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## An Assessment of the Communications Technology Laboratory at the National Institute of Standards and Technology: Fiscal Year 2019 (2019)

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**AN ASSESSMENT OF THE COMMUNICATIONS  
TECHNOLOGY LABORATORY AT THE NATIONAL  
INSTITUTE OF STANDARDS AND TECHNOLOGY**

**FISCAL YEAR 2019**

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

Laboratory Assessments Board

Division on Engineering and Physical Sciences

A Consensus Study Report of

*The National Academies of*  
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## Preface

A White House advisory council has noted: “If the Nation instead expands its options for managing federal spectrum, we can transform the availability of a precious national resource — spectrum—from scarcity to abundance.”<sup>1</sup> The use of radio-frequency technology for communications, radio location, entertainment, and more continues to experience tremendous growth, and with this it plays an increasingly critical role in our daily lives. Given the challenge of accessing additional RF spectrum for these technologies, it is essential to effectively and efficiently use these spectrum resources. The Department of Commerce operates the Communications Technology Laboratory (CTL), which provides the nation with a laboratory dedicated to improving the use of radio frequency spectrum. CTL was established in 2014 by the National Institute of Standards and Technology (NIST) by merging several components of existing NIST laboratories into a single entity focused on promoting standards and metrology in the area of communications technologies. In the last 5 years, CTL has grown to establish significant efforts in the areas of measurement and standards relating to spectrum use and other wireless technologies. The lab also has a prominent role in public safety communications, where it serves as the future technology lead for the Department of Commerce’s First Responder Network Authority (FirstNet), the emerging public safety broadband network in the United States. CTL has also recently launched the National Advanced Spectrum and Communications Technology Network, designed to help create a trusted spectrum testing and measurement organization to aid in spectrum sharing efforts.

In 2015, the National Academies of Sciences, Engineering, and Medicine report on the Boulder, Colorado, communications technology laboratory of the Department of Commerce<sup>2</sup> described many of the critical uses of radio communications and highlighted important research priorities for this laboratory. It also guided CTL to continue to refine and extend its efforts in wireless metrology, spectrum sharing, and public safety communications. In 2019, a second panel was engaged to assess efforts within CTL. The Director of NIST requested that the panel focus its assessment on the following factors: (1) the organization’s technical programs; (2) the portfolio of scientific expertise within the organization; (3) the adequacy of the organization’s facilities, equipment, and human resources; and (4) the effectiveness by which the organization disseminates its program outputs.<sup>3</sup> The panel was directed to focus on two main categories: public safety communications, and metrology for advanced communications. These include

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<sup>1</sup> President’s Council of Advisors on Science and Technology, 2012, *Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth*, Executive Office of the President, Washington, D.C., July 20.

<sup>2</sup> National Academies of Sciences, Engineering, and Medicine, 2015, *Telecommunications Research and Engineering at the Communications Technology Laboratory of the Department of Commerce: Meeting the Nation’s Telecommunications Needs*, The National Academies Press, Washington, D.C.

<sup>3</sup> W.G. Copan, Ph.D., Director, NIST and Undersecretary of Commerce for Standards and Technology, “Memorandum for Panel of the National Research Council Committee on National Institute of Standards and Technology Technical Programs,” March 14, 2019.

the four CTL priority areas: (1) public safety communications, (2) trusted spectrum testing, (3) fundamental metrology for communications, and (4) Next Generation Wireless (5G and Beyond). This report provides the National Academies' assessment of CTL. The panel also assessed the extent to which CTL followed the recommendations made in the 2015 National Academies' report.<sup>1</sup> The panel visited the Boulder telecommunications laboratories on June 25-27, 2019, meeting with staff from CTL to understand the current activities of the laboratory, its strengths and weaknesses as an organization, and its plans for the near future. The assessment included in this report stems from these visits and discussions, and the committee's own expertise.

Douglas Sicker, *Chair*  
Panel on Review of the National Institute of Standards and  
Technology's Communications Technology Laboratory

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<sup>1</sup> National Academies of Sciences, Engineering, and Medicine, 2015, *Telecommunications Research and Engineering at the Communications Technology Laboratory of the Department of Commerce: Meeting the Nation's Telecommunications Needs*, The National Academies Press, Washington, D.C.

## Acknowledgment of Reviewers

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.

We thank the following individuals for their review of this report:

Ian Akyildiz, Georgia Institute of Technology,  
Danijela Cabric, University of California, Los Angeles,  
Edward Frank,<sup>1</sup> NAE, Cloud Parity, Inc.,  
Alan Kaplan, Princeton University,  
Rob Leonard, Fire Department of the City of New York,  
Dennis Roberson, Illinois Institute of Technology, and  
Murat Yuksel, University of Central Florida.

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 Neil G. Siegel, NAE, University of Southern California. He was 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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<sup>1</sup> Member, National Academy of Engineering.



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## Summary

In 2019, at the request of the Director of the National Institute of Standards and Technology (NIST), the National Academies of Sciences, Engineering, and Medicine formed the Panel on Review of the Communications Technology Laboratory (CTL) of the National Institute of Standards and Technology (the “panel”), having earlier established the following statement of work:

The NASEM shall form a panel of experts who shall perform an independent technical assessment of the quality of the National Institute of Standards and Technology’s (NIST’s) Communications Technology Laboratory (CTL). The panel shall prepare a final report that reflects the expert consensus opinion of the panelists based on materials provided by NIST before and during a site visit to NIST laboratories in Boulder, CO. During this site visit, the panel shall conduct an in-depth technical assessment and draft a consensus report addressing the topics requested by the NIST Director in his or her charge to the panel. Subsequent to the site visit, the panel shall finalize the report draft and the NASEM shall conduct any necessary reviews to ensure that the final report is of high quality and is impartial and objective in its assessment of the NIST CTL.

The assessment shall be responsive to the charge from the NIST Director. The following draft criteria for the assessment are proposed by the NIST sponsor and are expected to be formalized in the charge of the NIST Director that will be provided at contract award, expected November 1, 2018.

1. The technical merit of the current laboratory program relative to current state-of-the-art programs worldwide;
2. The portfolio of scientific expertise as it supports the ability of the organization to achieve its stated objectives;
3. The adequacy of the laboratory budget, facilities, equipment, and human resources, as they affect the quality of the laboratory’s technical programs; and
4. The effectiveness by which the laboratory disseminates its program outputs.

The Director of NIST requested that the panel focus its assessment on the following factors: (1) the organization’s technical programs; (2) the portfolio of scientific expertise within the organization; (3) the adequacy of the organization’s facilities, equipment, and human resources; and (4) the effectiveness by which the organization disseminates its program outputs.<sup>1</sup>

One of the six laboratories of NIST, the CTL was created in 2014 and “promotes the development and deployment of advanced communications technologies through the dissemination of high quality

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<sup>1</sup> W.G. Copan, Ph.D., Director, NIST and Undersecretary of Commerce for Standards and Technology, “Memorandum for Panel of the National Research Council Committee on National Institute of Standards and Technology Technical Programs,” March 14, 2019.



measurements, data, and research supporting U.S. innovation, industrial competitiveness, and public safety.”<sup>2</sup> Of CTL’s four organizational units, three are located at NIST’s Boulder, Colorado, campus and a fourth in Gaithersburg, Maryland. As of June 2019, there were slightly fewer than 200 personnel in the CTL. There are in addition 29 term appointments.

The national importance of wireless communications provides an opportunity for CTL to play an important role in the economic vitality of the country. CTL can play an even greater role in the evolution of the connected world the public has come to expect through research advances. The anticipated deployment of a variety of new, connected “smart” devices will require greater access to spectrum and advanced networked communication technologies. Not only the devices, but new applications such as telehealth, machine-to-machine communications, and augmented reality will stimulate demand for wireless communications.

CTL’s role in communications research and engineering includes key areas such as: spectrum measurement and propagation modeling; applied research on wireless network access technologies; and applied research, testing, and evaluation of newly developed communication technologies. CTL also provides technical support to other federal agencies and the private sector, principally for spectrum measurement and analysis of spectrum sharing and service coexistence.

For this review, the CTL director asked that the panel focus on two main categories: public safety communications and metrology for advanced communications.<sup>3</sup> Public safety communications addresses the CTL priority area of the same name. Metrology for advanced communications addresses three of the four CTL priority areas: (1) trusted spectrum testing, (2) fundamental metrology for communications, and (3) Next Generation Wireless (5G and Beyond). The following paragraphs describe the accomplishments, opportunities, and challenges of the technical programs, as well as the expertise, adequacy of resources, and dissemination of outputs for work of the CTL divisions in support of these two main categories. Included as well are key recommendations the panel considered especially worthy of attention.

The panel visited the Boulder CTL laboratories on June 25-27, 2019, to receive briefings from and hold discussions with CTL staff—including staff who traveled from Gaithersburg, Maryland—to learn about current activities in CTL’s laboratories, strengths and weaknesses, and plans for the near future.

The first main category of CTL’s work addressed by the panel was Public Safety Communications. CTL’s Public Safety Communication Program is charged with important research tasks for enabling future broadband wireless capabilities for the public safety community. Through the Middle-Class Tax Relief and Job Creation Act of 2012, the Public Safety Communications Research (PSCR) Division was appropriated \$300 million<sup>4</sup> to conduct research focused on improving future broadband public safety wireless communications. The PSCR Division further defined this research through a successful and broad stakeholder outreach, to include the following: mission-critical voice, location-based services, analytics, enhanced user interface/user experience (UI/UX), security, and resilient systems. While the PSCR has been very successful in outreach, initial research, and engagement, there remain challenges for the group, including budget and human resources and the need to articulate a long term research plan that incorporates research from other industries and other parts of the federal government. PSCR has made use of open innovation tools such as prize challenges.<sup>5</sup> Key recommendations include:

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<sup>2</sup> National Institute of Standards and Technology (NIST), Undated, “This is CTL,” U.S. Department of Commerce, Boulder, Colo., p. 1.

<sup>3</sup> Ibid.

<sup>4</sup> The first portion of the allocated funds (\$100 million) became available to PSCR at the start of FY 2016, the second allocation (\$186.4 million) became available July 2016, and the final allocation (\$13.6 million) became available FY 2017.

<sup>5</sup> Prize challenges are financial award or incentive-based activities aimed at a diverse array of non-federal contributors working on discrete, well-defined challenges. These were authorized by the America COMPETES Reauthorization Act of 2010.

**Key Recommendation:** The PSCR Division should develop an 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. (Chapter 3)

**Key Recommendation:** CTL should update its roadmap for public safety analytics, taking into consideration projected future areas of interest. (Chapter 3)

**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 the study of new technologies. (Chapter 3)

Although the Division’s reliance on term employees makes sense given the short timeframe of the funding and it appears to be sufficient to make progress in each of the research areas, the limited growth of PSCR internal expertise is a concern. PSCR is addressing key issues in public safety, and it is likely that the research mission will continue to be of importance beyond the 2022 end date of the appropriated funds from the spectrum auction.

**Key Recommendation:** CTL should evaluate the possibility and pros and cons 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 be longer available. In addition, CTL should develop a plan for leveraging the expertise developed through the prize challenges. (Chapter 3)

The activities that fall under the second main category under review, metrology for advanced communications, address fundamental and near-term application measurement problems for emerging communication standards. The CTL is poised to capitalize on a number of timely and impactful opportunities, including: quantum-enabled metrology with applications in quantum information science and engineering (QISE); a new framework for channel metrology and modeling and innovative hardware and platforms for next generation wireless networks; and machine learning, data science, and statistical techniques. This group appears to be well-resourced for the tasks they are conducting. The staff are consistently and diligently engaged in dissemination of their scientific and technical findings. A key overarching recommendation is:

**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. (Chapter 4)

The physical infrastructure is mostly adequate for the current metrology programs. CTL’s measurement facilities—currently available on a supervised basis to outside users through mechanisms such as cooperative research and development agreements (CRADA)—can be monetized as a “paid service” to be provided to users in the research and business communities in the United States and

worldwide. For this to succeed, it is essential that the facilities be able to handle latent demand for such services.

**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. (Chapter 4)

Three organizational units contribute to the area of metrology for advanced communications: the Radio Frequency Technology (RFT) Division, the Wireless Networks (WN) Division, and the National Advanced Spectrum and Communications Test Network (NASCTN) program.

The RFT Division engages in fundamental radio frequency (RF) metrology research and standards to characterize both integrated circuits and systems, wired and wireless. The RFT team has delivered significant results, and, for example, the Rydberg atom electric field sensor appears to have breakthrough potential. The CTL has proactively identified optical communications and QISE as promising new areas for research.

**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 and the Information Technology Laboratory. (Chapter 4)

The Wireless Networks Division has been heavily focused in 5G (fifth-generation wireless) technology, metrology, and applications and is the steward for the successful 5G mmWave Channel Model Alliance. There are a number of opportunities and challenges for this division as their work progresses toward the millimeter-wave efforts, as well as outdoor measurements in novel applications, such as communication channels for unmanned aerial vehicles (UAVs).

**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. (Chapter 4)

CTL jointly established the NASCTN program in 2015 with the Department of Defense (DoD) and the National Telecommunications and Information Administration’s (NTIA’s) Institute for Telecommunication Sciences (ITS) to organize a network of test facilities to support spectrum-related testing, modeling, and analysis.<sup>6</sup> The work done by the NASCTN program in CTL, covering the broad topic of shared use of federal spectrum by commercial systems, has contributed to several high-value, high-impact spectrum reallocation efforts in the past few years and is positioned to have a continuing role in helping coordinate this very important national resource. Such efforts address coexistence metrics for shared-spectrum environments, test methods for spectrum management methods, and waveform metrology and calibration. The work has been addressing, in a necessarily reactive manner, problems in spectrum as they are identified. A more strategic and proactive approach toward spectrum sensing and sharing would enhance the impact of the team in regulatory actions and industry standardization activities.

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<sup>6</sup> An additional three federal agencies have since joined: the National Oceanographic and Atmospheric Administration, the National Science Foundation, and the National Aeronautics and Space Administration.

The current operating model in NASCTN is to respond to requests for spectrum sensing and characterization from industry or other federal agencies. Given the level of current staffing, this is probably appropriate. In the future, the program could have a much broader impact if it would independently select “hot-button” spectrum issues on which to work and increase the number of staff appropriately.

**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. (Chapter 4)

**Key Recommendation:** CTL should continue vigorous support for the spectrum sensing and sharing activity, which has delivered impactful results. (Chapter 4)

Since its inception in 2015, CTL has established significant efforts in measurement and standards relating to spectrum use and other wireless technologies. The four organizational units can all claim impressive achievements. The CTL has attained a prominent role in public safety communications, including FirstNet—the emerging public safety broadband network in the United States. CTL has also recently launched the multi-agency NASCTN, designed to help create a trusted spectrum testing and measurement organization to aid in spectrum sharing efforts. RTF and WN divisions have made novel findings for measurement of SI-derived quantities and for elaboration and testing of next-generation wireless concepts. There are opportunities and challenges to these portfolios created by the changing application space and stakeholder needs. The anticipated end in 2022 of the auction proceeds is a further challenge to mission and staffing. The recent upgrades to its facilities present opportunities to articulate with non-federal groups wishing to access these test beds, which, furthermore, could be monetized.

# 1

## Introduction

The National Academies of Sciences, Engineering, and Medicine has, starting in 1959, annually assembled panels of experts—from academia, industry, medicine, and other scientific and engineering communities of practice—to assess the quality and effectiveness of the NIST measurements and standards laboratories, of which there are now six,<sup>1</sup> as well as the adequacy of the laboratories’ resources. These reviews are conducted under contract at the request of the NIST.

In 2019, at the request of the Director of NIST, the National Academies formed the Panel on Review of the Communications Technology Laboratory of the National Institute of Standards and Technology (the “panel”), having earlier established the following statement of work:

The NASEM shall form a panel of experts who shall perform an independent technical assessment of the quality of the National Institute of Standards and Technology’s (NIST’s) Communications Technology Laboratory (CTL). The panel shall prepare a final report that reflects the expert consensus opinion of the panelists based on materials provided by NIST before and during a site visit to NIST laboratories in Boulder, CO. During this site visit, the panel shall conduct an in-depth technical assessment and draft a consensus report addressing the topics requested by the NIST Director in his or her charge to the panel. Subsequent to the site visit, the panel shall finalize the report draft and the NASEM shall conduct any necessary reviews to ensure that the final report is of high quality and is impartial and objective in its assessment of the NIST CTL.

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3. The adequacy of the laboratory budget, facilities, equipment, and human resources, as they affect the quality of the laboratory’s technical programs; and
4. The effectiveness by which the laboratory disseminates its program outputs.

For this review, the CTL director asked that the panel focus on two main categories: public safety communications and metrology for advanced communications.<sup>2</sup> Public safety communications addresses the CTL priority area of the same name. Metrology for advanced communications addresses three of the

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<sup>1</sup> The six National Institute of Standards and Technology (NIST) laboratories are the Communications Technology Laboratory, the Engineering Laboratory, the Information Technology Laboratory, the Material Measurement Laboratory, the Physical Measurement Laboratory, and the Center for Neutron Research.

<sup>2</sup> NIST, Undated, “This is CTL,” U.S. Department of Commerce, Boulder, Colo., p. 1.

four CTL priority areas: (1) trusted spectrum testing, (2) fundamental metrology for communications, and (3) Next Generation Wireless (5G and Beyond).<sup>3</sup>

The four organizational units of CTL are located in Boulder, Colorado, and in Gaithersburg, Maryland. The Boulder facilities were visited by the panel on June 25-27, 2019.

The panel's approach to the assessment relied on the experience, technical knowledge, and expertise of its members. Time constraints did not allow the panel to explore all aspects of CTL. Rather, the panel focused on the research that the leadership of the CTL chose to present to it and on a number of issues related to laboratory development that the panel identified as requiring particular attention. The panel's report includes recommendations that specify "who should do what" to address any determinations as to what might 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.

To accomplish its mission, the panel reviewed the material provided by the CTL prior to and during the review meeting. The choice of projects to be reviewed was made by the CTL. The panel applied a largely qualitative approach to the assessment. Given the nonexhaustive nature of the review, the omission in this report of any particular CTL project should not be interpreted as a negative reflection on the omitted project.

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<sup>3</sup> Marla Dowell, Ph.D., Director CTL, "Communications Technology Laboratory Overview," presentation to the panel on June 25, 2019.

## 2

## Overview of CTL

Created in 2014, the CTL of NIST “promotes the development and deployment of advanced communications technologies through the dissemination of high quality measurements, data, and research supporting U.S. innovation, industrial competitiveness, and public safety.”<sup>1</sup> There are four organizational units: (1) Public Safety Communications Research Division; (2) Radio Frequency Technology Division; (3) National Advanced Spectrum and Communications Test Network; and (4) Wireless Networks Division. With the exception of the Wireless Network Division, situated in Gaithersburg, Maryland, all the above are located at the Boulder, Colorado, campus of the Department of Commerce (DOC) located at 325 Broadway.

The budget for CTL was \$74.4 million in fiscal year (FY) 2019, the majority of which was funded through the Public Safety Trust Fund.<sup>2</sup> The next-largest portion is from annual congressional appropriations, followed by other agency funds and fees for calibrations—with these last two being variable year-to-year. The progression with time is shown in Figure 2.1. The percentage allocated to each of the four priority areas is shown in Figure 2.2.

The activities of the CTL consist of research and development, testing, fundamental measurements, calibration services, and convening and outreach activities. As of June 2019, there are slightly fewer than 200 personnel in the CTL. Their allocation to the four organizational units and to headquarters is shown in Figure 2.3. There are in addition 29 term appointments. Four current and one retired CTL staff members are fellows of the Institute of Electrical and Electronics Engineers.

Each of the four CTL priority areas is addressed by the work of one or more of the four organizational units. These relationships are outlined in Table 2.1.

CTL conducts an annual research planning process focused on its three program areas of public safety, trusted spectrum testing, and metrology for advanced communications. Group plans filter up to Divisions for coordination and approval, while the Division and CTL leadership set strategic direction and long-term planning based on NIST priority areas. The present report identifies opportunities in specific program areas where performing strategic planning exercises and road mapping would improve stakeholder engagement. These would have the further benefit of ensuring that CTL programs continue to address stakeholder needs. The annual reviews noted above will allow NIST to monitor progress.

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<sup>1</sup> National Institute of Standards and Technology (NIST), Undated, “This is CTL,” U.S. Department of Commerce, Boulder, Colo., p. 1.

<sup>2</sup> The Public Safety Trust Fund resulted from spectrum auction.

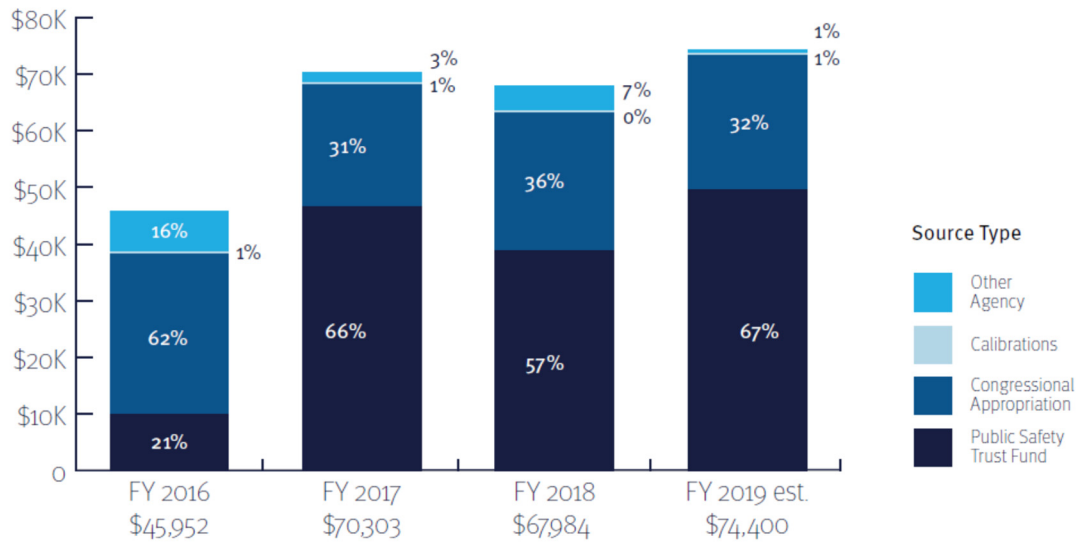


FIGURE 2.1 Communications Technology Laboratory budget and source of funds over the past 4 fiscal years. SOURCE: NIST, Undated, “This is CTL,” U.S. Department of Commerce, Boulder, Colo.

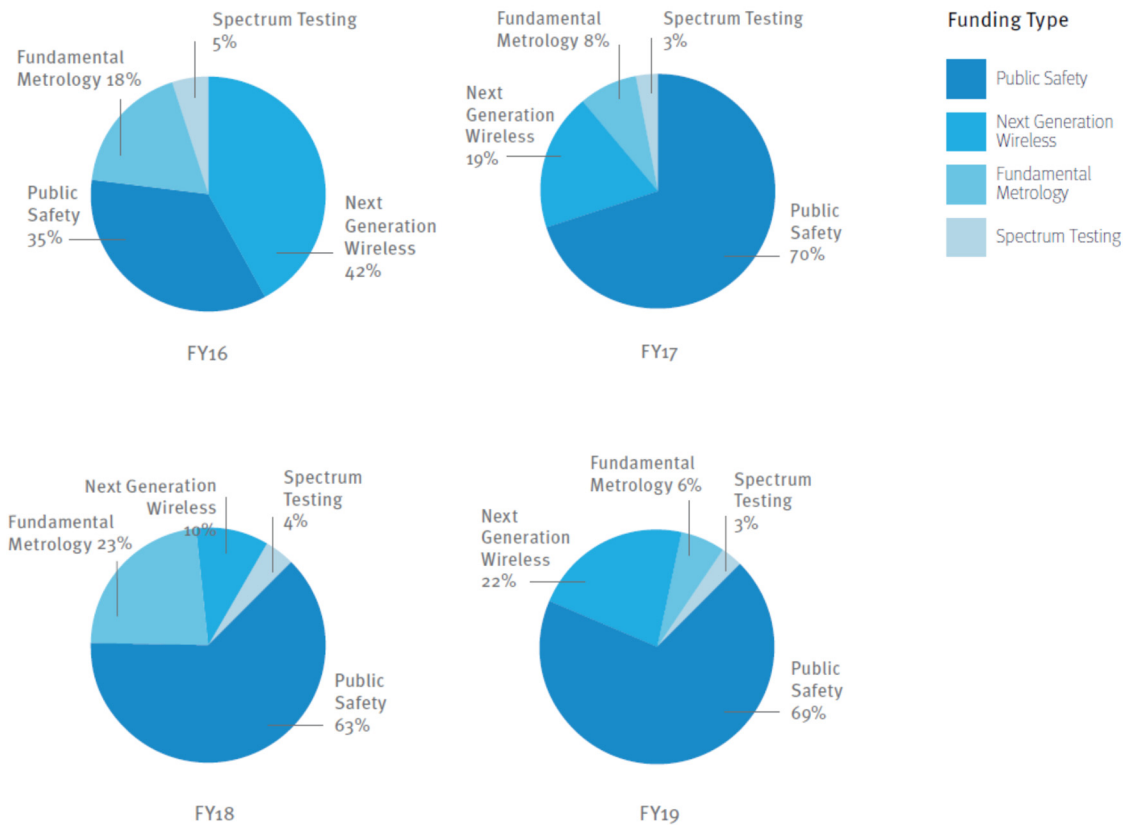


FIGURE 2.2 Allocation of Communications Technology Laboratory funds across its four priorities. SOURCE: NIST, Undated, “This is CTL,” U.S. Department of Commerce, Boulder, Colo.



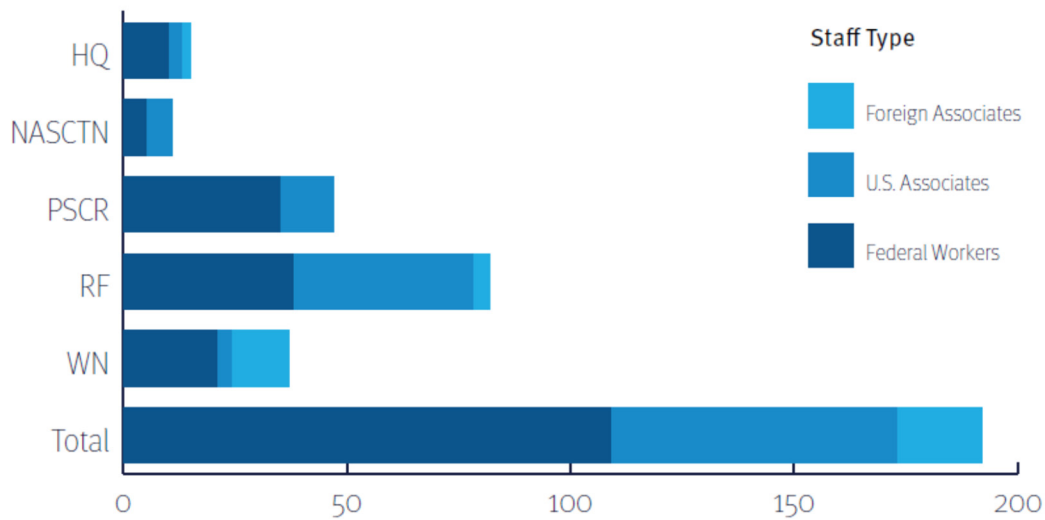


FIGURE 2.3 Communications Technology Laboratory staffing levels as of June 2019. SOURCE: NIST, Undated, “This is CTL,” U.S. Department of Commerce, Boulder, Colo.

TABLE 2.1 Communications Technology Laboratory (CTL) Priority Areas Addressed by Each Organizational Unit

	CTL Priority Areas			
	Public Safety Communications	Trusted Spectrum Testing	Next Generation Wireless	Fundamental Metrology for Communications
PSCR	X			
WN	X	X	X	
RFT		X	X	X
NASCTN		X		

NOTE: PSCR = Public Safety Communication Research Division; WN = Wireless Networks Division; RFT = Radio Frequency Technology Division; NASCTN = National Advanced Spectrum and Communications Test Network.

## 3

## Public Safety Communications Research

## INTRODUCTION AND OVERALL COMMENTS

The first main category of CTL’s work addressed by the panel, Public Safety Communications, is discussed in this chapter. The PSCR Division of CTL evolved from a program that was established in 2002 to provide research and development for public safety innovations and technologies.<sup>1</sup> Since its inception, PSCR has played a unique role supporting research with a focus on the distinctive requirements of future public safety communications “so that the public safety community can more effectively carry out their mission to protect lives and property during day-to-day operations, large-scale events, and emergencies.”<sup>2</sup> PSCR undertakes quarterly portfolio reviews to “monitor program effectiveness, mitigate risk [and] improve outcomes generated by PSCR.”<sup>3</sup>

The WN Division of CTL also works on the Public Safety Communications program. Funded in this effort by PSCR, WN focuses on “development and performance aspects of Mission-Critical Communications.”<sup>4</sup> This includes in particular the Mission-Critical Voice (MCV) portfolio, discussed below. (Separately, WN also works on the Metrology of Advanced Communications as discussed in Chapter 4.)

In 2012, PSCR was called to play a significant part in the future of broadband public safety communication; the Middle Class Tax Relief and Job Creation Act of 2012<sup>5</sup> (the “Act”) appropriated \$300 million from spectrum auction proceeds to NIST to be used as specified in Section 6303 of the Act as shown in Box 3.1.

Although the funds were appropriated in 2012, NIST was not granted borrowing authority and thus had to wait for the auction proceeds to become available before it could carry out the activities specified in the Act. The first portion of the allocated funds (\$100 million) became available to PSCR at the start of FY 2016, the second allocation (\$186.4 million) became available July 2016, and the final allocation (\$13.6 million) became available FY 2017. The Act specifies that at the end of FY 2022, all appropriated funds that are unused will be returned to the Treasury.

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<sup>1</sup> The PSCR effort was originally a joint effort between the National Institute of Standards and Technology (NIST) Office of Law Enforcement Standards (now the NIST PSCR Division within CTL) and NTIA’s Institute for Telecommunication Sciences.

<sup>2</sup> NIST, Undated, “This is CTL,” U.S. Department of Commerce, Boulder, Colo., p. 10.

<sup>3</sup> Dereck Orr, NIST, “Pulling the Future Forward: Accelerating Public Safety Communications Research,” presentation to the panel on June 25, 2019.

<sup>4</sup> NIST, Undated, “This is CTL,” U.S. Department of Commerce, Boulder, Colo., p. 16.

<sup>5</sup> P.L. 112-96, signed into law on February 22, 2012.

**BOX 3.1 Statutory Authority for Use of Auction Proceeds****47 USC 1443 SEC. 6303—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 6205(a), 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 programming 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).

In 2013, PSCR began a process of engaging stakeholders to identify the needs and technical requirements for future broadband public safety wireless communications. Stakeholders including public safety practitioners (police, fire, emergency medical service [EMS]), industry, academia and local, state and federal agencies provided input to identify and prioritize research needs that were specific to public safety and were not being met by efforts in industry or academia. This process resulted in the development of research portfolios in the following areas:

- MCV
- Location-Based Services (LBS)
- Public Safety Analytics
- Enhanced UI/UX

Along with two crosscutting efforts:

- Security
- Resilient Systems

The crosscutting efforts are focused on use cases that were identified as being important to PSCR stakeholders.

PSCR is using a variety of different mechanisms to achieve the requirements set forth by the Act. These instruments include internal research, research collaborations with government partners, external research grants and cooperative agreements, and prize challenges. Each research portfolio listed above includes a mix of these different instruments. Starting in FY 2017, PSCR began awarding grants for research and development projects focused on priority areas within the research portfolios that were not being addressed through internal research. To date, PSCR has funded 46 grants and cooperative agreements.

Prize challenges were devised as a mechanism to cost-effectively foster innovation in areas where the other research instruments were unlikely to achieve the desired outcome. They seek to raise awareness of public safety-specific technical issues, engage innovators around the world,<sup>6</sup> and facilitate multidisciplinary collaboration between participants, public safety, industry and government. PSCR prize challenges began in 2018. An example is the 2018 Unmanned Aerial Systems Flight and Payload Challenge, which addresses the trade-off of flight time versus payload that proves critical in the public safety domain. The 10 teams that participated developed drones at low cost that optimized energy efficiency and flexibility. Incentive prizes such as this are awarded throughout different phases of the challenges to encourage participants with the best ideas. Prize winners are also incentivized to make their software open source to increase the potential impact on the public safety ecosystem.<sup>7</sup>

As of June 2019, PSCR has 30 technical staff, 5 administrative staff and 2 support staff for a total of 37 employees. The workforce includes 16 permanent employees and 21 term employees. The permanent staff all have bachelor's degrees and 7 have master's degrees. There are no Ph.D.-level staff working in PSCR although some of the research portfolios include Ph.D.-level staff from other organizations in NIST. Unique among the four CTL divisions, PSCR has a greater number of term appointees than permanent ones, owing to the anticipated sunset of the funding from the spectrum auction in FY 2022, at which point the term appointees would no longer be working in CTL under current assumptions.

### Overall Public Safety Communication Discussion

The PSCR has adequate and stable near-term funding to carry out its mission. The technical quality of the team is excellent and the communication among team members is highly supportive of a collaborative, highly productive and interdisciplinary culture. The PSCR is a critical part of the public safety community and provides the leadership on communications research as well as on requirement gathering for the community. The importance of PSCR's mission will likely extend past the anticipated end of funding after 2022.

CTL staff has identified an appropriate set of projects to support future public safety communications needs. This work is centered on requirements gathering, research across six key technology areas, multi-stakeholder events, and standards work.

The process for the future strategic selection of new projects—to continue PSCR impact—was less clear from the standpoint of this review.

The PSCR staff is consistently and diligently engaged in the important task of disseminating its findings to the broader community of public safety professionals and stakeholders.

The prize challenges in general have the beneficial short-term impact of making the community aware of what's possible and to highlight those groups that are doing great work in relevant areas.

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<sup>6</sup> Only teams with at least one U.S. citizen are eligible for the cash prizes.

<sup>7</sup> In some cases, it is too soon to measure the impact of the prize winners—for example, the 2018 Differential Privacy Synthetic Data Challenge was completed in May 2019.

The PSCR is a unique national resource, and its scientific output and research need to be continued and made broadly available in order to ensure the highest impact of the work for the first responder community.

The CTL physical infrastructure is adequate for the current programs in public safety communications.

There is substantial evidence that PSCR has accomplished a significant amount in multiple areas of interest to its stakeholders in a short period of time.

## **ASSESSMENT OF TECHNICAL PROGRAMS**

Across the six portfolios identified in the above section “Introduction,” PSCR has established a strong set of research components critical to future public safety communications. While significant work remains to be done, to date the PSCR has provided the community a number of accomplishments, outlined below. These contributions would not have been possible without the significant funding provided through the Act.

### **Mission Critical Voice**

Several goals related to MCV were explicitly stated in the Act. These goals include the following: (1) accelerate technical and systems research to develop of mission critical voice communications, (2) enable public safety prioritization, (3) enable authentication capabilities, and (4) develop standard application programming interfaces.<sup>8</sup> Two divisions of CTL, PSCR and WN, contribute to this portfolio. The current activities in PSCR for MCV include: active participation (including contributions) to the 3GPP (3rd Generation Partnership Project) standards body;<sup>9</sup> maintenance of the list<sup>10</sup> of certified devices that meet appropriate protocols and standards for access to, use of, or compatibility with the nationwide public safety broadband network that FirstNet and their network partner, AT&T, build and maintain; research in critical open source tools that lower the barrier to entry for researchers and companies to perform research in the area of MCV; and development and improvement of tools, datasets, and models for public safety, commercial broadband operators, and outside researchers to simulate networks from the radio layer down through payload. (The authentication activities are part of the Security portfolio discussed below.) WN conducts work such as Device-To-Device (D2D) Communication, Mission Critical Push to Talk (MCPTT), and other areas.<sup>11</sup>

Future activities include: producing an inexpensive, trusted, and scientific measurement system that can be used by public safety practitioners and industry as a fair baseline and comparison of MCV capabilities; developing generic call models for public safety MCV that describe public safety’s existing Land Mobile Radio (LMR) use; creating a prototype system and release open-source software and capabilities that can be used by industry to create inexpensive solutions for public safety that bridge existing, non-Inter-RF-Subsystem Interface (non-ISSI) capable LMR systems with 3GPP standard interfaces (interworking function/ application server) on broadband networks; and implementing direct comparisons of LMR and broadband capabilities for MCV.

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<sup>8</sup> From The Middle Class Tax Relief and Job Creation Act of 2012 (P.L. 112-96).

<sup>9</sup> Specifically in the 3GPP TS 36.579 family of specifications and the 3GPP Core Network and Terminals Working Group 1 for Mission Critical Services.

<sup>10</sup> The Middle Class Tax Relief and Job Creation Act of 2012 (P.L. 112-96) directed NIST to ensure the development of a list of certified devices. PSCR authored the process document for this requirement and maintains the list (J.D. Kahn, “Process Document for the NIST List of Certified Devices,” October 24, 2017, <https://www.nist.gov/communications-technology-laboratory/pscr/process-document-nist-list-certified-devices>).

<sup>11</sup> See NIST, Undated, “This is CTL,” U.S. Department of Commerce, Boulder, Colo., p. 21.

## Accomplishments

Through FY 2019, PSCR has expended approximately \$41 million for MCV activities. The three primary accomplishments presented to the review team included the following:

- PSCR maintains the list of certified devices that meet appropriate protocols, and that list has been updated on a monthly basis with the most recent update being of August 6, 2019.
- PSCR has undertaken the role of representative for U.S. public safety at key standards organizations. Albeit not a research and development role, the NIST role at 3GPP (who formulates all of the worldwide cellular standards) has provided key value for FirstNet implementations and future cellular implementations. For example,
  - Recently, PSCR informed a delegate from FirstNet to the 3GPP Core Network and Terminals Working Group 1 (CT1) that a configuration table in 3GPP TS 24.483 needed many parameter changes.
  - PSCR interacts with delegates from various companies and organizations while informing 3GPP CT1 regarding required fixes in the reference specifications for Mission Critical Services.
- The internal research within NIST has focused on testing methodology for determining voice intelligibility. It is expected that this work will continue and provide additional results and impact. Primary research accomplishments to date include the following:
  - Studies of quality of experience (QoE) and subsequent metrics aimed at providing a high QoE including: end-to-end access time, speech intelligibility, voice quality and intelligibility, and probability of access and retention.
  - Initial M2E (mouth-to-ear) latency measurements comparison for Project 25 (P25) trunk and direct radio systems. This work can be used as a comparison when using 3GPP defined PTT user access time.
  - Voice quality and intelligibility analysis using Modified Rhyme Test (MRT) developed by the NTIA's ITS.

## Challenges and Opportunities

The review team focused on two of the three focus areas as discussed above: (1) involvement in the standards bodies and (2) MCV internal research.

Although not a research and development (R&D) function, the NIST role with the standards bodies and maintaining the certified device list has been valuable both from near-term as well as long-term perspectives. It is critical that the public safety community be represented by technically informed personnel in order to address highly technical issues within the standards bodies.

**Recommendation:** CTL's participation in standards bodies concerning Mission Critical Voice should be driven toward specific goals that should be explicitly agreed upon by the user as well as the research and development communities. Those goals should be internally and externally vetted.

The MCV Internal Research, representing a substantial amount of the PSCR expenditures, appears to be in its initial stages. This research is building on a great deal of work by NTIA, and it is interesting to note that there are not many cooperative interactions between the organizations. The specific role of this work versus the work done by other organizations (i.e., ITS [part of NTIA]; the Department of Homeland Security's Advanced Research Projects Agency; and DoD) was not made available to the panel but would be a useful input for planning research and standards. Although the radio

systems are unique, the problems that are to be addressed are very similar to those being addressed by these other organizations. Such interactions with other researchers could quickly allow bigger strides in resolving public safety MCV challenges.

There appears to be no roadmap of technology development for MCV and thus no knowledge of how the projected future development of technologies might be used to focus the various R&D efforts. Such a roadmap could assist CTL in coordinating with other federal entities and would justify the relatively small expenditure of resources needed to develop it.

**Key Recommendation:** The PSCR 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.

### Location-Based Services

PSCR aims to demonstrate capabilities that first responders can rely upon in three major research areas in LBS: (1) indoor mapping, (2) tracking, and (3) navigation. A major effort has been in pre-incident planning, by developing a point cloud database of major non-residential indoor environments, as well as sensor data fusion (i.e., fusing sensor data to participants). PSCR has engaged extensively with external organizations to build research capacity in the area of indoor LBS.

### Accomplishments

Some of the key accomplishments of the PSCR's LBS program include the following:

- 32 scientific and engineering articles have been published in the field of indoor localization and specific applications to public safety with 15 projects have been launched (12 grants, 1 contract, 3 NIST projects) that have engaged 140 R&D personnel, including 90 students and postdocs.
- PSCR has demonstrated that point clouds could be transformed to IndoorGML (Indoor Geographic Markup Language)<sup>12</sup> networks for use in indoor navigation.
- The Point Cloud City projects have already proven critical for two different LBS initiatives: (1) The Indoor Mapping and Navigation Pilot, and (2) internal PSCR research focused on object anonymization and scene classification—highlighting the importance, but lack of available, point cloud data sets for research.
- Work in the Indoor Mapping and Navigation Pilot has also made several key contributions to geospatial standards: (1) A public safety application domain extension (ADE) was created for the CityGML<sup>13</sup> (City Geographic Markup Language) standard and (2) the concept of an ADE was added to the IndoorGML standard, along with a new public safety specific ADE. The new CityGML and IndoorGML Public Safety ADEs provide a mechanism to enrich building models with new features and attributes required for public safety use cases. Interestingly, prior to this pilot, the concept of an ADE did not exist for IndoorGML. However, early on in the pilot it became clear that in order to serve effectively as a navigation model for the public

<sup>12</sup> Further information available on the IndoorGML website at <http://indoorgml.net/>.

<sup>13</sup> Further information available on the CityGML website at <http://www.citygml.org/>.

safety use case, or any specific use cases for that matter, the concept of an ADE would need to be extended to the IndoorGML standard.

## Challenges and Opportunities

In addition to ongoing efforts in mapping and navigation, the PSCR Division is preparing to launch a multi-year, multi-phase large-scale prize challenge that will engage innovators across industry and academia to meet or exceed the public safety responder community's desire for sub-meter indoor localization accuracy without the need for pre-deployed dedicated infrastructure. The challenge will occur in at least three different building environments and will mirror other challenges by seeking direct FirstNet<sup>14</sup> involvement and partnerships. The first track will focus on identifying the highest performing sensors in each of five categories broadly defined as: inertial-based, imagers and scanners, signals of opportunity, external anchors, and cooperative ranging. In this track, teams will be evaluated based on the performance of their sensor using test scenarios designed to stress that sensor category. The second track will focus on identifying the highest performing multi-sensor fusion algorithms. In this track, teams will be evaluated based on their ability to generate accurate positions of first responders by fusing the individual sensor data from the first track just mentioned as it is streamed in "real-time" to participants. This prize challenge, if executed successfully, will offer a great opportunity to engage the broader indoor LBS and data analytics community to introduce innovative solutions for the PSCR program.

The generated data from the Point Cloud City project is valuable for a wide range of other PSCR research, and will bring new opportunities in localization, object anonymization, and scene classification.

**Recommendation:** The PSCR Division should explore some of the recent developments in the 3GPP standardization group related to indoor localization enhancements using cellular networks and consider adding such to its own research agenda.

## Public Safety Analytics

The CTL analytics group staff is composed of five key personnel who are on loan to PSCR. Two of these individuals hold Ph.D.s, and all are experienced researchers. They are supplemented by several contractors who perform project research, principally at universities, under the guidance of the internal staff. The skill sets of the staff members are varied and complementary, which is a positive characteristic.

## Accomplishments

The principle accomplishments have been achieved by the external contractors monitored by the internal personnel. CTL stood up an external research program as of June 2017, with contracts that were fully engaged sometime after that date. The research portfolio includes research projects in emergency medical services analytics, firefighting analytics, crosscutting research in video analytics, differential privacy prize challenge, social media incident streams challenge (first-generation and a coming second-generation challenge), analytics container environment framework to support scalable streaming analytics, collaboration with Baltimore CitiWatch,<sup>15</sup> and a planned challenge in automated streams analytics for public safety. The output of this research has principally been conference papers and open-source software.

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<sup>14</sup> The First Responder Network Authority, or FirstNet, was created by the Middle Class Taxcut and Job Creation Act of 2012. Situated within the Department of Commerce, FirstNet is given the mission of developing and operating a nationwide broadband network for first responders.

<sup>15</sup> Further information available on the CityGML website at <http://www.citygml.org>.



While it is still early in the process to judge the outcomes from these research projects, there are some projects that stand out as potentially very useful. These include the work in: developing privacy analysis, developing metrics to assess video quality for analytics processing, and collecting relevant data sets for doing video analytics comparisons. The privacy issue in video analytics is of growing public concern, and it is timely and appropriate that CTL addresses this area in their long-term research portfolio.

In 2016 PSCR published the *Public Safety Analytics R&D Roadmap*<sup>16</sup> following an analytics summit. PSCR has undertaken many activities— both intramural and extramural—since that time that might need to be considered in its long-term planning.

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

## Challenges and Opportunities

Key challenges for the public safety analytics program include defining metrics to ensure that the overall portfolio is on track to produce (in the long term) results that will be useful to the public safety community through instilling into the performers the importance of quantifying impact or potential impact of their research. The metrics should allow for comparison of their work against similar work being done worldwide. These metrics could be very useful for the internal NIST researchers to gauge the performance of their contractors. The video analytics work is a start to understand the metrics that can be used to develop tangible operational metrics, and the work between CTL and Baltimore CitiWatch looks very promising for supplying validation data for those metrics. The video metrics work and the creation of useful data sets has the potential to be magnified in future research efforts.

The prize challenges in public safety have beneficial short-term impact of making the community aware of what's possible and to highlight those groups that are doing great work in relevant areas. The work of the PSCR Division might benefit from giving consideration to how this effort will produce long-lasting infrastructure, talent, and tools for public safety beyond the end date of the competition.

## Enhanced User Interface/User Experience

First responders face many unique communication challenges. The challenges vary based on factors such as task, environment and equipment constraints. In addition, broadband communication capabilities along with new sources of information have the potential to dramatically increase the amount of data available to first responders. Innovative tools and techniques that enable first responders to interact with these new capabilities and systems are needed. To facilitate this, the UI/UX portfolio focuses on UI research, virtual reality (VR) and augmented reality (AR)-based research and UX research. This portfolio includes internal and external research along with prize challenges. Seven external grants and cooperative agreements were awarded in 2018.

## Accomplishments

The major accomplishments of the PSCR UI/UX portfolio include the following:

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<sup>16</sup> NIST, 2016, *Public Safety Analytics R&D Roadmap*, NIST Technical Note 1917, U.S. Department of Commerce, Washington, D.C.

- PSCR has built a UI/UX research and development team to demonstrate the importance and utility of UI/UX design for public safety. The team has significant collaboration with the interdisciplinary Atlas Institute at the University of Colorado, Boulder.
- Two surveys of the public safety community were conducted to identify the required functionality for future communications systems. These surveys included 7,000 responses from public safety professionals and 200 in-person interviews. The findings from the interviews have been published as NIST reports.<sup>17,18</sup> Additionally, PSCR has a publicly available search tool for identifying quotes from the interviews based on a variety of criteria. This information could be useful in influencing the design and development of public safety technology.
- Three unique VR environments with scenarios for fire, police, and EMS were developed to serve as test platforms for potential UIs. These environments are instrumented to facilitate qualitative and quantitative measurements on the performance of UI prototypes. Notably, this set of tools is open source and available to the public.
- PSCR has completed a prize challenge to create a heads-up display (HUD) with unimpeded visual aids and has an ongoing prize challenge focused on haptic interfaces. Both of these challenges utilize the VR test environments. The interest of external partners in the prize challenges is increasing. Although FirstNet participated in judging the HUD challenge, there were no external partners. Currently PSCR has a number of official partners for the haptic challenge including the FirstNet Authority, AT&T, MSA, and West Metro Fire Protection District (CO).

## Challenges and Opportunities

Effective UI/UX design is one of the keys to the public safety community taking advantage of the new technologies enabled by broadband communication capabilities. By providing resources such as the first responder survey findings and open source VR tools, PSCR has the opportunity to facilitate expanded UI/UX research and development. In addition to the prize challenges, PSCR might consider other ways to raise awareness and understanding of public safety research problems to engage a broader community in the research and development. One potential avenue for reaching a broader academic audience would be use of the resources in education.

PSCR plans to launch several new UI/UX prize challenges and do continued development on new VR environments. UI/UX emerged as a priority for public safety stakeholders and it is critical to successful integration of new technologies into public safety operation. It is necessary to think about how to keep UI/UX in the forefront, particularly after 2022.

**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 the study of new technologies.

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<sup>17</sup> NIST, 2018, *Voices of First Responders—Identifying Public Safety Communication Problems: Findings from User-Centered Interviews. Phase 1, Volume 1*, NISTIR 8216, U.S. Department of Commerce, Washington, D.C.

<sup>18</sup> NIST, 2018, *Voices of First Responders—Examining Public Safety Communication Problems and Requested Functionality Findings from User-Centered Interviews Phase 1, Volume 2.1*, NISTIR 8245, U.S. Department of Commerce, Washington, D.C.

## Security

Though CTL considers PSCR security as a primary responsibility of FirstNet and its partners, CTL still identified use cases for security authentication that would be valuable to FirstNet. CTL has dedicated its efforts in this focus area and has built technology solutions around it.

A resource of about 10 personnel from CTL and other organizations within NIST have been dedicated to supporting PSCR security.

### Accomplishments

CTL invested heavily in PSCR security areas with funding levels of \$2.2 million in FY 2018 and \$2.6 million in FY 2019. Highlighted accomplishments from CTL's PSCR security program are the following:

- CTL supported 3GPP standardization efforts, including mandating elliptic curve implementation, analyzing drivers with 256-bit algorithms in 5G (5th Generation Wireless Network), and enabling applications to understand security postures with cellular connections.
- CTL PSCR program has built Mobile Single Sign-On (SSO) capabilities for improving authentication for public safety first responders.
- CTL has developed and published a NIST Interagency or Internal Report (NISTIR), *Security Analysis of First Responder Mobile and Wearable Devices*.<sup>19</sup> This document reviews the current and potential use cases of mobile and wearable devices by first responders and then analyzes these devices from a cybersecurity perspective. Ultimately, the goal of the document is to identify security objectives for mobile and wearable devices to assist jurisdictions with selecting secure devices and to enable industry to design and produce secure public safety devices.
- CTL launched and expanded the “SIM Card Use for Public Safety” challenge to investigate the possibility of using SIM card as a storage container for user credentials. PSCR will award up to \$100,000 to the winning teams that successfully propose and demonstrate their idea on how they will securely store a file on a SIM card; create a mobile application that accesses a credential stored on a SIM card; and authenticates to a FIDO2<sup>20</sup> (Fast IDentity Online) service provider. CTL has partnered directly with FirstNet, AT&T, IBM, and Nok Labs for this challenge.
- CTL developed a unified secure information access framework, called ICAM (Identity, Credential and Access Management), to meet the first responder community needs.
- CTL provided a test bed where industry, FirstNet, PSCR, and other research organizations can evaluate and incorporate public safety communication research objectives.

### Challenges and Opportunities

Besides performing research in mobile access authentication, the PSCR Division has opportunities for protecting user applications and user data in the PSCR mobile environment. User

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<sup>19</sup> NIST, 2018, *Security Analysis of First Responder Mobile and Wearable Devices*, Draft NISTIR 8196, U.S. Department of Commerce, Washington, D.C., January.

<sup>20</sup> A joint effort between the Fast Identity Online Alliance and the World Wide Web Consortium (W3C) to create authentication solutions.

applications need to be certified before installation. User data can only be accessed from authorized applications and with right privileges.

**Recommendation:** CTL should proactively seek best practices from industry and other government organizations for both mobile application and user data protection.

CTL has heavily leveraged collaboration partners from industry and other NIST organizations in the cyber security studies. This practice could result in lack of core competencies for its own team. CTL may consider devoting more resources for building up an internal research team in better support of PSCR stakeholders and development of its own core technologies.

Cyber security is essential for PSCR stakeholders. New cyber threats, new operational requirements, and technology advances present continuous challenges to the CTL PSCR program, especially when the 5G cellular system is in service. Providing proper support after year 2022 will be a challenge and an opportunity for the CTL PSCR program.

### Resilient Systems

The PSCR resilient systems portfolio is limited to specific use cases around rapidly deployable and fault tolerant networks that are valuable to FirstNet. There is significant resilient systems research across multiple sectors that can be directly leveraged by FirstNet and public safety. The resilient systems portfolio is comprised of prize challenges and external research.

### Accomplishments

- In 2018, PSCR designed and launched the UAS Flight and Payload Challenge. The competition was designed by NIST to support field operations for first responders. UAS operations in a public safety realm entail a tradeoff between payload versus flight time. There are different missions capabilities enabled by Vertical takeoff and landing (VTOL) of a UAS but their flight time is nonetheless limited. The parameters of payload capacity, energy source and flight time imply design trade-offs in the quest to optimize the vehicle for efficiency and flexibility. This prize challenge was thus designed to help public safety operations by keeping a UAS and its payload airborne for the longest time possible with vertical and hovering accuracy. Additionally, at a cost of less than \$20,000 per UAS, this challenge shows first responders that there may someday be an affordable drone in their toolkit to carry wireless networks for emergency operations.<sup>21</sup>
- In 2017, PSCR funded six grants to evaluate or enhance the resilience of public safety mission critical systems in the face of connectivity challenges. This includes traditional research, evaluation prototypes, and enhancements to existing systems. All six grants should be completed by the end of 2019.

### Challenges and Opportunities

Building on the results and lessons learned from the first UAS challenge, PSCR is designing a second Unmanned Aerial Systems Flight and Payload Challenge. The goal is to push the current limits of

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<sup>21</sup> Adapted from Office of Science and Technology Policy, 2019, *Implementation of Federal Prize and Citizen Science Authority: Fiscal Years 2017-18*, Executive Office of the President, Washington, D.C., June.

designing affordable UAS that can be used to carry wireless networks into areas that are not accessible to typical deployable units.

**Recommendation:** CTL should continue to work closely with FirstNet stakeholders to identify research needs relevant to the resilient systems use cases of interest to FirstNet.

## PORTFOLIO OF SCIENTIFIC EXPERTISE

To build the scientific expertise necessary to carry out the mission as mandated in the Act, PSCR has established research, testing and development expertise that aligns with the needs of their stakeholder population. PSCR has grown its permanent technical staff to 15, utilized experts from other organizations in NIST, funded 46 grants and contracts with teams from academia, industry, and public safety, and created a series of prize challenges open to innovators around the world. This approach to developing scientific capabilities is driven by the limited term of the \$300 million funding from the Act. It has resulted in significant accomplishments in each of the four research portfolios as well as the two crosscutting areas. (See “Introduction” to this chapter, above.)

## ADEQUACY OF FACILITIES, EQUIPMENT AND HUMAN RESOURCES

PSCR facilities and equipment are adequate to the mission. The PSCR team moved into a newly renovated building in early 2018. Their laboratories are well-equipped, and they also have a mobile research vehicle that provides a mobile research laboratory capability.

PSCR is comprised of a mix of permanent and term employees. Less than half of the staff (43 percent) are permanent employees. Term employees generally come from other government organizations as well as universities. The expiration of funding in 2022 makes it challenging to attract the best talent due to PSCR’s limited ability to hire permanent employees. As the 2022 end date approaches, PSCR will likely find it increasingly difficult to attract highly talented term employees as well.

PSCR is addressing key issues in public safety, and it is likely that the research mission will continue to be of importance beyond the 2022 end date of the appropriated funds from the spectrum auction.

**Key Recommendation:** CTL should evaluate the possibility and pros and cons 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.

## DISSEMINATION OF OUTPUTS

Dissemination is a key component of the PSCR goal to create a public safety ecosystem and this is an area where PSCR has established a strong and successful effort. PSCR has many different avenues for disseminating results. Every year since 2016, PSCR has held a multi-day stakeholder meeting with attendees representing the many different sectors interested in public safety communications. The 2019 stakeholder’s meeting held in Chicago had 486 attendees. The breakdown of attendees was as shown in Figure 3.1.

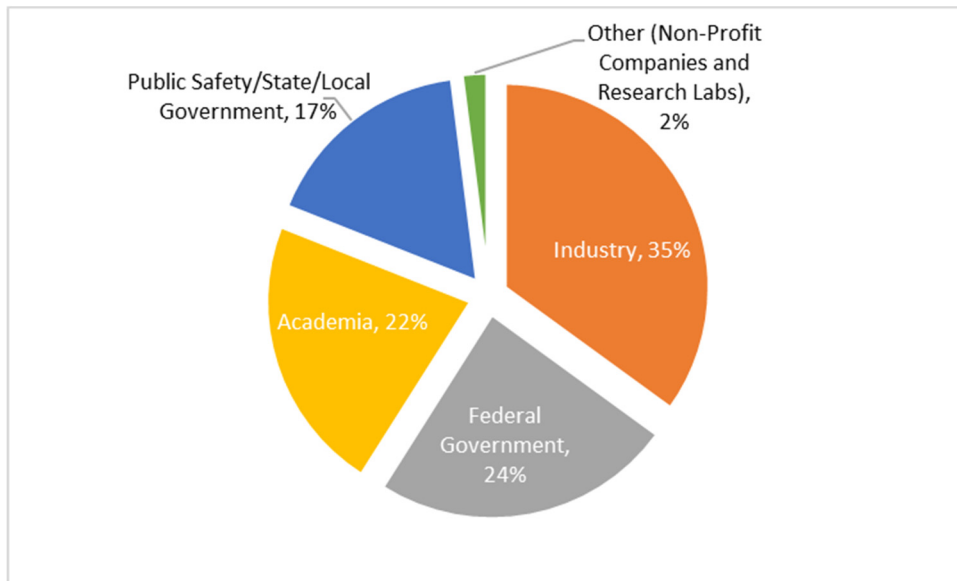


FIGURE 3.1 Attendees at PSCR Stakeholder Meeting, July 2019, by sector.

During the stakeholder's meeting, results from each of the portfolios and crosscutting areas were presented along with talks and panels from stakeholders. In addition there were demonstrations of capabilities developed. These meetings give stakeholders the opportunity to learn about the latest developments, provide input and interact with each other.

PSCR has made a point of requiring deliverables such as data sets, application programming interfaces and open-source tools—all of which encourage the growth of the public safety ecosystem and can be utilized by others and built upon. These results are freely available via the PSCR website and many have been integrated into prize challenges to facilitate new efforts. In addition, prize challenge winners are incentivized to make their winning systems open source. Results of PSCR activities are also published in appropriate scientific conferences and journals as well as in NIST reports.

## 4

## Metrology for Advanced Communications

The second main category of CTL’s work addressed by the panel, Metrology for Advanced Communications, is discussed in this chapter. This category is implemented through three of the four CTL priority areas: (1) Trusted Spectrum Testing, (2) Fundamental Metrology for Communications, and (3) Next Generation Wireless (5G and Beyond). As may be seen from Table 4.1, three of the organizational units in CTL address priority areas that comprise the main category of CTL work treated in this chapter. In the discussion below, the assessment of the work of the aforementioned three organizational units is subsumed within the discussion of each priority.

### OVERALL METROLOGY DISCUSSION AND RECOMMENDATIONS

CTL has adequate and stable funding to carry out its metrology mission. The scientific and technical quality of the team is excellent and the communication between team members is highly supportive of a collaborative, highly productive and interdisciplinary culture.

CTL staff has identified an excellent set of metrology projects to support future communications needs. This work is centered on solving fundamental and near-term applicable measurement challenges for emerging communications standards. Some of the projects clearly emerge from fundamental metrology scientific advances of clear practical import, and others seem to be (appropriately) driven by short term needs resulting from emerging national policy initiatives. The process for the future strategic selection of new projects—to maximize CTL impact—is unclear.

TABLE 4.1 Metrology for Advanced Communications and Its Implementation across Communications Technology Laboratory (CTL) Priorities and Organizational Units

	CTL Priority Areas within Metrology for Advanced Communications		
	Trusted Spectrum Testing	Next Generation Wireless	Fundamental Metrology for Communications
PSCR			
WN	X	X	
RFT	X	X	X
NASCTN	X		

NOTE: PSCR = Public Safety Communication Research Division; WN = Wireless Networks Division; RFT = Radio Frequency Technology Division; NASCTN = National Advanced Spectrum and Communications Test Network.

The CTL has capacity to grow in important metrology areas in order to address emerging communication needs in new technology and application areas, and the nation would be well served by this growth.

The CTL metrology staff are consistently and diligently engaged in the important task of dissemination of their scientific and technical findings to the broader community of technical professionals and stakeholders.

The CTL is a unique national resource, and its scientific output and test infrastructure need to be better publicized and made clearly available in order to have the highest impact.

The CTL physical infrastructure is mostly adequate for the current programs in its highly ambitious metrology mission.

There is substantial evidence that CTL has accomplished a significant amount in multiple areas of interest to its stakeholders on a relatively limited and uncertain budget in a short period of time.

Based on its significant accomplishments in a diverse portfolio of technical areas in a short period of time, the CTL is poised to capitalize on a number of timely and impactful opportunities, including: quantum-enabled metrology with applications in QISE; a new framework for channel metrology and modeling with the capability of predictive performance analysis to inform the design and deployment of next generation wireless networks; innovative hardware and platforms for testing and metrology of next generation wireless technology; continuing the growth and development of the NASCTN testbed and operational processes; leveraging machine learning, data science and statistical techniques to fully utilize the range of metrology capabilities at CTL and NIST to significantly increase, enhance and broaden the scope of its contributions and output to its stakeholders.

The stakeholders of CTL represent diverse communities (industry, government, academia and research communities in the various technical areas reflected in CTL's projects) and have different needs ranging from basic science and engineering to applied research for design and technology development to offering its test and measurement facilities for stakeholder projects. A range of metrics are needed to evaluate NIST CTL.

CTL—with the diverse expertise of its world-class staff—has significant latent capacity that it can leverage to capitalize on timely and impactful opportunities in collaboration with other NIST laboratories (e.g., the Physical Measurement Laboratory [PML], the Information Technology Laboratory [ITL], and the Engineering Laboratory).

**Key Recommendation:** CTL should develop a 3-year or 5-year strategic plan for its activities in metrology for advanced communications, 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.

## FUNDAMENTAL METROLOGY FOR COMMUNICATIONS

### Assessment of Technical Programs

Nearly a decade ago, NIST CTL researchers began investigations on better, more accurate ways to measure electric fields. This was done with an aim toward making such measurements more “traceable” to fundamental SI quantities.<sup>1</sup> Subsequent years of effort have borne impressive results.

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<sup>1</sup> The International System of Units (SI) is made up of 7 base units: kilogram (kg) mass, kelvin (K) temperature, candela (cd) luminous intensity, ampere (A) electric current, meter (m) length, second (s) time, and mole (mol)



The primary result is a practical, demonstrated, Rydberg atom-based, SI-traceable measurement method (and prototype devices) for precision electric field (E-field) and power measurements. This result extends the amplitude range, frequency range, and accuracy of E-field measurements. Through the use of lasers and microwave signals to induce transparency in a closed cell containing a vapor of particular atoms (rubidium or cesium), one or two electrons are excited to states causing their host atoms to have large dipole moments, allowing them to be used as very sensitive E-field detectors. Initial results indicate multiple orders of magnitude improvement in the measurement sensitivity compared to the state of the art.

This invention has been shown to enable several other applications, including measurement of phase and modulation of fields for communications transmitters and receivers, quantum-enabled imaging for medical and near-field applications, power calibrations and more.

The measurement capabilities developed by CTL using Rydberg atoms also offer a promising bridge to future research directions mentioned by the CTL director: quantum computing and optical communication networks. Rydberg atoms are being explored as promising candidates for physical realization of qubits (quantum bits) and CTL is well-positioned to build on their recent successes to initiate a research program in QISE in collaboration with other NIST laboratories, such as the PML, which are already engaged in QISE-related research. This is a timely opportunity given the recent announcement of the National Quantum Initiative (NQI) in December 2018 and the worldwide attention QISE is receiving. In this endeavor, CTL is well-positioned to identify strategic collaborative opportunities with PML (and other laboratories, such as ITL) that draw on its unique strengths in communication metrology and technology to advance the science, engineering and technology frontiers of quantum computing, quantum communication and quantum sensing.

The technical area of optical communication technology also represents a synergistic direction that CTL is interested in adding to its research portfolio in the future. On the one hand, the need for higher bandwidths, which is driving emerging wireless technologies (5G and beyond), is also driving new technologies and innovations in fiber-optic and free-space optical communications to which CTL can fruitfully contribute. On the other hand, optical and microwave communication techniques and technologies are expected to play a key role in the emerging QISE technologies, and this provides further impetus for CTL to develop core expertise in this area, possibly by hiring new scientists and engineers with the requisite expertise.

The RFT Division continues to perform fundamental metrology research and development of techniques for high-frequency measurements applicable to a wide array of industry and government stakeholders. This high impact work has significant impact on 5G integrated circuit development, a field of high national priority. Related work is in advanced vector network analysis and calibration. NIST is viewed as a best in the world resource in this area. They have also developed a “microwave uncertainty framework.” This framework will have much broader application than only the microwave frequency band.

The technological trend towards fully integrated communication devices, in which the digital processing, analog-digital converters, and RF hardware and antennas are all integrated onto a single board with multiple chips, is radically changing the paradigm for testing and characterizing the performance of these new devices. NIST CTL is at the forefront of pioneering a new approach to testing next generation wireless devices and systems that would combine on-wafer measurements of individual components with over-the-air (OTA) testing of integrated devices and complement them with new approaches for making near-field measurements of various components in an integrated board.

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amount of substance. SOURCE: NIST, 2017, *SI Measurement System*, NIST SP 304A, U.S. Department of Commerce, Washington, D.C., July.

## Accomplishments

The quality of the quantum SI-traceable measurements and application research is outstanding. The team is defining the state of the art in E-field amplitude, phase and polarization metrology. Among others, the developed Rydberg-atom-based methods are able to measure E-fields with amplitudes as low as 10 millivolt per meter (mV/m) at room temperature, over frequency bands ranging from tens of megahertz (MHz) to hundreds of gigahertz (GHz) or even terahertz (THz), with an instantaneous bandwidth of tens of megahertz. The team has also demonstrated the ability to accurately measure the phase of the E-field over a wide frequency range relying on the same fundamental principles. Several proof-of-concept demonstrators have been implemented, including analog (stereo AM/FM) as well as digital (up to 64 quadrature amplitude modulation [QAM]) modulation and demodulation.

The developed technology is also an enabler for high frequency (>110 GHz) calibration procedures. This is a field in which NIST is playing a key role in different ways, including the development of high-fidelity on-wafer measurement techniques and integrating these with on-board and over-the-air measurements to invent the future of vector network analyzers. The need for these new classes of measurements and network analyzers is driven by the advances in integrated circuit (IC) technology for communication applications in which the IC chips for various subsystems (e.g., RF transceivers, analog-digital convertors, and digital processors) are all integrated onto a single printed circuit board (PCB) with no connectors available for testing the individual systems. This is a stark departure from current testing methodologies that are based on conductive measurements of individual components. This area also ties in well with the increasing use of machine learning and data science techniques at CTL as evidenced by the newly-established laboratory space on the third floor of Building 3 that included a dedicated server for machine learning and high-intensity data analytics.

Overall, this program is an excellent example of how timely investment of resources for the exploration of very fundamental physics principles (Rydberg atoms) can lead to transformative practical solutions (SI traceable E-field measurements) for industry/societal problems (calibration of equipment). This is also an excellent example of how such investment of resources can also lead to serendipitous dividends in terms of new unanticipated opportunities; new programs in QISE and optical communication technologies, in this case. CTL's success in winning multiple Institute of Electrical and Electronics Engineers Instrumentation and Measurement Society (IMS) awards in these areas, in collaboration with other laboratories (e.g., PML and ITL), is commendable and reflective of the excellence of technical programs and the expertise of the staff.

A significant accomplishment has been the development of three different types of sounders, operating in 28 GHz, 60 GHz, and 83 GHz bands, with directional measurement capabilities using a variety of antenna architectures, including switched arrays and phased arrays. The measurements taken by these sounders have led to a set of "ground truth" propagation data that can be used for evaluating the performance of different sounders.<sup>2</sup> These measurement technologies, facilities, and advanced data processing capabilities are at the forefront of advanced metrology for next generation wireless communications.

## Challenges and Opportunities

Several technical challenges must be overcome before the Rydberg-atom based devices can become widely useable. These include further miniaturization and eventual embedding of the system in a compact probe, widening of modulation bandwidths (currently in the order of 20 MHz, set by the electron/atom relaxation time), application of filtering, etc. The team is well aware of these challenges, and is currently at work on addressing them.

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<sup>2</sup> Data are available at NIST, "5G mmWave Channel Model Alliance," <https://5gmm.nist.gov/>.

The accomplishments in quantum-enabled measurements also offer new opportunities in the growing and important area of QISE, in addition to new avenues in quantum-enabled sensing that team is already pursuing—for example, building on the measurement work to create higher-fidelity Rydberg atom-based qubits with longer coherence times. CTL’s expertise in optical and microwave metrology techniques would also be valuable in realizing high-fidelity signals for controlling the initialization and evolution of qubit states. A related opportunity is in the development of optical quantum communication techniques for exchanging qubits across multiple quantum processors (with tens to hundreds of qubits) to create a distributed quantum computer with larger number of qubits. NIST and CTL have made fundamental contributions to optical communications in the past and these potential opportunities align well with the CTL’s plan to re-establish its program in the area of optical communications. An important related research challenge is transduction of quantum states across multiple modalities—for example, between Rydberg atom-based qubits (for use within a quantum processor) and photonic qubits (for transporting qubits across quantum processors).

Another opportunity for the CTL within the quantum realm relates to new applications in quantum information science, supported by optical communications, the latter being a field in which NIST has made many fundamental contributions in the past. As the need for communication between quantum computing increases, developing technologies to support the reliable exchange of quantum bits is needed.

The CTL team has delivered exemplary results noted above. The Rydberg atom E-field sensor appears to have breakthrough potential.

**Recommendation:** CTL should continue to support work on the Rydberg atom E-field sensor to maintain development and extend applications.

The CTL team has proactively identified Optical Communications and Quantum Information Science and Engineering as promising new areas for research that synergistically build on the quantum-enabled sensing work.

**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 and the Information Technology Laboratory.

### Portfolio of Scientific Expertise

The RFT Division’s scientific expertise in SI-traceable measurements is closely matched to the program’s technical needs and strongly positions CTL at the forefront of the field, as evinced by the visibility and citations on this work.

### Challenges and Opportunities

While expanding CTL’s capabilities into the synergistic areas of QISE and optical communications is timely and potentially impactful, it would likely require hiring new scientists and engineers with requisite expertise that can provide a bridge between CTL’s capabilities in communication technology and metrology and the capabilities of the collaborating laboratories, such as PML, in quantum information science.

Future technical staff hiring may require expertise that can provide a bridge between CTL's capabilities in communication technology and metrology and the capabilities of the collaborating laboratories, such as PML, in QISE.

**Recommendation:** The CTL should evaluate the resource and staff needs for future efforts in quantum information science and optical communications, in consultation with collaborating NIST laboratories (e.g., PML and ITL) and develop a plan for meeting those needs through internal and external sources of funding.

## **Adequacy of Facilities, Equipment, and Human Resources**

### **Accomplishments**

CTL has made significant progress in developing in-house capabilities for fundamental metrology in the context of next generation wireless technologies, including those for channel modeling and measurement. In the work led by the RFT Division; a number of new measurement and testing facilities have been developed, including anechoic chambers with robotic arms for radiation pattern measurements in static and mobile scenarios, a robotic aperture scanning testbed for making measurements appropriate for antenna arrays, reverberation chambers for creating different multipath propagation environments, and new methodologies and testbeds for characterizing the performance of channel sounders, including angular measurements. (The complementary work by the WN Division on channel modeling is discussed below in the section, Next Generation Wireless.)

### **Challenges and Opportunities**

Sustainability of adequate personnel and facilities could present a programmatic challenge for building on recent accomplishments and expanding into new areas in quantum information science and optical communications. This effort will require strategic collaborations with other laboratories at NIST, such as PML and ITL. It is not clear whether the collective capabilities of CTL and other NIST laboratories, in terms of facilities, equipment and human resources will be adequate to successfully execute the potential new research activities. There appear to be multiple commercial opportunities for quantum-enabled metrology and potentially many future ones in the broader area of quantum information science. However, CTL will have to act in a thoughtful and strategic fashion to evaluate the resource needs and address them in a timely fashion.

The available resources in terms of facilities and staff seem to be adequate to sustain the current programs. However, growing into the new synergistic areas of optical communications and quantum information science will require strategic collaborations with other laboratories, such as the PML and the ITL, and likely require additional resources. The facilities and equipment being used for the quantum SI-traceable measurements are excellent. Overall RFT Division facilities are excellent.

## **Effective Dissemination of Outputs**

The publications and patents from the quantum SI-traceable measurement research are first-rate in terms of venue, quantity, and visibility.

## Accomplishments

This work has led to 17 journal publications in top-tier journals in the applied physics society, including *Physical Review Applied*, *Applied Physics Letters*, and *Journal of Applied Physics*, and 10 conference papers.<sup>3</sup> These works have had, and are having, a high impact in the community, as shown by the very high number of downloads in the short term as well as citations in the long term.

## Challenges and Opportunities

Opportunities exist in commercialization and development of applications. The novel modulation and musical demonstrations possible using the Rydberg atom could be used for outreach to K-12 student communities. Another opportunity may exist if the quantum SI-traceable measurement research could be connected with future applications in quantum information science and engineering.

## NEXT GENERATION WIRELESS

### Assessment of Technical Programs

CTL is tackling a diverse range of timely and significant problems in the area of 5G wireless technology, fundamental metrology, and applications, particularly on the topics of 5G Channel Modeling and Measurements. In addition, CTL is providing outstanding stewardship of the 5G mmWave Channel Model Alliance. This organization is a worldwide community of researchers engaged in research and development for new approaches to measurement and modeling of propagation channels at millimeter-wave frequencies. CTL also conducts work on other technologies that support 5G including for example, on massive multiple-input, multiple-output (MIMO) antennas on frequencies up to and including those of millimeter wave. Measurements of MIMO are enabled in the reverberation chambers of the National Broadband Interoperability Testbed on the Boulder campus as are over-the-air (OTA) measurements.

The CTL work on millimeter-wave channel measurements and modeling began in 2011, and CTL initiated the 5G mmWave Channel Model Alliance (the “Alliance”) in 2015. The Alliance has grown to include over 80 organizations from industry, academia, and government.

The Alliance has worked to develop multiple publications for the broader community, methodologies for channel measurements and model development, and has brought numerous individuals together for collaborations, who otherwise would likely not have interacted. The CTL team members have continued in a leading role in the Alliance, in direct response to a recommendation from the 2015 National Academies review.<sup>4</sup>

The CTL team has also taken several of their own measurement-based models and employed them in higher level network simulators, provided a commercial software vendor with code to enable the use of an 802.11 model by the wider community, and has also published widely. In addition to journal and conference papers, the Alliance has sponsored several workshops at major conferences.

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<sup>3</sup> Christopher Holloway, Matt Simons, and Joshua Gordon, NIST CTL, “Quantum SI Traceable Measurements and Calibrations: Radio Frequency Electric Fields and Power,” presentation to the panel, June 26, 2019.

<sup>4</sup> National Academies of Sciences, Engineering, and Medicine, 2015, *Telecommunications Research and Engineering at the Communications Technology Laboratory of the Department of Commerce: Meeting the Nation’s Telecommunications Needs*, The National Academies Press, Washington, D.C.

## Accomplishments

The 5G mmWave Channel Model Alliance has achieved significant accomplishments since its inception in July 2015. The membership of the alliance has grown significantly to over 80 members from industry, academia and U.S. government agencies. Two comprehensive white papers have been developed by the two working groups—one on channel modeling techniques, and one of channel measurement and verification—capturing the diverse expertise of the Alliance members.<sup>5</sup> NIST has also created a repository for sharing of data between the Alliance members and the wider research community.

CTL has also made significant progress in developing in-house capabilities in channel modeling and measurement. In the work led by the WN Division, channel models are being incorporated into network simulation software, and a framework for comparing the performance of different sounders is being developed. The measurement and verification work, led by the RFT Division, utilizes the testing facilities described above<sup>6</sup>—including anechoic chambers, a robotic aperture scanning testbed, and reverberation chambers.

A significant accomplishment has been the development of three different types of sounders, operating in 28 GHz, 60 GHz, and 83 GHz bands, with directional measurement capabilities using a variety of antenna architectures, including switched arrays and phased arrays. The measurements taken by these sounders, and extension of propagation parameters from those measurements, has led to a set of “ground truth” propagation data that can be used in the models for numerically evaluating the performance of different sounders

## Challenges and Opportunities

There are a number of opportunities in the area of 5G channel modeling and measurements and next generation wireless networks that the CTL is poised to pursue, including: expanding the work to higher THz frequencies; expanding the work to UAV network channels; measurement campaigns for outdoor scenarios; quantifying the effects of human occupancy on indoor and outdoor channels and developing accurate channel models and an appropriate network modeling framework that has the capability to predict network performance in a given deployment area.

The microwave uncertainty framework (MUF) is a powerful approach for studying and quantifying the impact of different sources of uncertainty in measurements of future wireless devices and systems—not inherently limited to the microwave band. New capabilities of future wireless systems, including higher frequencies, larger bandwidths, and directional antennas, coupled with new approaches to analysis and processing of data, including machine learning techniques, present exciting new opportunities and challenges for further developing this uncertainty framework.

CTL is well positioned to grow the effort in next generation wireless technologies by building on their accomplishments at millimeter-wave frequencies. Additional measurements and models will be needed for other (higher) frequency bands and multiple outdoor settings. Planning for the future—for example, 6G (6th Generation Wireless)—is beginning in the wider community. Another challenge—for which NIST may be well suited in collaboration with the National Institutes of Health—is to address human health impacts of the use of these frequency bands.

The approaches developed by CTL for advancing the state of the art of modeling and measurement of millimeter-wave channels reflects a high level of creativity and ingenuity to complement commercially available hardware/software with internal development of antennas, hardware, automated measurement capability, and software for data processing and visualization.

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<sup>5</sup> The white papers were undergoing peer review and final publication at the time of the panel’s review. Further information may be found at NIST, “5G mmWave Channel Model Alliance,” <https://www.nist.gov/ctl/5g-mmwave-channel-model-alliance>.

<sup>6</sup> See the subsection “Accomplishments” in the section “Fundamental Metrology for Communications.”

Data science and machine learning offer a powerful new approach that CTL is beginning to leverage in its work on metrology of future highly integrated wireless devices, propagation channel modeling and measurement, and creating traceable measurements and associated uncertainty analysis.

**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.

### Portfolio of Scientific Expertise

The CTL staff engaged in Next Generation Wireless are highly qualified and represent a diverse range of expertise (including in channel modeling and measurement) that is essential for this cross-disciplinary effort, including RF hardware design, testing and measurement expertise, channel and network modeling, and data processing and analysis. In FY 2019, 22 percent of CTL's budget authority went to Next Generation Wireless priority area.

### Adequacy of Facilities, Equipment, and Human Resources

The facilities and equipment being used for the next generation wireless metrology, including millimeter-wave and higher frequencies, are state of the art. This includes components and capabilities developed locally by CTL staff to augment commercial measurement equipment such as vector network analyzers. The CTL facilities fall into two categories: (1) very modern, well equipped, well maintained new infrastructure, and (2) one rather old building that houses valuable instrumentation and capabilities but suffers from lack of infrastructure such as high speed network connectivity, and modern HVAC. The panel did not make a site visit to Gaithersburg, Maryland, where the WN Division's facilities are located so cannot comment on facilities located there.

CTL allows users outside of NIST to have access, on a supervised basis, through formal mechanisms, such as CRADAs, and informal collaborations. In addition CTL can also serve as a testing location for programs that need a neutral third party to serve as the technical evaluator, for example, the Defense Advanced Research Projects Agency. The precise rates of utilization through such agreements and arrangements are not readily available.

CTL's measurement facilities can be of great use to users in the research and business communities in the United States and worldwide. For this to succeed, it is essential that the facilities be able to handle the data and infrastructure requirements of modern communications challenges.

**Key Recommendation:** CTL should undertake planning and resource allocation for renewal and renovation of its measurement facilities with a degree of urgency to support latent demand for time at such facilities in the research and business communities. CTL should aim to provide the usage of these facilities as a "paid service" to these communities.

### Effective Dissemination of Outputs

The outputs of the millimeter-wave channel measurement and modeling work are numerous, and are of relevance and use to the community. These include the two white papers on modeling and measurement developed by the 5G mmWave Channel Model Alliance, contributions to standards bodies,

and hosting of a series of workshops on the topic over the last few years. In addition, various members of CTL have also disseminated this work through invited presentations and engagement in other organizations such as the National Science Foundation (NSF)-sponsored research coordination network on millimeter-wave wireless.

## Accomplishments

The growth and outputs of the 5G Millimeter Wave Channel Model Alliance are substantial outcomes. At least one book is being published, datasets are being archived, and software and hardware instrument makers are likely to use some of the Alliance outputs. The three millimeter-wave channel sounders that CTL has developed are also a community asset. The new capabilities for testing and measurement being developed for next generation wireless system at the CTL would further build on these assets.

## TRUSTED SPECTRUM TESTING

### Assessment of Technical Programs

The CTL team's work in the broad topic of shared use of federal spectrum by commercial systems has been enormously important. This work consists of (1) two NASCTN projects in the context of advanced wireless services (AWS)-3 spectrum sharing (1755-1780 MHz paired with 2155-2180 MHz), and (2) work in the WN Division on technologies for sharing of the 3550-3700 MHz band. The RFT Division provides expertise and collaboration in shared spectrum metrology on NASCTN projects using the National Broadband Interoperability Test Bed (NBIT) on the Boulder campus. Additionally, RFT works on spectrum sharing through contributions to the ANSI 63.27 standard and through research on techniques for quantifying the ability of wireless systems to coexist. The NASCTN projects also include independent measurements on the MITRE testbed and there are contributions from numerous other groups including NASA, NTIA and Johns Hopkins Applied Physics Laboratory.<sup>7</sup>

The projects in the context of AWS-3 sharing are very important as they aim to produce tools and methodology for characterizing interference of commercial LTE (long-term evolution [an early 4G protocol]) user equipment (UE) to Aeronautical Mobile Telemetry (AMT) systems and provide confidence to DoD and Commercial Service Providers (CSP) that their radio systems effectively co-exist in the band. This activity has two good projects: (1) Characterizing LTE User Equipment Emissions: Develop method for modeling LTE UE emissions, a component of the DoD aggregate interference model (proposed by the Defense Spectrum Organization [DSO]); and (2) LTE Impacts on AMT (proposed by Edwards Air Force Base).

The newly promulgated rules found in Part 96 of Title 47 of the Code of Federal Regulations (47 CFR Part 96) apply to use of 150 MHz of the 3550-3700 MHz band termed as Citizens Broadband Radio Service (CBRS). This represents significant regulatory policy innovation promoting shared use of valuable radio spectrum. As per these rules, incumbent systems such as naval radars, Fixed Earth Satellite Stations (FSS), government radio sites, and wireless Internet service providers (ISPs) share the spectrum with commercial radio networks. The rules require 3-tier spectrum access priority structure wherein (1) incumbent systems occupy the top tier and have highest priority access, (2) the bottom most tier called Generalized Authorized Access (GAA) provides lowest-priority access without interference protection, whereas (3) a middle tier called Priority Access License (PAL) provides protection from GAA devices. The rules also require a Spectrum Access System (SAS)—a network resident server to manage the

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<sup>7</sup> Jason Coder, Adam Wunderlich, and Melissa Midzor, NIST CTL, "AWS-3 Spectrum Sharing," presentation to the panel on June 25, 2019.



sharing in this tiered framework, and Environmental Sensing Capability (ESC)—a network of sensors to detect activity of dynamic incumbent and provide information to SAS for successful incumbent protection.

The development and advancement of CBRS spectrum sharing technologies based on this three-tier architecture has been undertaken in the Spectrum Sharing Committee—a multi-stake holder group consisting of industry and government members in the Wireless Innovation Forum (WinnForum) standards organization. The consensus standards developed in this forum are expected to drive rapid adoption of CBRS spectrum driving new business models and new use cases such as private wireless networks for diverse verticals and enterprises.

## Accomplishments

The CTL team members have been valued participants in the WinnForum standardization activities and have made contributions that have had significant impact on standards and component technologies. Their key contributions are in the following areas: (1) development of SAS test procedures for incumbent protection, (2) a “Move List Computation” methodology for assessing and limiting the impact of commercial systems to prospective locations of naval radars in the dynamic protection area (DPA) and development of SAS test procedures—this methodology will be adopted in all commercially operating SAS systems; (3) development of algorithms for selection of installation sites for ESC sensors to provide coverage of DPAs; (4) development of machine learning and statistical processing based algorithms for detection of naval radars in ESC sensors; and (5) extensive collection and analysis of naval radar data under a NASCTN project for characterization of incumbent signals. This work has provided valuable insights to community toward development of ESC sensors and availability of CBRS spectrum when radar is active.

## Challenges and Opportunities

With demand for more sub-6 GHz spectrum for 5G networks in the United States continuing unabated, the Federal Communications Commission is considering opening up new bands such as 3.1-3.5 GHz and several new U-NII (unlicensed national information infrastructure) bands in 5.925 to 7.125 GHz range. Many of these spectrum bands have incumbent systems, and simplified spectrum sharing may be employed to accelerate availability of these bands for commercial use. The NIST CTL team has an opportunity to leverage its expertise and experience with CBRS to contribute to the development of solutions for these new bands, balancing the need for incumbent protection and the need for guaranteed spectrum access for commercial networks.

The CTL team might also make contributions to the design of solutions to the problem of co-existence of 5G new radio<sup>8</sup> in unlicensed bands with other systems such as 802.11ax and WiFi-6.

The CTL team in the NASCTN program and WN Division have delivered exemplary results noted above, with a small staff. However, their activities have been opportunistic and reactive. A more strategic and proactive approach towards spectrum sensing and sharing would enhance the impact of the team in both regulatory actions and industry standardization activities.

The current operating model in NASCTN is to respond to requests for spectrum sensing and characterization from industry or other federal agencies. Given the level of current staffing, this is probably appropriate. In the future, the program could have a much broader impact if it would independently select “hot-button” spectrum issues on which to work and scale-up the number of staff appropriately.

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<sup>8</sup> “5G New Radio (NR) is the global standard for a unified, more capable 5G wireless air interface” (Qualcomm, 2019, “We’re leading the charge to 5G NR,” <https://www.qualcomm.com/invention/5g/5g-nr>).

**Recommendation:** NASCTN should develop a roadmap on research needs for spectrum sensing characterization, including areas where NIST was primary and areas in which industry and other federal agencies were primary. This roadmap would feed into the 3- to 5-year research plan the panel recommends.

**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.

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

### **Portfolio of Scientific Expertise**

The CTL staff engaged in NASCTN are highly qualified and represent a diverse range of expertise that is essential for this cross-disciplinary effort, including RF hardware design, testing and measurement expertise, spectrum measurements, and data processing and analysis. Their stated role as a neutral and unbiased testing source is adhered to carefully, and they have become a trusted source of information and expertise on spectrum management issues. The accomplishments of the group are especially impressive given their relatively small size—in FY 2019, 3 percent of CTL’s budget authority went to trusted spectrum testing.

### **Adequacy of Facilities, Equipment, and Human Resources**

The review panel toured the anechoic chambers and reverberation chamber utilized by NASCTN, RFT, PSCR, and other NIST laboratories and located in Building 24. Together, these chambers comprise the aforementioned NBIT (see Figure 4.1) and the NIST Antenna and Communication Metrology Laboratory (ACML), which includes the Large Antenna Positioning System and the Configurable Robotic MilliMeter-wave Antenna Facility. The anechoic and reverberation chambers themselves are impressive and can be configured to provide a range of electro-magnetic environments by configuring absorbent and reflective materials as appropriate to the required testing. Staff noted the lack of high-speed data connections from Building 24 to other parts of the NIST-Boulder campus, necessitating that the large data sets generated be carried by hand on portable drives between buildings. In addition, the HVAC system has not been upgraded in some time and does not offer ideal temperature and humidity control.

### **Dissemination of Outputs**

NASCTN has had a significant impact with its report on the effect of LTE deployments on GPS (Global Positioning System) receivers. The team also developed a curated set of LTE uplink waveforms, and made these widely available for use by the community. NASCTN led the effort to characterize the spectrum in the 3.5 GHz band and published the results of these tests widely. Overall, NASCTN has had a significant impact on the community thanks to the wide dissemination of its test results.



FIGURE 4.1 The anechoic chamber of the National Broadband Interoperability Testbed located on the Boulder, Colorado, campus of NIST. SOURCE: NIST, available at [https://www.nist.gov/sites/default/files/styles/480\\_x\\_480\\_limit/public/images/2017/02/14/nbitanechoicchamber.jpg?itok=tTjw56mZ](https://www.nist.gov/sites/default/files/styles/480_x_480_limit/public/images/2017/02/14/nbitanechoicchamber.jpg?itok=tTjw56mZ).

## 5

## Look-Back at Previous Review

This chapter assesses the extent to which CTL followed the recommendations made in the National Academies' 2015 report, *Telecommunications Research and Engineering at the Communications Technology Laboratory of the Department of Commerce: Meeting the Nation's Telecommunications Needs*.

**Recommendation:** CTL should maintain a position of leadership in the 5G mmWave [millimeter wave] Channel Model Alliance, seek to expand the membership of the alliance, and engage in mm-wave work with other standard and industry bodies.

CTL has maintained and even enhanced its leadership in the 5G mmWave Channel Model Alliance. Launched in July 2015, the NIST 5G mmWave Channel Model Alliance helps accelerate the development and use of measurements and models for next-generation communications technologies. By bringing together researchers from multiple stakeholder groups, including communications technology companies, wireless service providers, academia, and government, CTL has developed consensus technical findings that benefit standards and best practices for 5G deployment. Currently, the Alliance includes participants from over 75 organizations, and this effort is a great success within CTL.

**Recommendation:** CTL should develop a more defined research agenda that outlines in detail its research goals and future plans.

CTL conducts an annual research planning process focused on its three program areas of public safety, trusted spectrum testing, and metrology for advanced communications. Group plans filter up to divisions for coordination and approval, while the division and CTL leadership set strategic direction and long-term planning based on NIST priority areas. CTL's process consists of three major steps: (1) process review, (2) program review, and (3) resource allocation. CTL focuses its resources on meeting its priorities by asking, "What do you need to accomplish task x?," rather than simply status quo funding of projects.

This approach to research planning appears sound, but CTL did not sufficiently explain how these plans might align with the needs of industry or how well the Divisions were able to meet these plans. Therefore, while CTL has defined a general research agenda setting process, the goals and future plans might be more readily shared with future National Academies panels.

**Recommendation:** CTL should quickly hire and train personnel to establish a leading-edge skill set in areas associated with their research goals and upgrade aging facilities and instrumentation.

CTL has done very well in terms of hiring junior personnel across its various research areas. CTL has also been successful in upgrading its buildings, facilitates, and laboratory instrumentation. These new

facilities include the NIST Large Antenna Positioning System, the NIST Configurable Robotic Millimeter-Wave Antenna Facility, the NIST Broadband Interoperability Testbed, as well as renovating an entire building to house the PSCR Division. Beyond the substantial federal hiring, CTL has also engaged in innovative use of contractors and detailees on loan from other federal agencies to fill hiring needs. The CTL has been using the NIST Professional Research Experience Program to attract staff.

**Recommendation:** CTL should further develop opportunities to quickly and frequently engage outside stakeholders and obtain frequent outside technical reviews as it moves its research plan forward.

Parts of CTL have been very successful in engaging outside stakeholders (e.g., NASTCN, PSCR, and NIST 5G mmWave Channel Model Alliance), but CTL might benefit from looking at how other groups can better engage outside stakeholders for technical review and input. Of course, there is the Visiting Committee on Advanced Technology (a FACA committee) that provides input, but this is limited in scope and not directly mapping to each of the research domains/divisions within CTL. There is considerable activity by the CTL staff in presenting research at conferences and in journals, but this may not directly engage the stakeholders most important to the industry-focused mission of CTL. CTL might consider establishing a broader structure for stakeholder engagement.

**Recommendation:** ITS and CTL leadership should work to build an environment of trust and collaboration across both laboratories.

There does not appear to be the amount of collaboration that had been envisioned in the 2015 National Academies report. While CTL does support ITS staff in a limited manner, the hope was that the Center for Advanced Communications (CAC) would serve as a vehicle for uniting CTL and ITS on common mission research planning and development. With the shutdown of the CAC, there appears to be a new opportunity to consider how best to enable engagement between these valuable research groups within the DOC.

**Recommendation:** The Public Safety Communications Research Program should be considered as a template for collaboration across the laboratories.

The PSCR continues to thrive. The nature of its outreach mission and the significant funding allows PSCR to engage both within DOC and with other parts of the government (including state and local government). PSCR continues to be an example of a successful collaboration template.

**Recommendation:** The National Advanced Spectrum and Communications Test Network should be made fully functional as soon as possible to be able to handle the important mission that it has been assigned. This includes the recruitment of customers and additional government, academic, and industrial organizations to utilize the skills in the various affiliated laboratories.

NASCTN has successfully ramped up operations and has completed several projects in the last few years. Its membership now includes the National Oceanic and Atmospheric Administration, the NASA, NSF, the NTIA and DoD. NASCTN has brought together federal agencies and commercial operators to develop common measurement framework methods and has enabled technical input for sharing of valuable spectrum resources. NASCTN is encouraged to grow its membership and to engage in projects where multiple sides of a given debate might fund the research output. NASCTN will need to remain as a neutral body from the perspective of its stakeholders for conducting these important technical sharing efforts.

**Recommendation:** The Department of Commerce (DOC) should develop short- and long-term application and basic research plans that would provide the country with the necessary knowledge

base in spectrum areas and enhance the capability for spectrum sharing and repurposing analysis. The DOC plans should include opportunities for various users of spectrum to identify their needs and long-term objectives. A research agenda should consider the most efficient use of DOC's—and the relevant laboratories'—resources and develop an effective organizational structure and funding strategies to ensure that research goals are met and resources are effectively used.

While CTL did provide evidence of long-term research planning, they did not provide input specific to this recommendation as it relates to spectrum sharing and repurposing analysis. CTL would benefit from further implementing this recommendation.

**Recommendation:** The Boulder telecommunications laboratories should expand their visible leadership roles by providing technical expertise for agencies and policy makers and providing objective scientific expertise.

The CTL has taken an active role in engaging with agencies on a variety of research engagements, leading advisory roles across federal agencies, standards development organizations, as well as industry consortium. These organizations include the NSF Millimeter-Wave Research Coordination Network Steering Committee, the NIST 5G mmWave Channel Model Alliance, the Telecom Infra Project, and other efforts. However, there remains a bigger opportunity for CTL to provide more input to policymakers outside of the DOC on a wide set of wireless and public safety issues.

**Recommendation:** The Boulder telecommunications laboratories should fully engage in the current and emerging work in Institute of Electrical and Electronics Engineers (IEEE) 802 LAN/MAN Standards Committee, the 3rd Generation Partnership Project, and the Internet Engineering Task Force. This must be a long-term commitment, because the time constant for standards evolution is on the order of 3 to 10 years.

CTL has engaged with a number of standards efforts, including IEEE 802, 3GPP, Telecom Infra Project, and the Internet Engineering Task Force. PSCR won a NIST Bronze Medal for their contributions to 3GPP standards for mission critical voice for public safety. PSCR has worked to create dozens of standards that were ultimately accepted and met all public safety mission critical voice requirements. Nonetheless, there is still room for growth of CTL in terms of broader engagement in standards efforts, particularly beyond the impressive work related to public safety.

## 6

### List of Key Recommendations

#### PUBLIC SAFETY COMMUNICATION

**Key Recommendation:** The PSCR 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. (Chapter 3)

**Key Recommendation:** CTL should develop a roadmap for public safety analytics, taking into consideration projected future areas of interest. (Chapter 3)

**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. (Chapter 3)

**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. (Chapter 3)

#### 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. (Chapter 4)

**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.

**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 and the Information Technology Laboratory. (Chapter 4)

**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. (Chapter 4)

**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. (Chapter 4)

**Key Recommendation:** CTL should continue vigorous support for the spectrum sensing and sharing activity, which has delivered impactful results. (Chapter 4)





## Acronyms

3GPP	3rd Generation Partnership Project
5G	Fifth-generation Wireless/Cellular Network
AR	augmented reality
AWS	advanced wireless services
CAC	Center for Advanced Communications
CBRS	Citizens Broadband Radio Service
CRADA	cooperative research and development agreement
CTL	Communications Technology Laboratory
DOC	Department of Commerce
DoD	Department of Defense
DPA	dynamic protection area
EMS	emergency medical service
FY	fiscal year
FirstNet	First Responder Network Authority
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Standards Organization
ISSI	Inter-RF Subsystem Interface
ITL	Information Technology Laboratory
ITS	Institute for Telecommunication Sciences
LAN	local area network
LBS	Location-Based Services
LMR	Land Mobile Radio
LTE	long-term evolution
MAN	metropolitan area network
MCV	Mission-Critical Voice
MIMO	multiple input, multiple output

NASCTN	National Advanced Spectrum and Communications Test Network
NIST	National Institute of Standards and Technology
NTIA	National Telecommunications and Information Administration
PML	Physical Measurement Laboratory
PSCR	Public Safety Communications Research Program
QAM	quadrature amplitude modulation
QISE	quantum information science and engineering
R&D	research and development
RF	radio frequency
RFT	Radio Frequency Technology Division
SAS	Spectrum Access System
UAV	unmanned aerial vehicle
UE	user equipment
UI	user interface
UX	user experience
U-NII	unlicensed national information infrastructure
VR	virtual reality
WN	Wireless Networks Division