter assesses the extent to which the Communications Technology Laboratory (CTL) followed the key recommendations made in the 2019 National Academies of Sciences, Engineering, and Medicine report *An Assessment of the Communications Technology Laboratory at the National Institute of Standards and Technology: Fiscal Year 2019*.[1] The recommendations in this chapter are from Chapter 6 of the 2019 report.

PUBLIC SAFETY COMMUNICATION

Key Recommendation: The PSCR [Public Safety Communications Research] Division should develop a research and development roadmap for mission-critical voice, considering how the various activities it includes therein can be used as integral elements. CTL should consult on the roadmap's development with other organizations, both government and commercial, to determine overlap of technology development. CTL should conduct its own critical technology assessment to inform its roadmap.

The PSCR group has built a broad stakeholder community that spans government, industry, and academia. They have leveraged this community to collect input on mission-critical voice (MCV) strategic priorities and measurement research, particularly around quality of experience for public safety users. Each year at the annual stakeholder meeting, MCV results are presented along with future directions to enable continual feedback that PSCR can use to refine priorities as necessary. PSCR has identified the MCV portfolio as a key priority for support moving beyond 2023.

Key Recommendation: CTL should develop a roadmap for public safety analytics, taking into consideration projected future areas of interest.

[1] National Academies of Sciences, Engineering, and Medicine, 2019, *An Assessment of the Communications Technology Laboratory at the National Institute of Standards and Technology: Fiscal Year 2019*, Washington, DC: The National Academies Press, https://doi.org/10.17226/25602.

After fiscal year (FY) 2022, the future of PSCR's public safety analytics portfolio is uncertain since it is not one of the CTL PSCR priorities for ongoing support. To ensure continuity, PSCR has verified that the core analytics research areas are included in recent technology roadmaps developed by its partners at the First Responder Network Authority (FirstNet). PSCR will continue to collaborate with FirstNet in this area.

> **Key Recommendation:** The PSCR Division should consider integration of the UI/UX (user interface/user experience) research and prize challenges with the other PSCR portfolios as appropriate, provided efficiencies can be gained by such integration. The division should consider developing a methodology and process for studying UI/UX along with study of new technologies.

PSCR has successfully integrated user interface and experience research with its other research portfolios and projects through prize challenges and both intramural and extramural research projects. There are many examples of this, and it is clearly a strength of PSCR. Given the importance of user interface and experience to the eventual deployment of public safety technology, it would be useful for PSCR to document lessons learned and formalize a process for integration based on its recent experience. This could be valuable to the community as well as to PSCR as project funding becomes more competitive.

> **Key Recommendation:** CTL should evaluate the possibility of a strategic expansion of PSCR's internal research staff aimed at ensuring continuity of research in key priority areas in particular after fiscal year 2022 when the spectrum auction funds will have been spent or no longer be available. In addition, CTL should develop a plan for leveraging the expertise developed through the prize challenges.

PSCR has done significant planning and analysis with a goal of maintaining continuity in key research activities beyond FY 2022. It has secured funding to retain permanent federal staff. The CTL effort to manage the transition is admirable, but the concern of funding for key public safety research priorities remains.

Although the prize challenges have not been used as a recruiting tool, they have been part of expanding the public safety ecosystem through building technology capabilities and a marketplace.

METROLOGY OF ADVANCED COMMUNICATION

> **Key Recommendation:** CTL should develop a 3-year or 5-year strategic plan for its activities in metrology for advanced communication, to include: identifying and evaluating new research directions and opportunities for growth; developing strategic partnerships with other NIST laboratories for pursuing new areas; identifying resource needs (equipment, facilities, staff) for pursuing strategic growth areas of research; identifying and pursuing internal and external sources of funding to support the plan; and developing measurable criteria and metrics for annually evaluating progress toward 3-year and 5-year goals. The strategic plan should explain how its execution will support the successful attainment of the CTL priorities.

CTL engaged in strategic planning and underwent a reorganization in 2021. The reorganized CTL leverages existing strengths in research and development, metrology, and standards coordination with an expanded scope. CTL expanded from four focus areas to six research focus areas—Core Network Technologies, Fundamental Electromagnetic Technologies and Standards, Next-Generation Wireless Systems, Public Safety Communications, Smart Infrastructure and Manufacturing, and Spectrum Sharing and Sensing. Metrology is now integrated throughout the focus areas and has a prominent role in the strategic plans and roadmaps for these areas.

Key Recommendation: CTL should undertake planning and resource allocation for renewal and renovation of its measurement facilities with a degree of urgency to support their functioning as a "paid service" to the research and business communities.

Because this assessment was conducted remotely, the panel did not have the opportunity to visit CTL facilities. It is clear that there is still an urgent need for planning and resource allocation for the renewal and replacement of measurement facilities.

Key Recommendation: The Radio Frequency Technology Division should broaden its research portfolio into the areas of optical communications technology and quantum information science and engineering—both of which it has identified already—while leveraging strategic collaborative partnerships with other NIST laboratories, including the Physical Measurement Laboratory (PML) and the Information Technology Laboratory (ITL).

As a result of the CTL reorganization and strategic plan, the Emerging Network Technologies program within the Radio Frequency Technology Division has expanded its research portfolio to include quantum optical networking. The Quantum Optical Networking program develops new measurement techniques, tests and performance procedures, standards, and best practices. This is part of a larger quantum networking effort that spans a number of organizations at the National Institute of Standards and Technology (NIST), including the Physical Measurement Laboratory and the Information Technology Laboratory. There are significant opportunities for NIST to provide leadership in this area, but coordination between the different organizations is critical.

Key Recommendation: To develop closer partnerships with industry, academia and governments and to explore new sources of revenue the Wireless Networks Division and Radio Frequency Technology Division should integrate and build on the recent accomplishments in 5G millimeter-wave channel modeling, millimeter-wave propagation channel sounding and measurements, on-wafer measurements, over-the-air measurements, and a new design framework for future vector network analyzers.

CTL has been heavily focused on 5G and millimeter-wave efforts. The recent reorganization has broadened the scope of work in the Wireless Networks and Radio Frequency Technology divisions by adding application perspectives to these efforts. The Wireless Networks Division has been focused on 5G technology, metrology, and applications and is the steward for NextG Channel Model Alliance. The Radio Frequency Technology Division is currently leading an Innovations in Measurement Science program to develop new vector network analyzers to support quantum communications.

Key Recommendation: Consistent with its future staffing levels, NASCTN should take a more proactive role in advising on future spectrum allocation decisions. NASCTN should engage impartially with all sides of the debates on emerging and urgent issues.

The National Advanced Spectrum and Communications Test Network (NASCTN) is currently hosted within CTL in the Spectrum Technology and Research Division. As the technical lead for NASCTN, CTL provides measurement methods and validated data to enable spectrum sharing technologies. CTL is also involved in disseminating new measurement methods and validated data that result from NASTCN projects.

The CHIPS and Science Act of 2022 (P.L. 117-167), includes authorization language that would allow NIST to independently fund projects that have met the NASCTN selection criteria and receive a majority vote from the NASCTN Steering Committee.

Key Recommendation: CTL should continue vigorous support for the spectrum sensing and sharing activity, which has delivered impactful results.

As part of the CTL reorganization in 2021, a new Spectrum Technology and Research Division was established to expand spectrum sharing and sensing activities. The mission of this new division is to "research, develop, and deploy innovative measurement methods and tools to promote novel and efficient use of spectrum through improved access, sharing, atmospheric sensing, and precision timing. The division creates new metrology to understand and improve sharing and sensing wireless communications that use and harness the spectrum by utilizing tools in sensing (such as greenhouse gases), precision time, and future optical networks."[2]

[2] See https://www.nist.gov/ctl/spectrum-technology-and-research-division.

11

Key Recommendations

CORE NETWORK TECHNOLOGIES

Key Recommendation 1: NIST should ensure there is adequate coordination of work across the multiple laboratories engaged in quantum networking efforts to make sure that synergies and efficiencies are realized and different laboratories do not work at cross purposes, especially across the various NIST laboratories involved in quantum computing and metrology research.

Key Recommendation 2: CTL should establish an artificial intelligence (AI)/machine learning (ML) 5-year roadmap. This roadmap should include the application of AI and ML to 5G and 6G core networks, energy efficiencies, data management, and digital twins.

Key Recommendation 3: CTL should accelerate the development of a testbed with the Next-Generation Wireless team to enable a system that can fully test 5G/6G systems. CTL should foster collaboration between the Core Networks and Next-Generation Wireless teams to find and leverage synergies.

FUNDAMENTAL ELECTROMAGNETIC TECHNOLOGIES AND STANDARDS

Key Recommendation 4: Given the fundamental nature of FETS, the Radio Frequency Technology Division should create a system or database that tags key projects and links them to other work within or between different CTL focus areas, divisions, or NIST laboratory projects. Such a system would provide tracking of the work throughout CTL and allow others to better understand the connections, impacts, uses, evolution, and sunsetting of the work.

Key Recommendation 5: CTL should investigate the reasons behind the trend in the number of calibrations performed annually. Specifically, CTL should understand (1) the significant drop in 2018, (2) the surge in 2019, and (3) the trend during the pandemic. The results of this investigation should inform a strategic plan for determining if there needs to be a goal for achieving the desired amount of CTL calibration work and what that amount might be.

NEXT-GENERATION WIRELESS

Key Recommendation 6: CTL should create a roadmap of what the next 5 years of NextG Channel Model Alliance's work will look like. The group should use this roadmap to determine where they can leverage CTL's unique capabilities to focus on the key gaps and make the biggest impacts on next-generation wireless technology and its deployment in the next 5 years.

Key Recommendation 7: The Next-Generation Wireless group should be actively involved in the Open RAN testbed selection process in collaboration with the Core Networks group. The selection process and criteria of the Open RAN testbed process should be well documented and disseminated to the other national laboratories that are also looking to acquire similar testbeds in the near term.

PUBLIC SAFETY COMMUNICATIONS RESEARCH

Key Recommendation 8: The PSCR Division should define its mission beyond the mandates of the Public Safety Trust Fund. Changes to the nation's infrastructure and technology need to be taken into consideration for PSCR to position itself to stay ahead of the evolving needs of the first responder community, and effectively support public safety communication in a changing world. Working with stakeholders to understand the impact of changes and prepare for them requires collaboration with other divisions in CTL, such as with the teams working on smart connected systems and next-generation networking.

Key Recommendation 9: The PSCR Division should take a leadership role in developing a sustainable model for bringing together stakeholders to research, develop, and commercialize public safety innovations. CTL should ensure the continuation of the PSCR Division's community leadership role and its functions in convening meetings of stakeholders and PSCR community groups.

SPECTRUM SHARING AND SENSING

Key Recommendation 10: CTL should engage actively with industry, including wireless standards groups, to remain aware of upcoming and pressing spectrum coexistence issues. The Spectrum Technology and Research Division should develop a framework that allows fast pivoting of resources (and techniques) as new bands become available to be able to contribute timely, accurate, and unbiased assessments of coexistence among increasingly dense and disparate spectrum uses.

Key Recommendation 11: The Spectrum Sharing and Sensing team should collaborate closely with the Rydberg Atom-based Radio Frequency Field Probe team to examine the probe's potential application to spectrum sensing and metrology and identify key technology opportunities in the space of spectrum metrology.

FACILITIES, EQUIPMENT, AND PERSONNEL

Key Recommendation 12: CTL should immediately prioritize its budget allocations to rectify the Building 24 issues by making improvements or relocating its work to an improved facility.

Key Recommendation 13: As its workforce continues to grow and mature, CTL should find ways to showcase select important technologies developed in the course of its work as part of its diversity strategy. These efforts should make use of popular culture and lay language to appeal to the broadest base possible.

Key Recommendation 14: As part of the CTL diversification staff strategy, CTL should encourage and partner with technical staff to develop a strategic plan that leverages existing and potential opportunities available for growing and training the talent pool within the desired areas of expertise with the help of professional societies and minority-serving institutions campuses. Examples of these opportunities include partnering with historically black colleges and universities, Hispanic-serving institutions, Project Connect, and the Advancing Minorities' Interest in Engineering organization.

Appendixes

A

Acronyms and Abbreviations

3GPP	3rd Generation Partnership Project
AI	artificial intelligence
AWS	Advanced Wireless Services
BGP	Border Gateway Protocol
BGPSec	security extension of BGP
CBRS	Citizens Broadband Radio Service
CTL	Communications Technology Laboratory
CRADA	Cooperative Research and Development Agreement
DARPA	Defense Advanced Research Projects Agency
DNS	Domain Name System
DNSSEC	DNS Security Extension
DoD	Department of Defense
FETS	Fundamental Electromagnetic Technologies and Standards
HBCU	historically black college and university
ICN	Information Centric Networking
IEEE	Institute of Electrical and Electronics Engineers
IMS	Innovations in Measurement Science
IoT	Internet of Things
IIoT	Industrial Internet of Things
LTE	Long-Term Evolution

ML	machine learning
NASCTN	National Advanced Spectrum and Communications Test Network
NDN	Named Data Network
NIST	National Institute of Standards and Technology
NTIA	National Telecommunications and Information Administration
OUSD (R&E)	Office of the Under Secretary of Defense for Research and Engineering
PSCR	Public Safety Communications Research
PSITC	Public Safety Immersive Test Center
RAN	Radio Access Network
SysML	Systems Modeling Language

B

Panel Biographical Sketches

CYNTHIA S. HOOD, *Chair*, is an associate professor of computer science and engineering within the Computer Science Department at the Illinois Institute of Technology (IIT), where she is also the director of the Wireless Networks, Communication and Policy (WiNComP) Research Center. WiNComP operates the IIT Spectrum Observatory, which has been monitoring the 30-6000 MHz spectrum in Chicago since 2007. Her current research focuses on utilizing artificial intelligence and machine learning techniques to automate the labeling and analysis of spectrum measurements by combining quantitative and qualitative information. Other research interests include spectrum management, network management, socio-technical systems, and computing in public policy. Dr. Hood is currently a member of Representative Lauren Underwood's (IL-14) Science, Technology and Environment Advisory Council for the 117th Congress. She is a recipient of a National Science Foundation (NSF) CAREER Award and will be a Fulbright Scholar in Poland in 2023. Dr. Hood is a senior member of Institute of Electrical and Electronics Engineers (IEEE) and a member of the Association for Computing Machinery (ACM). She received her BS in computer and systems engineering from Rensselaer Polytechnic in 1987, her ME in electrical engineering from the Stevens Institute of Technology in 1989, and her PhD in computer and systems engineering from Rensselaer Polytechnic Institute in 1997.

NATHAN RAEN BROOKS is a senior technical fellow for Boeing in Electromagnetics (EM) and Antenna Systems. Dr. Brooks primarily provides technical expertise and leadership for Boeing's Signal Intelligence capabilities. He has 20 years of experience in EM and numerical optimization including graduate and postdoctoral research at the National High Magnetic Field Laboratory, the Center for Advanced Power Systems, and the European Organization for Nuclear Research (CERN). Dr. Brooks is a key contributor to advanced EM capability efforts for military, government, and commercial customers, including the Defense Advanced Research Projects Agency (DARPA) and the Intelligence Advanced Research Projects Activity. He performs three-dimensional EM modeling and simulation of antenna systems on air, land, sea, and underwater platforms; antenna selection, characterization, and performance predictions for communication, jamming, beam-forming, and direction-finding; and co-site and radio frequency propagation analysis. He develops inverse problem-solving algorithms for challenging applications such as navigation in urban or GPS-denied areas, power-based geolocation, and underground target detection. He is a leading member of site survey, system design, and installation teams for programs around the world. Dr. Brooks received multiple Black Engineer of the Year conference awards; the 2019 National Society of Black Engineers Golden Torch Lifetime Achievement in Industry award; and the 2020 Boeing Defense Engineer of the Year award. He received his PhD in electrical engineering from Florida A&M University.

MILIND M. BUDDHIKOT is currently a Nokia Bell Labs fellow and a Distinguished Member of Technical Staff (DMTS) in Nokia Cloud and Network Services business unit. He serves as the head of Nokia Digital Automation Cloud (NDAC) New Jersey Technology Center and as the head of End-to-End Spectrum Solutions for the NDAC business division. In these roles, he leads a group of engineers to research, develop, and build end-to-end wireless and cloud solutions for the next generation of networks for industrial automation. In a research career spanning over 22 years, of which 20 were in Bell Labs, he has made significant contributions, scientifically as well as to the business aspects of wireless, intellectual property, and multi-media networking. Dr. Buddhikot's areas of expertise include wireless networks, large-scale networked systems, video communications, network security, and mobile and cloud computing. His recent work focuses on developing end-to-end architectures, systems, protocols, and cloud solutions for dynamic spectrum access (DSA), spectrum aggregation and sharing, service load balancers, high-capacity video transport, large-scale Internet of Things (IoT), and emerging drone applications. He has authored over 47 technical papers and holds 18 U.S. or international patents, some of which are in the key areas of spectrum sharing and aggregation. According to Google Scholar, Dr. Buddhikot's research publications have recorded over 9,200 citations (H-index: 43, i10-index: 73) and are well recognized within the research community. His research has correctly predicted new technology directions well ahead of time. For example, four concepts he pioneered and researched—the concept of database coordinated dynamic spectrum access (2004); ultra-broadband small cells using shared spectrum (2009); policy-driven, flexible, multiband spectrum and link aggregation (2012); and 3.5 GHz Citizens Broadband Radio Service end-to-end architecture and protocols (2015)—have now emerged or have already been established as new technology and U.S. wireless policy directions. Dr. Buddhikot is a recipient of the Bell Labs President's Silver Award for outstanding innovations and contributions (2003), Bell Labs Team Award (2003), Lucent Chairman's Team Award (2006), Alcatel-Lucent DMTS award (2012), Nokia Bell Labs Fellow Award (2018), Nokia Top Innovator Award (2019), and Nokia Business Excellence Award (2020). He has been a co-founder and the chief architect of three wireless technology ventures and has successfully transitioned assets created in his research projects to business divisions. Dr. Buddhikot is a co-founder of the IEEE DySPAN symposium, which has emerged as a premier conference on the topic of DSA. He has served as an associate editor of the prestigious IEEE/ACM *Transactions on Networking* and Elsevier's *Computer Networks Journal*, secured over $1.35 million in research funding and regularly participates in Federal Communications Commission (FCC), NSF, and conference panels and technical program committees of major IEEE and ACM conferences. Dr. Buddhikot has served as a member of the steering committee of the WINNFORUM Spectrum Sharing Working Group that developed 3.5 GHz Citizens Broadband Radio Service (CBRS) Industry Standards. In the recent past, he has also served as the co-chair of FCC Technological Advisory Council (TAC) Working Group on Future Unlicensed Services (2015), member of the FCC TAC Working Group on Future Spectrum Sharing, and the chair/coordinator of the DySPAN steering committee (2012-2015). Dr. Buddhikot has frequently delivered invited presentations and tutorials on future technology directions to audiences in top-tier research forums and trade shows and to business customers worldwide.

L. JEAN CAMP is currently employed as a professor at the Luddy School of Informatics, Computing, and Engineering with appointments in informatics and computing science at Indiana University Bloomington. She joined Indiana after 8 years at Harvard University's Kennedy School where her courses were also listed in Harvard Law, Harvard Business, and the Engineering Systems Division of the Massachusetts Institute of Technology (MIT). Dr. Camp is a member of the 2022 class of fellows of ACM. She was selected as a fellow of IEEE since 2018. She was elected a fellow of the American Association for the Advancement of Science in 2017. She was inducted into the national research honor society Sigma Xi in 2017. She spent the year after earning her doctorate from Carnegie Mellon University as a senior member of the technical staff at Sandia National Laboratories. She began her career as an engineer at Catawba Nuclear Station after a double major in electrical engineering and mathematics, followed by an MSEE in optoelectronics at the University of North Carolina at Charlotte.

CHARLES CLANCY serves as a senior vice president at MITRE where he heads MITRE Labs. There he leads a team of over 4,000 scientists, engineers, and clinicians in solving problems for a safer world through the federally funded research and development centers operated by MITRE on behalf of the federal government. Previously he served as the Bradley Professor of Electrical and Computer Engineering at Virginia Tech and started his career as a researcher at the National Security Agency. Dr. Clancy's field of expertise is in wireless communications and information security, with major contributions to the fields of spectrum sharing, wireless/mobile security, and machine learning for signal processing. He was elected a fellow of IEEE in 2021 and serves on the board of directors for the Armed Forces Communications and Electronics Association International. Additionally, Dr. Clancy has helped launch several venture-backed startups in wireless, including Federated Wireless, HawkEye 360, DeepSig, and SecureG. He received his PhD in computer science from the University of Maryland, MS in electrical engineering from the University of Illinois, and BS in computer engineering from the Rose-Hulman Institute of Technology.

ANDREW CLEGG is the Spectrum Engineering Lead for Google. He is one of the lead developers of the CBRS standards. Prior to joining Google, he served as the spectrum manager for NSF for 11 years. At NSF, he founded the Enhancing Access to the Radio Spectrum program, a $50 million program dedicated to funding academic and small business research focused on improving spectrum efficiency and access. Prior to NSF, he was a lead member of technical staff at what is now AT&T Mobility. He has over 20 years of experience in national and international spectrum management for both government and commercial applications, and he was a member of the U.S. delegation to two World Radiocommunication Conferences. Dr. Clegg has previously served on the National Academies of Sciences, Engineering, and Medicine's Panel on Achieving Science with CubeSats, and was the NSF sponsor for the National Academies' Committee on Radio Frequencies. He holds a BA in astronomy and physics from the University of Virginia and an MS and a PhD in radio astronomy from Cornell University.

RHONDA R. FRANKLIN is the McKnight Presidential Endowed Professor of Electrical and Computer Engineering and the Institute for Engineering in Medicine (IEM) Abbott Professor for Innovative Education at the University of Minnesota. She obtained a BSEE from Texas A&M University and MS and PhD from the University of Michigan in electrical engineering. Her research investigates planar circuits and antennas, integration/packaging techniques, and characterizes electronic/magnetic nanomaterials and liquids for communication, biomedical, and nanomedicine applications. She has co-authored over 130 refereed conferences and journals, six book chapters, and has nine patents and disclosures. In IEEE Microwave Theory and Technology Society (MTT-S), she served as the *IEEE Microwave and Wireless Components Letters* associate editor, a *Journal of Microwaves* editorial board member, the MTT-S Technical Coordination Committee past chair of integration and packaging, and the International Microwave Symposium (IMS) Technical Program Review Committee packaging and interconnect subcommittee chair. To broaden participation, she co-founded and led IMS Project Connect in microwave engineering and is the co-director of the IEM Inspire Program in biomedical engineering. She is a researcher and integration director in the NSF Advanced Technologies for the Preservation of Biological Systems' Engineering Research Center to advance bio-preservation of biological systems. Select awards include NSF Presidential Early Career Award for Scientists and Engineers, IEEE N. Walter Cox Service Award, IEEE Member and Geographic Activities Diversity and Inclusion Award, University of Minnesota Sara Evans Faculty Scholar Leader, and University of Michigan Distinguished Alumni Educator.

MONISHA GHOSH is a professor of electrical engineering at the University of Notre Dame. She is also the policy outreach director for SpectrumX, the first NSF Center for Spectrum Innovation. Her research interests are in the development of next-generation wireless systems: cellular, Wi-Fi, and IoT, with an emphasis on spectrum sharing and coexistence and applications of machine learning to improve network performance. Prior to joining the University of Notre Dame in 2022, Dr. Ghosh was the chief technology officer at FCC, a program director at NSF, and a research professor at the University of Chicago. She spent 24 years in industry research at Bell Labs, Philips Research, and Interdigital. She obtained her BTech from IIT Kharagpur and PhD from the University of Southern California. She is a fellow of IEEE.

THOMAS L. MARZETTA is the Distinguished Industry Professor at the New York University (NYU) Tandon School of Engineering, Electrical and Computer Engineering Department, and the director of NYU WIRELESS. Prior to joining NYU in 2017, he had three industrial research careers: petroleum exploration (Schlumberger-Doll Research, 1978-1987), defense (Nichols Research, 1987-1995), and telecommunications (Bell Labs, 1995-2017). At Bell Labs, he directed the Communications and Statistical Sciences Department within the former Mathematical Sciences Research Center and he was elected a Bell Labs fellow. He originated Massive MIMO, the most spectrally efficient wireless scheme yet devised and a foundation of 5G wireless. He is the lead author of the book *Fundamentals of Massive MIMO*. Dr. Marzetta was elected a member of National Academy of Engineering in 2020. Additional recognition includes the 2019 Radio Club of America Armstrong Medal, 2017 IEEE Communication Society Industrial Innovation Award, 2015 IEEE Stephen O. Rice Prize, and 2015 IEEE W.R.G. Baker Award. He was elected a fellow of IEEE in 2003 and received an honorary doctorate from Linköping University, Sweden, in 2015. Dr. Marzetta received his PhD and SB in electrical engineering from MIT in 1978 and 1972 and MS in systems engineering from the University of Pennsylvania in 1973.

DAVID R. ORAN was a fellow at Cisco Systems until 2016. He is now independent and pursuing his research interests in a number of areas, including in-network computing and information-centric networking (ICN). He also has an appointment as a research affiliate at the MIT Media Laboratory. His recent work has been in congestion control for ICN and using ICN as a substrate for modern distributed computing languages. His long-term technical interests lie in the areas of quality of service, Internet multimedia, routing, and security. He was part of the original team that started Cisco's Voice-over-IP business in 1996 and helped grow it into a multi-billion-dollar revenue stream. Prior to joining Cisco, Mr. Oran worked in the network architecture group at Digital Equipment, where he designed routing algorithms and a distributed directory system. Mr. Oran has led a number of industry standards efforts. He was a member of the Internet Architecture Board, co-chair of the Speech Services working group, and served a term as area director for routing in the Internet Engineering Task Force. He currently serves as the co-chair of the Information Centric Networking Research Group of the Internet Research Task Force. He was on the board of the SIP Forum from its inception through 2008. He also serves on the technical advisory boards of a number of venture-backed firms in the networking and telecommunication sectors. Mr. Oran has a BA in English from Haverford College.

MORRIS REPETA leads the Advanced Wireless Technology group in the office of the chief technology officer at Dell. Mr. Repeta has over 35 years of experience in semiconductor fabrication and design and advanced wireless technology research and development at Nortel Networks, BlackBerry, Huawei Technologies, and now Dell. He has been involved in radio-related work from 2G to now beyond 5G and 6G from 700 MHz to 86 GHz. His last 7 years at Huawei were focused on the design radio-frequency integrated circuits and Antenna-in-Package used to demonstrate a multi-hotspot access with 200 Gbps data at 71-73.4 GHz. Mr. Repeta holds a BEng and an MEng in engineering physics from Ecole Polytechnique de Montreal and an MBA from the University of Ottawa and he is a senior IEEE member.

BISHAL THAPA is a recognized research leader in the field of cognitive wireless networks and wireless security. Dr. Thapa joined Raytheon BBN in 2011. He got his PhD in wireless communication and security from Northeastern University. His PhD thesis work focused on jamming and anti-jamming of wireless communication. Since he has been at BBN, he has been a principal investigator (PI) or a tech lead on many DARPA tactical data networking and wireless security projects. Currently he is a PI on a multi-domain tactical Internet project that connects seabed sensors with space networks in situ. He is also the networks lead on ongoing 5G Network Enhancement project at Hill Air Force Base. He has won best paper award from ACM WiSec 2011, been nominated as one of the 50 DARPA Risers from across the U.S. defense and academic institutions in 2015, won Raytheon Technical Excellence, Innovation awards, and recently received the Presidential coin. He participated in DARPA Hackfest and DARPA Spectrum Challenge where his team won the first prize in the cooperative spectrum challenge. He also recently led a team to a second place win on Navy's Project Overmatch AINETX Networking challenge. He is an open-source GNURadio and Battle of Meshes enthusiast.

DANIELA TUNINETTI is a professor and the department head of the Electrical and Computer Engineering Department at the University of Illinois Chicago, which she joined in 2005. Dr. Tuninetti received her PhD in electrical engineering from Télécom ParisTech in Paris, France, in 2002. She was a postdoctoral research associate with the School of Computer and Communication Sciences at the Swiss Federal Institute of Technology in Lausanne, Switzerland, from 2002 to 2004. She received the NSF CAREER Award in 2007. She was named University of Illinois Scholar in 2015. She is currently a distinguished lecturer and a member of the board of governors of the IEEE Information Theory Society. She is a fellow of IEEE. She was the editor-in-chief of the *IEEE Information Theory Society Newsletter* from 2006 to 2008. She was an editor of *IEEE Communications Letters* from 2006 to 2009, of *IEEE Transactions on Wireless Communications* from 2011 to 2014, of *IEEE Transactions on Information Theory* from 2014 to 2017, and she is currently an editor of *IEEE Transactions on Communications*. Dr. Tuninetti is a leader in the area of multi-user information theory—a highly mathematical branch of electrical engineering that seeks to understand the fundamental limits of data communication and compression in networks in a technology independent way. She has published over 200 papers in the most prestigious peer-reviewed international journals and conferences in the field. Her current work is focused on high reliability and low latency wireless communications, and on cache-aided distributed computing.