THIS IS CTL

COMMUNICATIONS TECHNOLOGY LABORATORY

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CONTENTS (CONTINUED)

Executive Summary: A Guide to this Document

Welcome to the Communications Technology Laboratory (CTL) of the National Institute of Standards and Technology (NIST). An independent, unbiased arbiter of trusted measurements and standards to government and industry, CTL unifies NIST's many wireless communications research and development efforts into one organization. CTL is comprised of three major programmatic areas: Public Safety Communications, Trusted Spectrum Testing, and Metrology for Advanced Communications.

In Fiscal Year (FY) 2019, Dr. Walter Copan, Undersecretary of Commerce and Director of NIST, charged the National Research Council (NRC) with the task of conducting an in-depth review of the lab's technical programs, scientific expertise, facilities, equipment, human resources, and program outputs. This document details each of these elements as they relate to the three programmatic areas.

The first chapter of this document provides an overview of CTL, including its overarching goals, structure, budget, staffing, outputs, and opportunities and challenges. It also highlights CTL's strategic plan and annual planning process. Finally, this chapter highlights each of CTL's major programmatic areas.

The second chapter focuses on one of CTL's largest research areas: Public Safety Communications. In FY19, this research area comprised 69% of CTL's budget, up from 35% in FY16. The Public Safety Communications Research (PSCR) Division serves as the headquarters for the CTL Public Safety Communications Program. PSCR has grown substantially since the Middle Class Tax Relief and Job Creation Act of 2012 mandated developing and implementing a robust and impactful public safety communications research and development program. The Public Safety Communications Program is comprised of vibrant research programs across CTL, NIST, and the U.S. public safety community through PSCR's extramural funding programs.

The third chapter focuses on the Trusted Spectrum Testing programmatic area. This area is led by the National Advanced Spectrum and Communications Test Network (NASCTN). NASCTN was established in 2015 to serve as a trusted partner for developing test methods and networks to inform future spectrum policy and regulations for both private and public sectors.

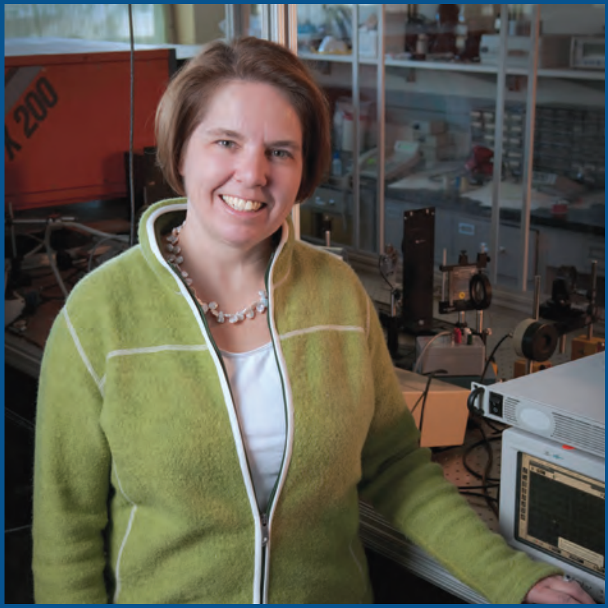
The Metrology for Advanced Communications programmatic area is the subject of the fourth chapter. Its activities are based in the Radio Frequency Technology (RF) and Wireless Networks (WN) Divisions. Major themes include Next-Generation 5G wireless communication, wireless channel sounding and modeling, over-the-air metrology, wireless coexistence metrology, spectrum sensing and monitoring, Citizens Broadband Radio Service, massive multiple-input, multiple-output (MIMO) measurement and modeling, and millimeter-wave circuit technologies.

Finally, Appendix A includes CTL's responses to the 2015 NRC Panel Recommendations. This section is divided into the following parts:

- Assessment of CTL
- Collaboration at the Boulder Telecommunications Laboratories
- National Telecommunication Research Needs and the Future Role of the Boulder Telecommunications Laboratories

CTL takes these prior recommendations seriously and has worked to strategically address each. CTL appreciates the NRC's review of our progress since 2015 and the opportunity to share the laboratory's more recent achievements and challenges.

A Message from the Director



On behalf of CTL, I would like to begin by expressing our gratitude for your participation on the panel for the 2019 NRC Review of the Communications Technology Laboratory (CTL) at NIST. Serving on this panel is time consuming and labor intensive. However, this review provides NIST with the critical insights into our laboratory that are greatly appreciated. Thank you for sharing your dedication and expertise with us through this assessment process.

CTL's mission is to advance the measurement science underlying communications technologies through dissemination of high-quality measurements, data, and research supporting U.S. innovation, industrial competitiveness, and public safety. In short, CTL serves as the national resource for metrology to support communications technology development and deployment. For this review, our work shall be divided into two main categories for your evaluation: Public Safety Communications and Metrology for Advanced Communications, which includes the following priority areas:

- Trusted Spectrum Testing
- Next Generation Wireless (5G and Beyond)
- Fundamental Metrology for Communications

The information provided in the following pages of this booklet, the presentations and tours we will provide, and discussions you will enjoy during your time here will illuminate CTL for you, and will enable you to meet the charge that Dr. Copan has given the panel for this review. CTL has made so much progress since its first NRC review in 2015. You will see the objectives, results, and progress of our world-class research programs. You will evaluate the impacts of our facilities, equipment, and scientific expertise as they are applied towards our priority areas. You will gain insights into the challenges we encounter and the opportunities we pursue. Finally, you will discover how we interface with stakeholders and how we share the results of our research with relevant communities to meet NIST's mission, which is, "to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life."

We are eager to share our laboratory with you and look forward to reading your evaluation of CTL and your recommendations for our future.

Sincerely,

Marla L. Dowell, Ph.D.

Director, Communications Technology Laboratory

OBJECTIVES, RESULTS, AND PROGRESS

CTL Communications Technology Laboratory

UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
Gaithersburg, Maryland 20899-
OFFICE OF THE DIRECTOR

MAR 1 4 2019

MEMORANDUM FOR Panel of the National Research Council Committee on National Institute of Standards and Technology Technical Programs

From: Walter G. Copan, Ph.D.
Under Secretary of Commerce for Standards and Technology &
Director, National Institute of Standards and Technology

Subject: Charge to the National Research Council Board on Assessment of the National Institute of Standards and Technology Communications Technology Laboratory in FY 2019

The National Institute of Standards and Technology (NIST) asks the National Research Council (NRC) to conduct an annual assessment involving review of a portion of the NIST laboratories by a panel of the Committee on NIST Technical Programs. For fiscal year (FY) 2019, NIST looks forward to the panel's review of the Communications Technology Laboratory (CTL). The assessment process will consist of a site visit by the panel, which will then draft a comprehensive report.

For the FY 2019 assessment cycle, I ask that the panel focus its assessment of this laboratory on the following factors:

1. Assess the organization's technical programs.
   - How does the quality of the research compare to similar world-class research in the technical program areas?
   - Is the quality of the technical programs adequate for the organization to reach its stated technical objectives? How could it be improved?
2. Assess the portfolio of scientific expertise within the organization.
   - Does the organization have world-class scientific expertise in the areas of the organization's mission and program objectives? If not, in what areas should it be improved?
   - How well does the organization's scientific expertise support the organization's technical programs and the organization's ability to achieve its stated objectives?

NIST

3. Assess the adequacy of the organization's facilities, equipment, and human resources.
    - How well do the facilities, equipment, and human resources support the organization's technical programs and its ability to achieve its stated objectives? How could they be improved?
4. Assess the effectiveness by which the organization disseminates its program outputs.
    - How well are the organization's research programs driven by stakeholder needs?
    - How effective are the dissemination methods and technology transfer mechanisms used by the organization? Are these mechanisms sufficiently comprehensive?
    - How well is the organization monitoring stakeholder use and impact of program outputs? How could this be improved?

The context of this technical assessment is NIST's mission, which is "to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life." The NIST laboratories conduct research to anticipate future metrology and standards needs, to enable new scientific and technological advances, and to improve and refine existing measurement methods and services.

We are extremely grateful to the members of the Committee on NIST Technical Programs and of its panels for the time, effort, and expertise they devote to evaluating the technical quality of NIST's laboratory programs. Your findings, communicated through your reports and meetings, are excellent vehicles for informing key stakeholders and are a central component of our performance evaluation system. The panel reviews help NIST remain a significant national asset as the world's leading measurement and standards organization and they are featured in our reports to the Administration and Congress. In assessing our laboratory programs, NIST highly values your hard work and insights, and as always, we look forward to working closely and productively with you in FY 2019.

CHAPTER 1: THE COMMUNICATIONS TECHNOLOGY LABORATORY

OVERVIEW

The Communications Technology Laboratory (CTL) was created in 2014 to address national needs and administration goals to revolutionize public safety communications and increase the nation's communications capacity. NIST's response to the administration's focus on communications is timely, placing NIST in a position to make an extraordinarily substantial impact in an atypically short time. The explosive societal demand for communications is driving new technologies and applications that have inherently complex measurement challenges and ensure a high-impact role for NIST for several decades.

Mission and Functional Statement

CTL 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. CTL staff conduct leading-edge research and development on measurement science and facilities underlying the physical phenomena, materials capabilities, and complex systems relevant to advanced communications.

CTL promotes the development and deployment of advanced communications technologies through dissemination of high-quality measurements, data, and research.

With expertise honed over decades of theoretical and experimental work in antennas and wireless propagation, materials science, and electronics measurement and testing, CTL serves as an independent, unbiased arbiter of trusted measurements and standards to government, industry, academia, and the public safety community. CTL overcomes resource limitations by leveraging its external partnerships, which bring strategic focus to its programs and maximize NIST's impacts in the communications technology space. Our external stakeholders help to ensure that our program outputs meet the measurement needs of the public safety community, federal agencies, and U.S. industry.

Overarching Goals

What do smartphones, radar, military and public-safety radios, satellite phones, mobile video, wearable devices, the Internet of Things, and smart vehicles have in common? They all depend on wireless spectrum. With insatiable demand from these and countless other wireless applications, there is an unprecedented crowding of the airwaves. This drives the development of increasingly sophisticated technologies and applications capable of transmitting and receiving signals at higher frequencies and in shared frequency bands.

CTL is at the forefront of this broad transformation. With input from its external stakeholders, CTL has identified four major priority areas: 1) Public Safety Communications, 2) Trusted Spectrum Testing, 3) Next Generation Wireless (5G and Beyond), and 4) Fundamental Metrology for Communications. These areas are united by NIST's overarching mission to advance fundamental measurement science in support for communications. CTL's fundamental research leverages advanced capabilities in photonics, atomic physics, complex circuit design and testing, and data science to develop the next generation of measurement infrastructure—from novel RF lasers, based on Rydberg atoms, to compact photonic channel sounders, for characterizing RF propagation in complex, highly reflective and electrically noisy manufacturing environments. CTL's capabilities result in economic benefits for the American public; many U.S. companies don't see profit incentive to conduct this resource-intensive measurement and fundamental research themselves. Instead, they look to CTL for guidance, data, and research techniques that enable them to bring better products and services to market faster.

ORGANIZATIONAL STRUCTURE

Established in 2014, the CTL organization is spread across the NIST Boulder and Gaithersburg campuses. CTL consists of four organizational units, depicted in Figure 1.

Public Safety Communications Research Division

Since 2002, NIST's Public Safety Communications Research Division (PSCR) has worked to drive innovation and advance public safety communication technologies through cutting-edge research and development (R&D). PSCR works directly with first responders and the telecommunications sector to enable public safety's urgent need to access broadband communications and state-of-the-art technologies that commercial network consumers now expect. As shown in Figure 2, PSCR has organized the division into Security and Lab Operations, Open Innovation, Technology Acceleration and Extramural Research, Research, Testing and Evaluation, Capabilities and Integration, and Administrative Support.

PUBLIC SAFETY COMMUNICATIONS RESEARCH DIVISION	RADIO FREQUENCY TECHNOLOGY DIVISION	WIRELESS NETWORKS DIVISION	NATIONAL ADVANCED SPECTRUM AND COMMUNICATIONS TEST NETWORK
DERECK ORR, CHIEF	PAUL HALE, CHIEF	NADA GOLMIE, CHIEF	MELISSA MIDZOR, PROGRAM MANAGER

Figure 1. CTL Laboratory organizational units. Cross-cutting metrology programs for advanced communications.

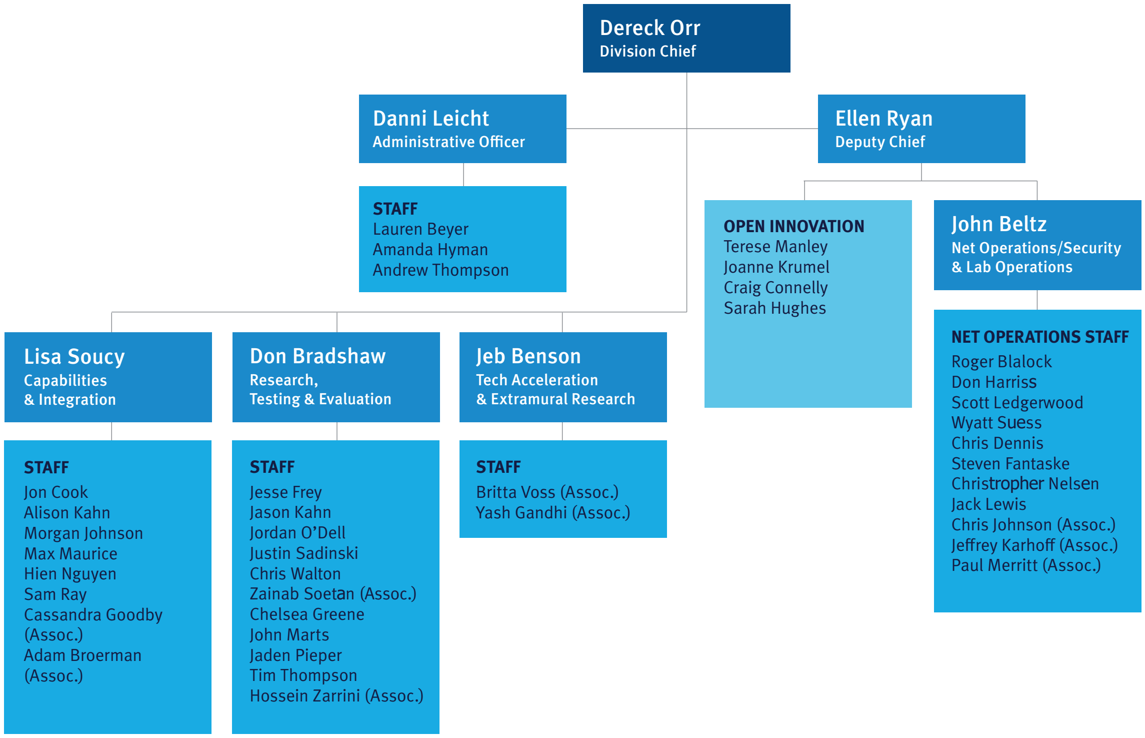


Figure 2. PSCR Organizational Chart

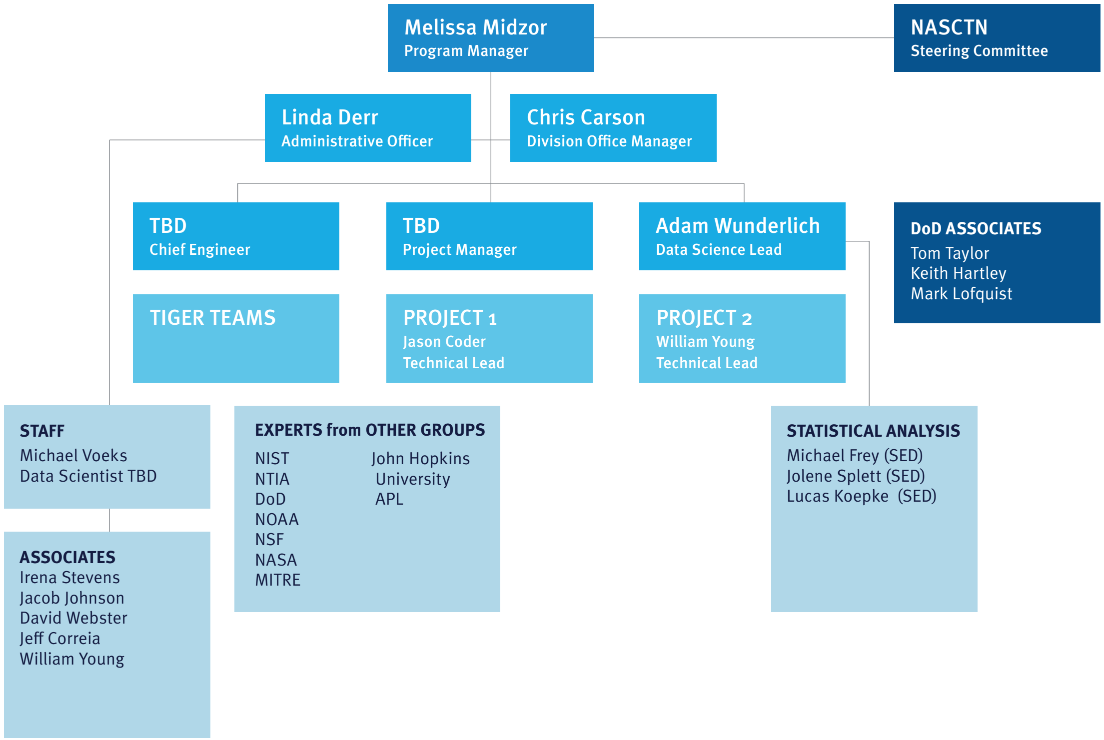


Figure 3. NASCTN Organizational Chart

National Advanced Spectrum and Communications Test Network

CTL also supports the National Advanced Spectrum and Communications Test Network (NASTCN), a network of government, academic, and commercial capabilities able to coordinate the use of intellectual capacity, modeling and simulation, laboratories, and test ranges to meet national spectrum interests and challenges. NASCTN was formally established by a Memorandum of Agreement (MOA), which was signed by NIST, the National Telecommunications Information Administration (NTIA), and the Department of Defense (DOD) in March of 2015. The NASCTN Charter, which defines NASCTN members' responsibilities and the NASCTN's governance structure, was signed by NIST, NTIA, and DOD in 2016.

Radio-Frequency Technology Division

NIST CTL's Radio Frequency (RF) Technology Division develops theory, metrology, and standards for the technologies upon which the future of wireless communications depends. The work spans on-chip measurements of the transistors that generate wireless signals; the testing of free-field signals and the antennas that send and receive them; and the characterization of the integrated circuits that receive and process signals. CTL's RF Technology Division tackles fundamental RF measurement problems applicable to a wide array of industry and government players.

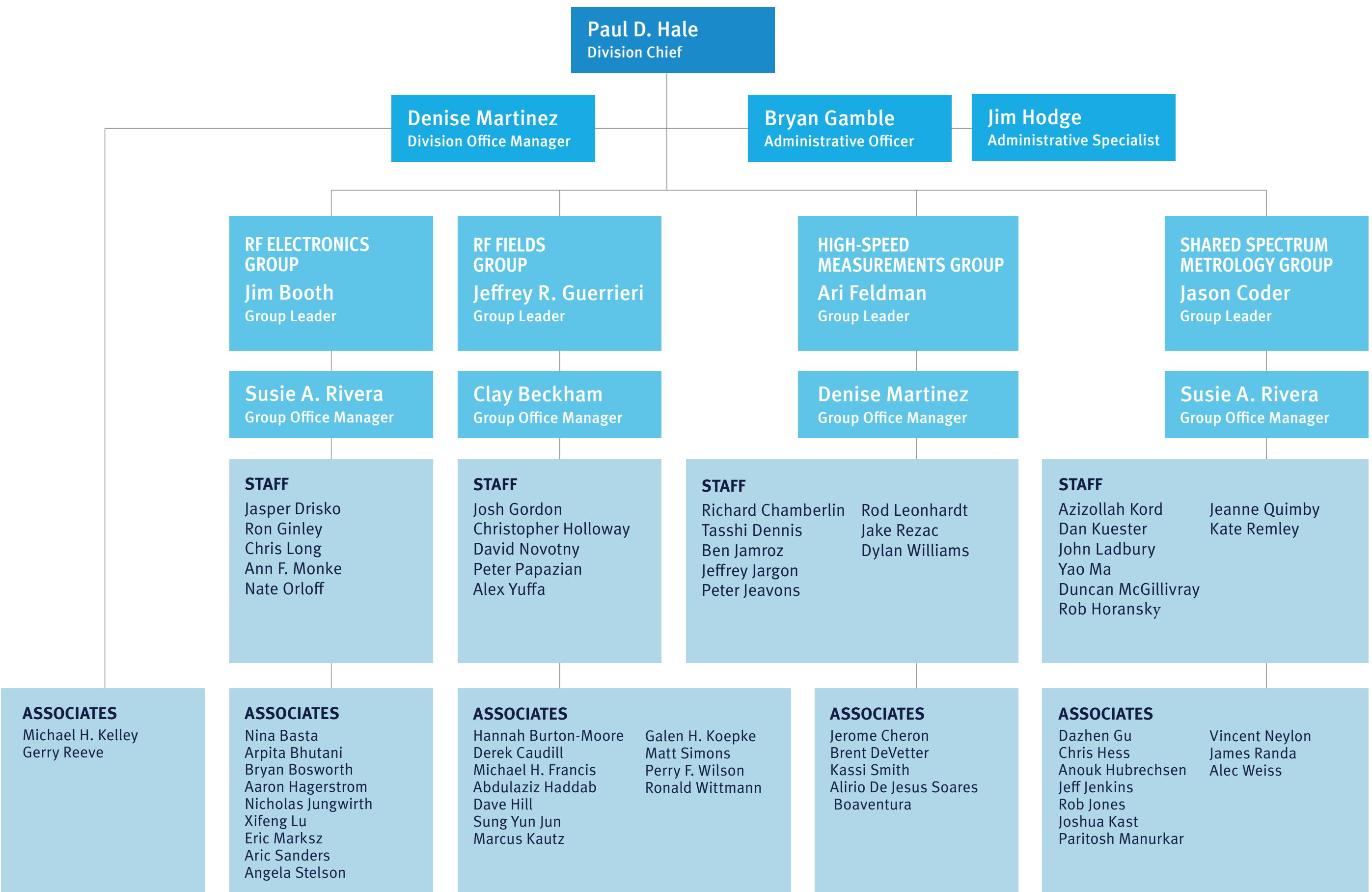
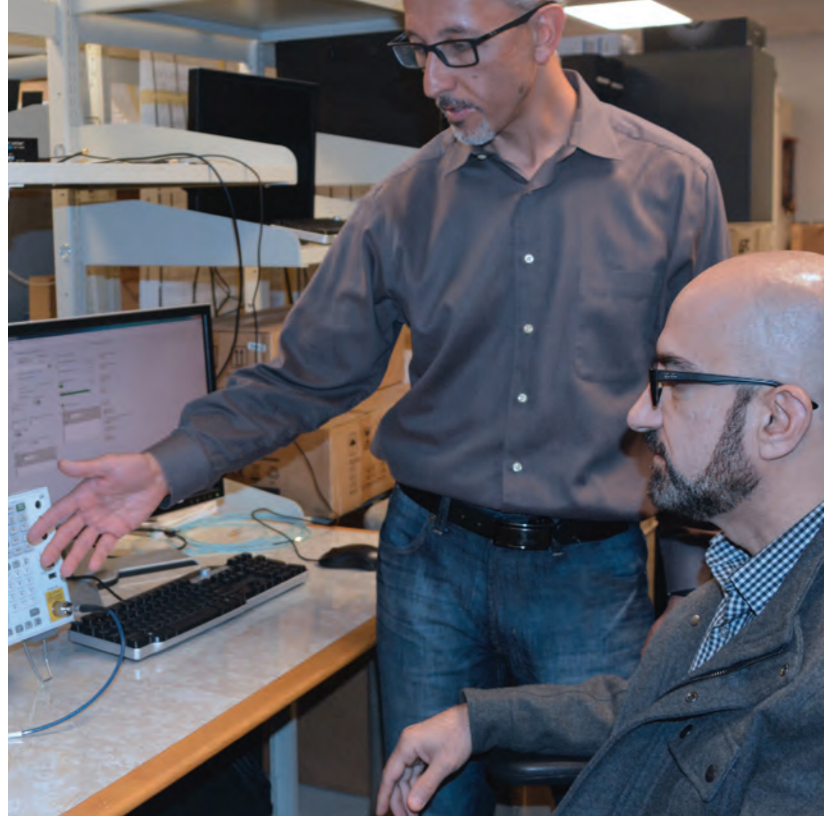


Figure 4.
RF Organizational Chart

Wireless Networks Division

NIST CTL's Wireless Networks Division works with industry to develop, deploy, and promote emerging technologies and standards that will dramatically improve the operation and use of wireless networks. The team, based at NIST's main campus in Gaithersburg, Maryland, specializes in the performance evaluation of communications networks and protocols and in the digital communications technologies that make those networks possible. As seen in Figure 5, this team has a diverse set of staff and associates working on these emerging technologies and standards.



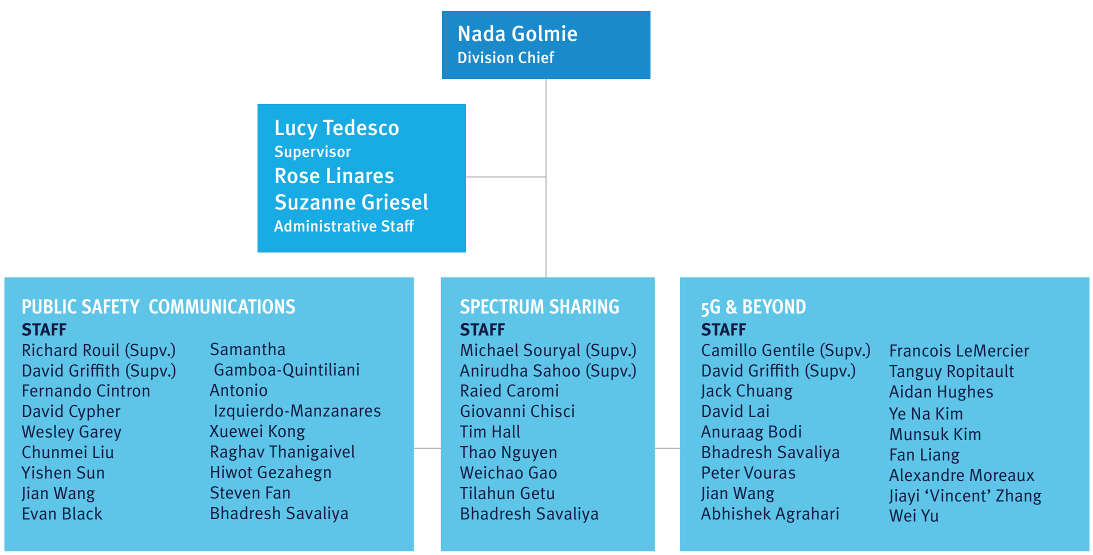
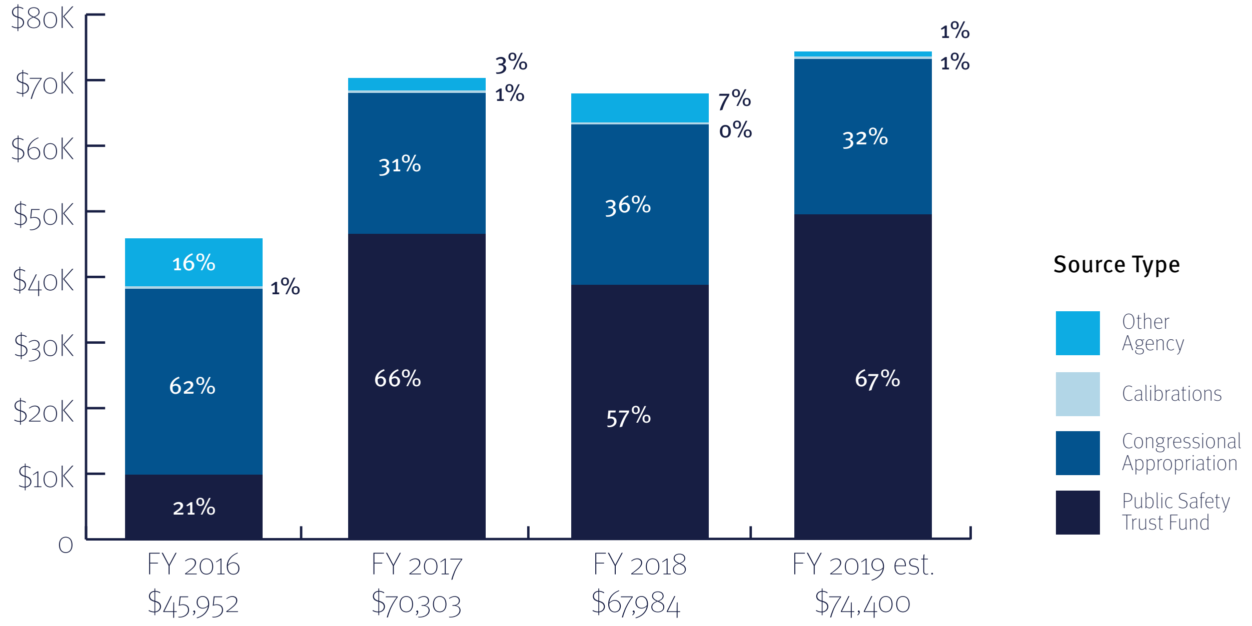


Figure 5.
WN Organizational Chart

BUDGET

CTL has an annual operating budget of approximately $70M, including funds received from the Public Safety Trust Fund (57%), Congressional appropriations (36%), other federal agencies (6%), and calibrations (1%). The table below shows the distribution of these funds over the past four fiscal years.



Public Safety Trust Funds

Public Safety Trust Funds are a federal appropriation resulting from the Middle Class Tax Relief and Job Creation Act of 2012, which mandated the auction of a portion of the United States frequency spectrum to private business. The proceeds from that sale supplied $300M to NIST to conduct research and assist with the development of standards, technologies, and applications to advance wireless public safety communications in support of the development and deployment of the National Public Safety Broadband Network (NPSBN). Although the legislation was passed in 2012, the first increment of funding from the auction became available to NIST in mid-FY16. PSCR expects to expend about $50M per year through FY22, when the program's period of funds availability ends.

NIST Appropriations

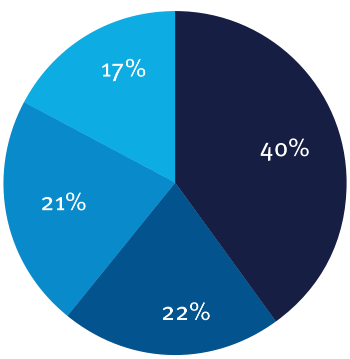
Congressional appropriations dedicated to advancing NIST's scientific mission are referred to as Scientific and Technical Research and Services (STRS). These funds support general research and operations across CTL, with approximately 40% directed to Congressionally approved budget initiatives. Examples of recent budget initiatives include: communications technology, forensic science, and advanced manufacturing.

External Funding

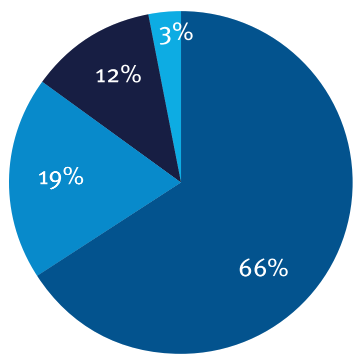
Calibrations makes up a small portion of CTL's overall effort. CTL performs calibration services on electromagnetic equipment for industry and federal partners such as the DOD. CTL is dedicated to developing the next generation of measurement techniques aimed at the characterization and measurement of electromagnetic waveforms, and expects these services to grow significantly in the next few fiscal years.

CTL is often called upon to provide measurement science support to other federal agencies. Examples of other agency work at CTL include public safety communications work for the Department of Homeland Security (DHS), waveform characterization for the DOD, and interference analysis testing for the Global Positioning System (GPS) operation, for which CTL received a Department of Commerce (DOC) Gold Medal, the highest honor within DOC. The massive growth of the communications industry, the need for more reliable wide-band data transfer, and continued movement to an Internet of Things (IoT) environment will stress the availability of assigned ranges within the frequency spectrum. NIST's role as an independent, impartial, and highly accomplished scientific test organization allows CTL to provide robust test processes and validated measurement data necessary to develop, evaluate, and deploy spectrum sharing technologies that can increase access to the crowded frequency spectrum by both federal agencies and non-federal users. CTL accepts funds from other agencies when it serves the combined purpose of assisting the other agency with a nationally-important problem while also advancing the NIST mission.

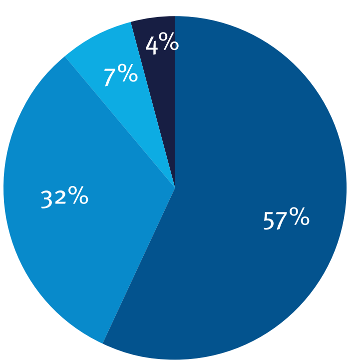
The following graphs detail CTL's annual funding sources since FY16 for Public Safety, STRS (NIST's appropriation dedicated to CTL), STRS Non-Base (NIST's appropriation to labs other than CTL subsequently sent to CTL to support collaboration between CTL and the funded lab), and other agency funding. The second set of graphs provide details about how CTL has distributed funding to each priority area since FY16. The funding shift from FY16 to FY19 for Public Safety will be discussed in greater detail in Chapter 2.



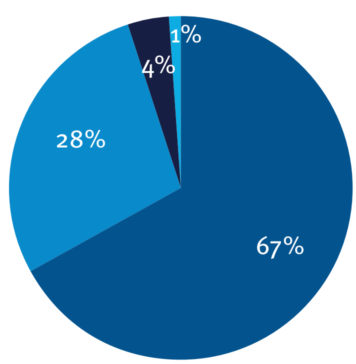
FY16 Budget ($46M)



FY17 Budget ($70.3M)

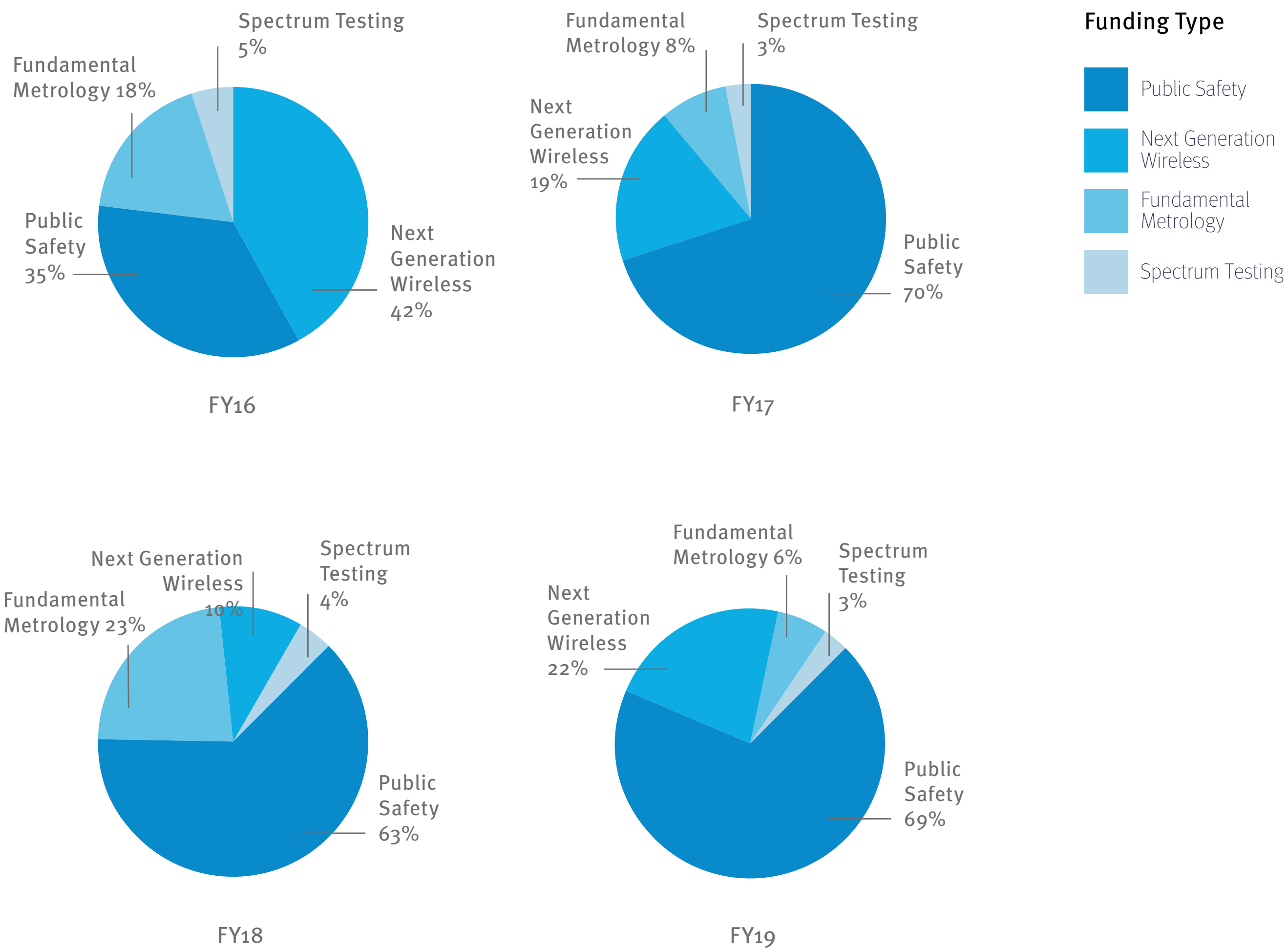


FY18 Budget ($68M)



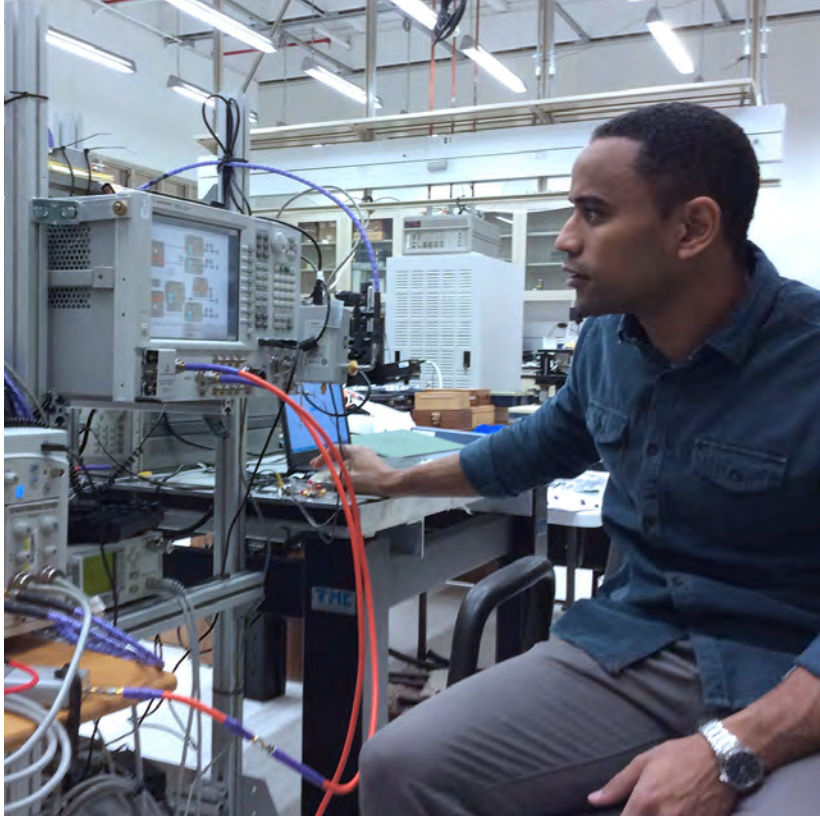
FY19 Budget ($74M)

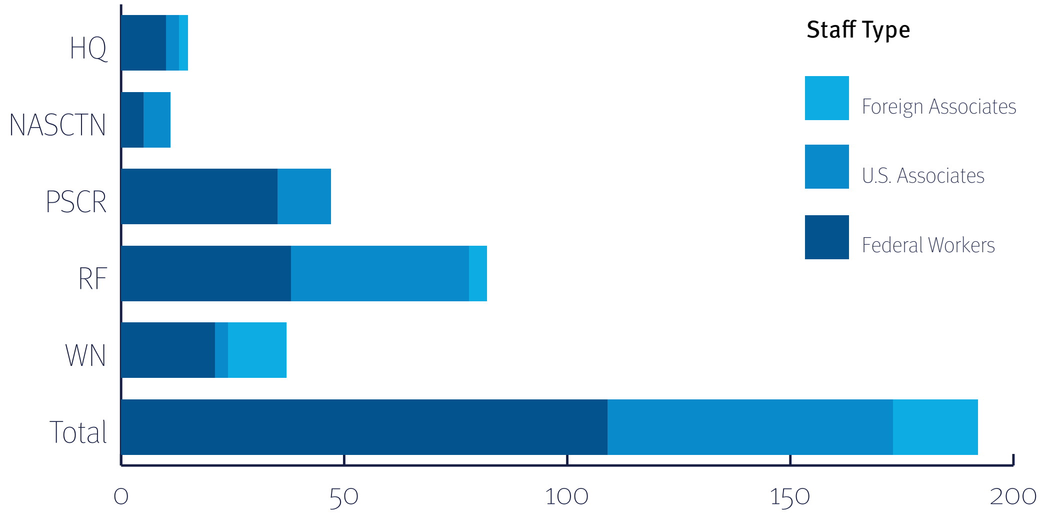
The graphs below provide details about how CTL has distributed funding to each priority area since FY16. The funding shift from FY16 to FY19 for the Public Safety Program Area will be discussed in greater detail in Chapter 2.



STAFFING

CTL staff represent a broad cross-section of the NIST staffing model. CTL relies on a mix of permanent and temporary staff to carry out its mission. Temporary staff include term-limited federal employees, contractors, guest researchers, postdoctoral fellows, and students. CTL serves as an incubator for early career professionals to become immersed in the metrology environment. Part of CTL's technology dissemination model is to ensure that temporary staff develop a sound foundational knowledge of measurement science that will help advance their careers. Staff development is undertaken through both formal and informal avenues. The majority of CTL permanent staff have participated in NIST Leadership Development Programs. Other mechanisms include formal classes at universities and conferences. The laboratory sponsors seminar series and mentorship opportunities.





STRATEGIC PLAN

In FY15, CTL undertook a lab-wide component programs assessment to identify the current state of the new organization, where the organization needed to go in the future, potential challenges to achieving success, and most importantly, what steps were required to set CTL up for sustained success.

ANNUAL PLANNING PROCESS

CTL prioritizes the application of resources by objective, rather than determining how much can be accomplished given a certain level of funding. Asking the important question, "What do you need to accomplish task x?" is a better approach than asking the question, "How much can you get done with $y?" This allows us to deliberately focus resources to meet program objectives.

The CTL strategic planning process for the upcoming fiscal year begins in the last quarter of the current fiscal year. Project leaders propose project plans that are adjusted at the division level to ensure resources are not overcommitted. Project plan goals are used to produce individual performance plans for the next fiscal year. Project leaders then formulate out-year goals and make adjustments to the previous year's long-range plan. The CTL leadership team meets to evaluate these plans (with input sought from project leaders and others) and provides feedback through Group Leaders. Project reviews comparing previous year's goals to results allow the CTL leadership team to make prioritization and funding decisions as the process progresses. From this information, CTL formulates group-level, and then division-level, long-range plans. Once fully vetted by the division chiefs, the plan is brought to the Organizational Unit (OU) director for approval. During this process, management typically selects areas that require additional support, such as labor and funding, and commits to meet those needs. Finally, the penultimate plan is posted on the CTL shared drive for staff accessibility.

LEVERAGING NIST INNOVATIONS IN MEASUREMENT SCIENCE PROGRAM

CTL leverages the NIST Innovations in Measurement Science (IMS) Program to provide seed funding for high-risk communications-related metrology programs. The purpose of the NIST IMS Program is to fund the most innovative, high-risk, and transformative measurement science ideas generated by NIST Laboratory staff. The impacts of selected IMS projects should be realized by stakeholders at NIST, industry, commercial labs, other federal agencies, or academia. Proposals must clearly indicate how the research and the project outcomes would support NIST's mission: "To promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life." In addition to the NIST IMS program criteria, CTL IMS proposals must also address a metrology gap in some aspect of communications technology in one of the CTL priority areas. CTL IMS proposals should position CTL to grow in areas that leverage the expertise of its existing programs to significantly impact the four NIST Strategic Focus Areas (Artificial Intelligence and Data, Internet of Things, Quantum SI, and Biological systems) as they are related to national communications needs.

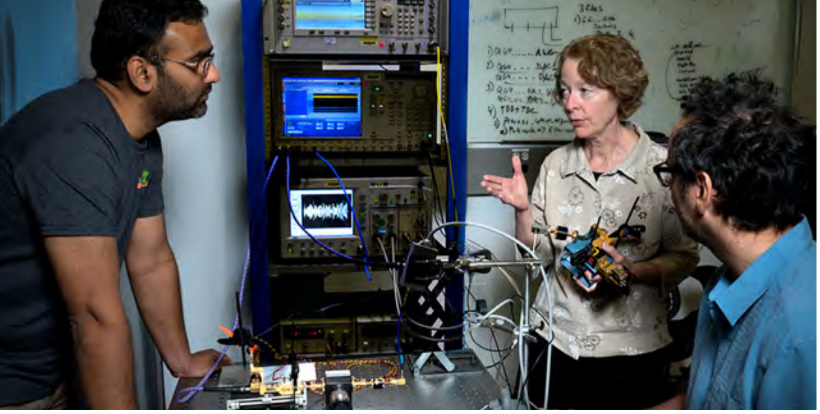
CTL has been very successful in leveraging the NIST IMS Program to initiate significant research programs over the past four years. These programs include:

1. Programmable waveform synthesizers with quantum-based accuracy for communications metrology, joint with the NIST Physical Measurement Laboratory (FY16)
2. DC to 1 THz Large-Amplitude Optoelectronic Multitone Electrical-Signal Synthesizer, joint with the NIST Physical Measurement Laboratory (FY18)
3. Establishing the S&T of networks for superconducting quantum computing, joint with the NIST Information Technology Laboratory and NIST Physical Measurement Laboratory (FY19)

Each of these programs represent a significant investment ($5M+) by NIST over a five-year period.

OUTPUTS AND TECHNOLOGY TRANSFER

CTL leverages multiple vehicles to aggressively disseminate CTL technology and support CTL programs. In addition to the more traditional patent, CRADA vehicles, and industry consortium, CTL utilizes grants and federal Prize and Challenge opportunities to stimulate private sector investment in communications technology issues.



Since 2014, CTL staff have published nearly 500 papers in prestigious journals such as IEEE Transactions series and Applied Physics Letters, Nature, and Nano Letters. Staff have disseminated their knowledge through more popular professional magazines, such as IEEE Communications Magazine, IEEE Antennas and Propagation Magazine, IEEE Microwave Magazine, IEEE Vehicular Technology Magazine, as well as conference presentations and industry workshops. CTL has been a driver for several industry R&D roadmaps for both Public Safety Communications and the often-cited Future Generation Wireless Research and Development Gaps Report. CTL continues to be active in these roadmapping and documentary standards efforts, including the IEEE “5G and beyond” roadmap working group, Wireless Innovation Forum, 3rd Generation Partnership Project (3GPP), and international committees comprised of staff from other national metrology institutes.

In 2018, CTL was awarded the Department of Commerce Silver Medal Award for leadership. The group is recognized for cross-organizational leadership of NIST’s first design-build project in a new, state-of-the-art facility for the Communications Technology Laboratory. The team expertly united construction, administrative, and scientific experts identifying facility requirements while creatively using resources to meet mission needs. The team flawlessly executed the project with painstaking attention to detail, resulting in a fully functional mission-oriented research facility approximately 1.5 years faster, and 39% savings over the traditional design-bid-build methodology.

In 2017, CTL staff were recognized with the Department of Commerce Gold Medal Award for their work on the impact of Long Term Evolution (LTE) signals on GPS receivers that resulted in rigorous measurands for assessing GPS receiver performance. CTL staff have also been recognized by professional societies and external organizations for their contributions.

CUSTOMER ENGAGEMENT AND PARTNERSHIPS

Communications technology is a critical enabling technology that crosses all federal agencies that need to share information internally and externally—from Navy radar systems, to broadband communications for first responders, to electric field measurements in healthcare environments. As a result, the Laboratory has strong relationships with support from DOD, DHS, NIH, NTIA, and others for its research programs. Our partners include the following:

Universities:

- Johns Hopkins University, University of Southern California, TU Eindhoven, Aveiro, University of Washington, University of San Diego, George Washington University, IMDEA Spain, Center Tecnologic de Telecommunications de Catalunya (CTTC) Spain

Industry:

- Telecom Infra Project (TIP), NIST 5G mmWave Channel Model Alliance, service providers (e.g., AT&T, Verizon, T-Mobile, Sprint), test and equipment manufacturers (e.g., Nokia, Qualcomm, National Instruments, Keysight, Samsung, Intel, Ball, Anritsu), emerging entrants (Google, Microsoft, Federated Wireless, Facebook)

Standards Development Organizations:

- 3GPP, IEC, IEEE 802, Wireless Innovation Forum Spectrum Sharing Committee

Professional Societies:

- IEEE, CTIA

Governmental Organizations:

- National Public Safety Telecommunications Council, DHS, DOD, FirstNet, NTIA, NIH, NASA, FCC

Cooperative Research and Development Agreements (CRADAs):

- 700 MHz Public Safety Broadband Demonstration Network (PSCR; includes over 75 companies and institutions)

Summary of Opportunities and Challenges

OPPORTUNITIES

Internet of Things

Applications of the Internet of Things (IoT) technologies are increasingly pervasive, changing the interactions with the world around us. CTL advances the networking, sensor, and analytical capabilities that will allow internet-connected IoT devices to effectively and securely share information through a variety of next generation network platforms. Near-term IoT commercialization opportunities represent a significant driver of economic growth for U.S. hardware manufacturers, communications operators, and providers of applications and services. One study estimates that IoT applications can offer a potential economic impact of $3.9 T – $11.1 T by 2025. There is a pressing need to address fundamental questions of security, connectivity, and interoperability of IoT systems, and to develop new ways to measure and understand systems performance while focusing on a diverse set of applications including those in industrial settings. CTL is uniquely positioned to provide measurements and research to support connectivity and interoperability of IoT systems. The adoption of new wireless communications technologies that enable millisecond or better sensing and control can allow manufacturers to leverage agility, flexibility, scalability, and cost savings that wireless IoT could provide, but is unattainable with current wireless technologies. Reliability, which is currently missing, is the key roadblock to the adoption of wireless IoT on the factory floor. Verified channel propagation measurements with uncertainties and compact propagation models are needed to design Industrial IoT (IIoT) systems that will adapt to the harsh, rapidly changing propagation environment and achieve the required latency and reliability. This opportunity will require coordination across both CTL and NIST to bring together the necessary communications instrumentation, modeling, and measurement expertise with comparable expertise in the industrial manufacturing environments. NIST has made a small step in that direction with the publication of its Guide to Industrial Wireless Systems Deployments (NIST Advanced Manufacturing Series 300-4).

Leveraging PSCR Open Innovation Model for other NIST Programs

As you will discover in Chapter 2, the ultimate goal for PSCR is to have a measurable impact on the products and services developed for public safety communications by increasing research capacity (developing new tools, platforms, and datasets for the R&D community supporting public safety use); developing disruptive research approaches, technical capabilities, and products; educating standards bodies on public safety's communications requirements; and training public safety users on the availability of new technologies and how to best leverage them in daily operations. PSCR sponsors a portfolio of research programs spanning four NIST Laboratories, including CTL. In this capacity, the Division is enabling the realization of FirstNet, a dedicated nationwide LTE broadband network for first responders. In a few short years, the PSCR Open Innovation (OI) Program has leveraged the resources of over 150 external organizations—including industry, academia, and public safety professionals—to accelerate the development of public safety communications technologies. There is an opportunity to expand this successful OI model to other NIST programs.

CHALLENGES

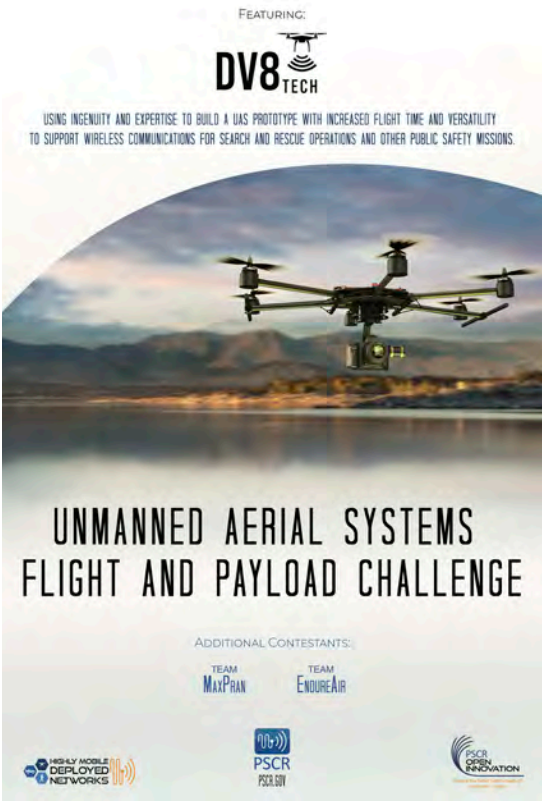
CTL faces a number of challenges related to the time-limited nature of its largest source of funding. First, is the need for neutrality in an ecosystem where policy decisions can have significant impact on business operations decisions. Second, is network infrastructure that relies on Category 3 cable (Cat 3 cable) dating back to the 1990's in some of its laboratories. This cable is more suitable for voice communication than the routing of Terabit-sized datafiles.

Expiring Public Safety Funds

CTL faces the operational challenges of ensuring a vibrant, sustainable research program once the funds from the Public Safety Trust Fund expire in 2022. Because of this funding expiration date, many of the current staff positions are temporary, either term-limited federal positions or associates, rather than permanent positions. Some term employees have departed NIST because the Laboratory cannot commit permanent slots without an increase in associated base funding for those positions. Moreover, the laboratory management structure is lean with most of the resources focused on laboratory bench activities to maximize the impact of CTL programs for external stakeholders. Therefore, CTL relies on other parts of the NIST organization to provide timely support—from procurements and hiring to topical news items to legal decisions on cooperative agreements and grants. Delays of even a few months can have serious impact on CTL's ability to execute its public safety obligations within the remaining four years left on the Public Safety Auction funds. In terms of executing research programs, the differences in these timelines may require CTL to significantly expedite the Public Safety Innovation Accelerator Program (PSIAP) to ensure timely execution of CTL priorities in public safety research.

Neutrality to Ensure Trusted Spectrum Testing

The NASCTN Program has been extremely successful in convening federal research organizations and facilities to serve as a neutral forum for design and deployment of spectrum-sharing technologies. This requires coordination amongst the NASCTN members. NASCTN's reports such as the NASCTN Impact of Aggregate LTE on GPS report have resulted in proposed changes to spectrum policies and brought intense scrutiny in turn. Therefore, it is critical that NASCTN maintains its neutral role that is independent of federal spectrum policy regulators and industry.



2018 Unmanned Aerial Systems Flight and Payload Challenge

One of the barriers for drone use in the public safety realm is payload versus flight time. In 2018, NIST launched the Unmanned Aerial Systems Flight and Payload Challenge to help address this challenge.

Team DV8 and nine (9) other participants used their ingenuity and hardware build expertise to create a UAS prototype and demonstrate flight capabilities! In the end, only (1) team accumulated the required 270 points to be eligible for an award, however, all teams displayed perseverance and innovation in their flight design and operation. Additionally, the teams who scored points in the final stage of the contest were invited to attend the 2018 Public Safety Broadband Stakeholder Meeting, where the final results were announced and presented. Congratulations to all of the contestants and their unique designs!

NIST Public Safety Communications Research Program launched this 3-stage challenge January 2018, with prize awards up to $432,000.00 (including travel and prototype builds) for the top 10 designs. In addition to cash prizes, the top 10 participants of stage 2 were given $20k to build a UAS prototype and, based on compliance with safety and flight requirements, they were offered paid travel to the finals. The final stage of the contest included three (3) UAS Challenge teams competing for a 1st place prize of $50,000.00. Each team flew their UAV (e.g. drone) at the R/C Club in Fredericksburg, VA, where we had 3 days of good weather for flying. The teams demonstrated their abilities based on the UAS Safety checks, Safety flights, positioning & accuracy tests, and payload flights. Each teams' UAS was required to lift a 10, 15, and 20 lb. payload and hover-in-place for the longest time possible. The finalists from stage 3 who scored points were additionally eligible to showcase their UAS at the 2018 PSCR Stakeholder Conference.

This competition was designed by NIST to support field operations for first responders. One of the barriers for UAS used in a public safety realm is payload versus flight time. Vertical takeoff and landing (VTOL) of a UAS provides many different mission capabilities, but their flight time is limited. The payload capacity, energy source and flight time are linked through design trade-offs that can be optimized for efficiency and flexibility. With these parameters in mind, this challenge was 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 $20k per UAS, this challenge shows first responders that there may someday be an affordable drone in their toolkit to carry wireless networks for search & rescue operations. PSCR is proud to continue its efforts to advance research in support of first responders!

Source: https://www.nist.gov/ctl/pscr/funding-opportunities/prizes-challenges/2018-unmanned-aerial-systems-flight-and-payload

NIST

CHAPTER 2: PUBLIC SAFETY COMMUNICATIONS

WELCOME AND INTRODUCTION

America's first responders deal with emergencies every day. Whether it is a routine traffic stop, a multi-alarm fire, or large-scale events such as hurricanes Harvey and Sandy, or the events of 9/11, the ability of first responders to communicate with each other—on-scene as well as through incident command—remains one of the most critical determinants of success for emergency response. The primary means of communication for first responders is Land Mobile Radio (LMR), a proven narrowband technology that is used for mission-critical voice communications; LMR is also known as "push a button to talk" technology. As of 2019, almost all information, such as changes in fire behavior, personnel and asset location, status updates, and weather conditions, are transmitted via these radios.

PUTTING TECHNOLOGY IN THE HANDS OF FIRST RESPONDERS

CTL imagines a world in which future technology—for example, highly deployable drones with autonomous flight controls—serve as communications hubs, allowing for not only voice communications, but location-mapping, video analytics, and real-time weather updates. CTL imagines that all of this information could be easily transmitted to first responders' broadband devices, such as smartphones, tablets, and heads-up displays. Putting this technology in the hands of first responders would help them assess emergency scenarios safely and smartly before sending in personnel, reduce harm to people and damage to property, and avoid unnecessary injury or death. CTL believes that innovative technologies can help and are working to accelerate their arrival.

CTL's Public Safety Communications Research Division is the primary federal research laboratory for public safety communications technologies and the headquarters of the CTL Public Safety Communications Research Program. PSCR's mission is to research and develop critical technologies and features identified by public safety entities so that these practitioners will soon have access to smarter and more effective life-saving technology. PSCR works closely with public safety, government, academic, and industry stakeholders through workshops and summits to publish R&D roadmaps that outline opportunities and challenges associated with integrating next generation communications technology with responder operations. PSCR leverages the data and relationships resulting from these roadmaps to develop targeted program strategies and project plans. PSCR also works closely with their federal partners—including FirstNet and DHS's Science and Technology Directorate and Office of Emergency Communications—to ensure effective coordination mechanisms are in place to support the shared public safety mission.

Working closely with, and with funding from the PSCR Division, the Wireless Networks Division (WN) has staff that focus on the development and performance evaluation of Mission-Critical Communications. WN provides the public safety community with the performance analysis tools needed to better understand emerging network technologies that may not be available yet for laboratory testing, facilitating its evaluation prior to deployment. In addition, the simulation and modeling capabilities are useful for the evaluation of worst- and best-case network deployment scenarios without the expense of deploying a large testbed. The outcome of these efforts is used to inform how well new technologies support public safety requirements, the development of quantitative requirements for public safety communications, and support the development of next generation network standards for public safety communication needs. The group has been actively participating and contributing to the 3GPP specifications development cycle, including the development of the requirements and technical specifications.

Mission and Functional Statement

The mission of the CTL Public Safety Communications Program is to accelerate the adoption and implementation of the most critical communications capabilities 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. CTL's PSCR Division supports this mission by leading research efforts across NIST and providing extramural research that delivers a clear, visible impact on the communications products and services developed for public safety.

STRUCTURE

CTL leverages both PSCR and WN capabilities, resources, and expertise for this priority area. PSCR conducts internal research across five key public safety technology areas: LMR to LTE, Mission Critical Voice (MCV), User Interface/User Experience (UI/UX), Location-Based Services (LBS), and Public Safety Analytics. In addition, PSCR performs research in two cross-cutting areas: Security and Resilient Systems. WN performs research in collaboration with, and with funding from, PSCR to support the MCV technology area.

STRATEGIC APPROACH

The CTL PSCR staff conducts internal research and leverages substantial resources into promoting the development of these technologies externally through grants, cooperative agreements, and Open Innovation Prize Challenges.

NIST was charged with developing and implementing a robust and impactful Public Safety Communications R&D plan as mandated in Section 6303 of the Middle Class Tax Relief and Job Creation Act of 2012. One component of that legislation charged NIST with conducting an R&D Program to help FirstNet and the public safety community design and implement a nationwide broadband network. With funding from the Public Safety Trust Fund, NIST set out to help the public safety community overcome critical technical barriers, spur innovation and investment in public safety broadband, and realize the full potential of wireless broadband capabilities. However, it was decided at an early stage that the funding available for Research, Development, Testing, and Evaluation

(RDT&E) is finite and must remain focused on the highest priority issues which provide benefits across public safety disciplines; the first of these high priority issues—1) LMR to LTE integration and eventual migration and 2) MCV over broadband—were written into the legislation.

PSCR has been performing research, development, testing and evaluation, and creating standards to support first responder communications since 2002. While Congressional funding for the CTL Program was legislated in 2012, the program—led by the PSCR Division—could not access the funds until 2016. However, the delay of funds did not prevent PSCR from strategically planning its use of the funding. In 2013, to facilitate the transition to broadband, PSCR initiated a public, transparent R&D planning process to determine what technology investments are of highest priority to the public safety community.

ROADMAP WORKING GROUP

PSCR hosted a Public Safety Broadband R&D Roadmap Workshop at the DOC Boulder Laboratories campus in Boulder, Colorado from November 13–15, 2013. Intended to provide an opportunity to envision public safety broadband R&D needs in the long-term (5–10 and beyond years out), the workshop was a highly interactive event, with participation limited to 150 people representing the public safety community, including: state, local, and federal partners; industry representatives; international organizations and associations; and academia.

During the workshop, participants extracted 238 new technology capabilities from the three public safety scenarios they were presented. Through the process of "bucketing" and organizing into technology layers, all 238 new technology capabilities were categorized into 34 buckets based on research or capability area; the 34 buckets are not mutually exclusive from an R&D perspective. Further analysis of the data showed that by conducting R&D on one bucket in the "Software/Applications" layer, many technology capabilities would be addressed to some extent in the Network and Device layers as well. Given the funding PSCR has had available for R&D, the cross-cutting approach to R&D allowed PSCR to maximize its impact and enhance future operational capabilities across multiple public safety disciplines. During the workshop, the participants were facilitated through a prioritization exercise, informed by investment criteria developed in partnership with FirstNet. Criteria included feasibility, leveragability, results/rewards, impact on public safety processes, uniqueness to public safety, cost of investment, and cost of ownership. The goal was to use these criteria to prioritize the research opportunities PSCR could pursue. PSCR later used this data to determine the following research/technology areas to pursue further: LBS, data analytics, and enhanced user interfaces (UIs).

Roadmap Publication

Following the workshop, PSCR sought to craft R&D roadmaps, which would gather more information about the top three technology areas identified. PSCR launched a market research effort to create a "best of breed" roadmapping framework, leveraging best practices from the public and private R&D sectors.

For each identified technology area, PSCR convened Roadmapping Working Groups made up of 30–60 relevant industry, academia, public safety, and government officials. Over the course of several months, PSCR hosted virtual Working Group meetings and leveraged a cloud-based Wiki platform to collaborate on an ongoing basis. PSCR compiled the Working Group's inputs into formal R&D roadmaps.

- The LBS R&D Roadmap was published in May 2015.
- The Public Safety Analytics R&D Roadmap was published in April 2016.
- The Enhanced UIs R&D Roadmap was published in April 2017.

Roadmap Summit

To socialize and validate the R&D roadmaps with more stakeholders, PSCR hosted two-day Roadmap Summits following the publication of each roadmap. The summits built on the findings of the roadmaps and determined the core technology challenges inhibiting public safety's use of that technology. The summits resulted in pared down lists of R&D focus areas which would align with the needs and requirements of public safety. Each of the focus areas were prioritized against PSCR's investment criteria, and attendees developed specific problem statements relating to the technology challenges within each area. To close the summits, attendees also described specific requirements, standards, measurement capabilities, and technology capabilities which needed to be developed if public safety intended to integrate new capabilities effectively into day-to-day operations. In addition, attendees brainstormed potential R&D project opportunities for any research organizations supporting public safety technology to consider in their own R&D programs.

- The LBS Summit was held in October 2015.
- The Public Safety Data Analytics Summit was held in August 2016.
- The Enhanced UI Summit was held in July 2017.

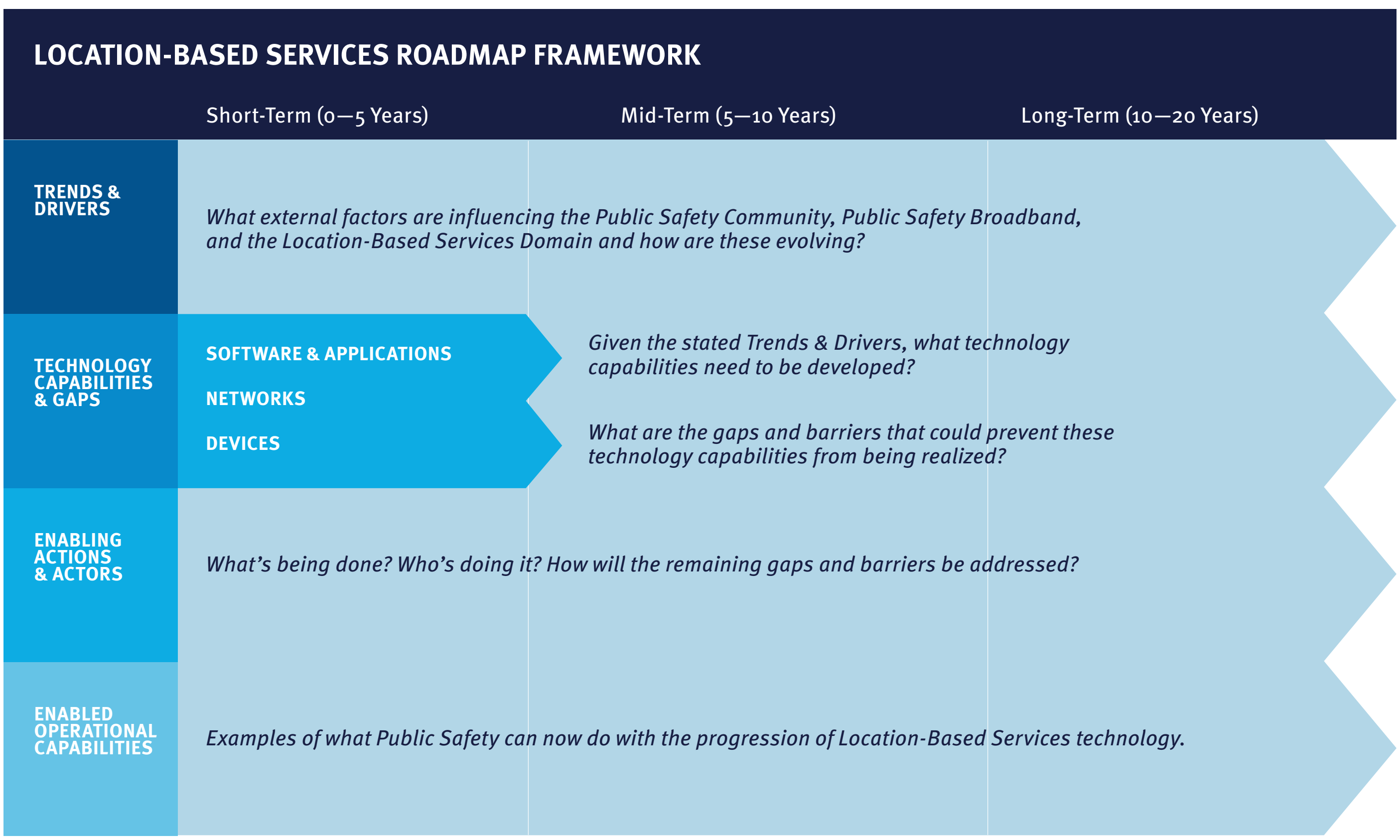
Summit Report

Following each R&D Summit, PSCR developed a Summit Report that documented the purpose, methodology, and outcomes for each technology area. The Summit Reports were used to inform PSCR research initiatives and provide crucial traceability back to public safety requirements and industry analysis.

The public safety roadmaps and summit data have guided the focus of the funding provided to PSCR from the Public Safety Trust Fund on the following critical areas:

Development of broadband requirements, standards, technologies, and applications for public safety, including:

- Mission Critical Voice over LTE
- LMR to LTE integration and eventual migration



Addressing R&D necessary for critical features identified by public safety entities beyond current generation of broadband technology, including:

- Location-Based Services
- Data Analytics
- Enhanced User Interface/User Experience

These areas became the five research portfolios which comprise PSCR's Division structure. The designated lead for each portfolio was charged with reviewing the potential R&D areas resulting from roadmapping and summit efforts, and weighing them against certain program criteria including time allotted, funding required, and redundancy with work from other agencies. This evaluation yielded the portfolio strategies and subsequent project plans. By 2016, identified projects per each portfolio were scoped and launched. At this time, portfolio leads planned efforts related to bespoke contracts, grants, and prize challenges.

The intended goals and outcomes for each of these R&D topics is as follows:

- PSCR will award one or more contracts/grants/prizes to address each topic and any existing technology gaps
- PSCR will create and publish measurement methods for each topic and potential solutions
- PSCR will be validated and demonstrate a viable solution (provided by contract awardees) for each topic area
- Public safety agencies can procure standards-based solutions that meet their needs for each topic area

Since 2016, CTL has worked on and funded research which ties back to roadmapping efforts, summit data, and division criteria fueled by public safety stakeholder insights. Each program area highlighted in this document outlines portfolio strategies, goals, and projects at a high level. Every quarter, the designated portfolio lead provides a status report to PSCR leadership on the progress of the respective portfolio's projects.

PSCR's success framework and key performance indicators (KPIs) are described in the Outputs section of this document.

STAFFING

Staffing for the Public Safety Communications program area consists of full time and part time staff from both the PSCR and WN Divisions.

FACILITIES UPDATE

In early 2018, CTL moved to the newly renovated Building 3 on the Boulder campus. This new facility enabled PSCR to build the new PSCR Innovation Laboratory with the goal of developing next generation communication capabilities for first responders. The PSCR lab maintains a 40-gigabit core network with high-density virtual servers that host an Evolved Packet Core (EPC) and an IP Multimedia System (IMS). The EPC establishes voice and data connections between a variety of user devices, while the IMS delivers streaming media content to the network. PSCR duplicated live telecommunications air traffic using base stations (eNodeBs) from multiple vendors and load testing simulators to generate heavy call traffic like that experienced during a crisis situation. The lab includes two RF chambers that provide an isolated environment to test Band 14 devices. The remote Green Mountain tower network extension allows testing of P25 phase 1 and 2 as well as interoperability testing between 700MHz LMR and LTE networks. Outside of the lab's core network, PSCR tests multiple rapidly deployable networks including aerial drone-based systems, which achieve portable communication technology in remote areas. A dedicated area for virtual (VR) and augmented reality (AR) development allows PSCR to test how innovative UIs can assist first responders in realistic emergency scenarios. The lab hosts frequent high profile visitors, conducting tours and demos on critical communications research areas. The PSCR Innovation Laboratory is fully equipped to enhance tomorrow's public safety leading-edge communication capabilities.

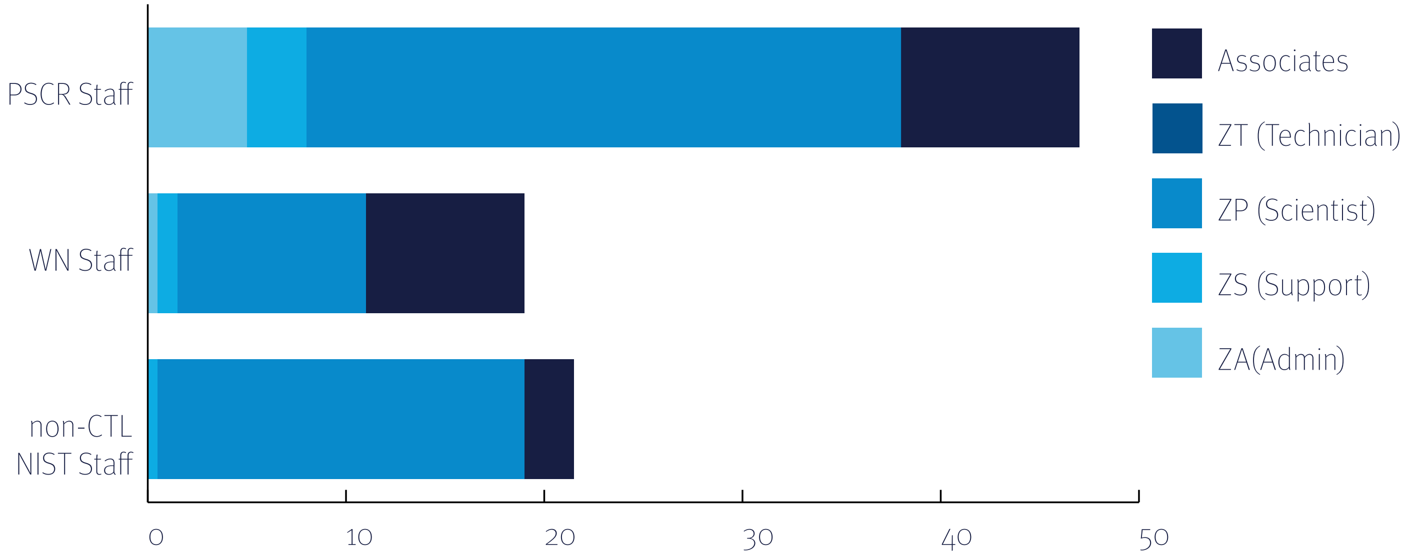
In late 2018, PSCR acquired a Mobile Research Vehicle for conducting static and mobile research activities for the public safety community both in the Denver/Boulder metro area and nationwide. This vehicle, a heavily modified cargo van, is outfitted with a 20-foot extendable mast and roof mount points for antennas, 8-kilowatt generators, rack space for equipment, and a user workspace. This flexible platform provides the capability to conduct scientific radio-frequency and communications systems measurements across the MCV portfolio and provide a mobile laboratory for all PSCR portfolios.

RESEARCH AREAS

While organizations like 3GPP and IEEE 802 offer unprecedented capabilities that have the potential to improve the effectiveness of first responders, Public Safety Communication Program efforts are aimed at evaluating whether or not those emerging solutions meet current public safety needs, and what improvements are necessary to meet future needs. The CTL Public Safety Communication Program also provides the public safety community with the performance analysis tools needed to better understand emerging technologies and facilitate the evaluation of network deployment scenarios, investigation of how well new technologies support public safety requirements, develop quantitative requirements for public safety communications, and develop next generation network standards in support of public safety communication needs.

LMR to LTE

The purpose of the LMR to LTE research area is to ensure voice interoperability between current land mobile radios and new broadband devices for the period of time that these two technologies will coexist. This research area is critical to the success of public safety broadband networks. Current efforts by PSCR include building an open-source, low-cost prototype LMR radio layer to 3GPP interworking function (IWF)/application server (AS) interface; PSCR is currently the only entity doing this work. PSCR gets feedback on this R&D from first responders via the DHS Advanced Technology Working Group. Ultimately, PSCR aims to involve industry stakeholders to make the technology affordable and available to public safety units across the country.



Mission Critical Voice (MCV)

Ever-increasing operational demands on first responders, along with new technological opportunities and capabilities, are driving Public Safety Organizations (PSO) to adopt broadband technologies, such as LTE for mission critical data. While access to broadband data is improving public safety operations and providing new applications, voice remains the most critical communications capability. However, a true MCV capability has yet to be deployed on any LTE network. An operational MCV capability includes many key functions, and successful implementation using LTE will require incorporation of a broad set of technologies, some of which are new or developing. Based on the standards landscape, industry roadmaps, and potential impact to public safety, PSCR will focus on three key areas for further R&D: mission critical push-to-talk, direct mode operations, and group communications. All three of these areas will be measured by MCV Quality of Experience (QoE) and KPIs, currently under development. Recent laboratory achievements in MCV include developing mission-critical voice measurement methods which will allow public safety entities and industry to compare LMR with broadband, so as to determine when and if transition to broadband is possible for voice communications.

MCV PORTFOLIO MISSION:

To advance the availability and performance of mission critical voice, forge partnerships to expand their sphere of research with well-qualified universities and agencies, and be influential in the standards community by participating in regular 3GPP events.

MCV PORTFOLIO VISION:

PSCR, through its research and encouragement of exploration in the area of Mission Critical Voice, will be seen as a trustworthy leader by the public safety community in regards to their voice communication needs as LTE technology becomes ubiquitous for public safety use and beyond.

With funding from the PSCR Division, WN plays an important role in the MCV portfolio by conducting research in several key areas such as Device to Device (D2D) Communication, Mission Critical Push to Talk (MCPTT), and QoS, Priority and Preemption (QPP). D2D communications in support of MCPTT and the ability for public safety personnel to communicate in situations where the coverage provided by the network infrastructure (i.e. cell towers) may be missing or insufficient. This feature is added to the LTE standards starting with Release 12 via the Proximity Services (ProSe). Mission Critical Push-To-Talk (MCPTT) was introduced in 3GPP Release 13. Using modeling and simulation, PSCR and WN are able to verify the protocols' correctness and optimize parameter configurations to ensure that the solutions will deliver the best possible performance for first responders.

Location-Based Services (LBS)

The ability to locate, track, and inform first responders while indoors under difficult conditions remains an important question to be answered on behalf of the public safety community. Law enforcement officers enter buildings every day, often alone and in peril, without the benefits of indoor tracking. Firefighters continue to die or become seriously injured each year because they are lost, disoriented, or difficult to locate in emergency situations. Therefore, the focus of the LBS portfolio involves advancing location-based services for personnel and assets, especially inside of buildings.

LBS PORTFOLIO MISSION:

Advance and demonstrate that indoor mapping, tracking, and navigation capabilities that first responders can depend on are within reach.

LBS PORTFOLIO VISION:

Position PSCR to transition the innovative technologies, approaches, and research capacity created in this portfolio to products, standards, and public safety systems.

One of the most recent projects in LBS involves using state-of-the-art laser technology to quickly and easily map and develop three-dimensional models of buildings for the creation of enhanced maps and location tracking for responders. This is possible using Light Detection and Ranging technology, (LiDAR), to produce point clouds.

Point clouds are a collection of spatial 3D data points defined by a given coordinates system (typically x,y,z coordinates). A point cloud is made up of tiny data points in the three-dimension world to ultimately reflect a physical space. They are collection from a scanner, e.g. LiDAR in a 3D coordinate system, and used to create 3D models such as architecture or VR applications. PSCR awarded three applicants to the Public Safety Innovation Accelerator Program (PSIAP) Point Cloud City funding opportunity totaling over $750,000.

User Interface/User Experience (UI/UX)

The UI/UX portfolio strives for first responders to have interfaces designed around their specific context, tasks, and requirements—faster than ever before. Therefore, researching advanced UIs for their ability to access and transmit complex information is the focus of this program area.

Historically, UI design has been broad in nature and rarely targeted for the public safety community. Technology specific to the various specialties did not take into consideration the context of use and the environment presented. For public safety to complete operations successfully, they must have the ability to efficiently and effectively complete their tasks with minimum impediment from technology.

In 2013, PSCR drove the roadmapping effort that identified UI/UX as a priority research area for PSCR. UI, as defined in the UI/UX Technology Roadmap, is "the means by which a user and a technology system interact; including how users input, access, and navigate data and communications through the technology." Some examples of UIs are haptic feedback mechanisms (e.g., sound, vibration), vocal commands, and visual indicators (e.g., heads-up displays). To deliver success within the UI/UX Portfolio, the following is necessary: a sound understanding of the user, the user's requirements, and the inherent features that make a system usable. In late 2018, PSCR began fielding a research study on the subject of usability among first responders.

Also in 2018, the UI/UX portfolio created the VR Test Environment to measure the impact of future UIs on public safety operations. The purpose of the PSCR VR Environment is to provide quantitative measurements of key performance indicators for first responders and technology developers to create next generation UIs. The goal is to spur industry to come up with UIs—visual indicators, sounds, voice commands—that are better, cheaper, proven effective, and brought to market faster than otherwise would be possible. Such interfaces could be embedded in firefighters' masks or smart glasses worn by emergency medical technicians, for example. In working with PSCR's Open Innovation team, UI/UX also launched and completed a VR Heads Up Display (HUD) prize challenge competition in 2018. The top six teams presented their designs in live-judging at the 2018 Public Safety Broadband Stakeholder Meeting, and were awarded over $85K. In 2019, UI/UX researchers incorporated public safety stakeholder feedback and created a more realistic VR environment. Subsequently, the team developed a prize challenge competition for fire, police, and Emergency Medical Services (EMS) scenarios using haptic interfaces. Other 2019 research projects include a lip-reading analysis and secure image-tampering prevention contest.

UI/UX PORTFOLIO MISSION:

Work with the public safety community, stakeholders, and vendors to create an environment that encourages industry to develop reliable, intuitive, and mission-focused technology for the public safety community.

UI/UX PORTFOLIO VISION:

Enhance the ability of the public safety user to effectively interact with, and obtain information from, the system. Ensure public safety devices are designed around operational needs through innovation and collaboration with industry and the public safety community.

Public Safety Analytics

Analytics was identified as one of the key areas for R&D investment by first responders, government officials, industry leaders, and academics who participated in the strategic planning effort initiated by PSCR in 2013. Public Safety Analytics was explored in depth in the Analytics Roadmap in 2015, the Video Analytics in Public Safety Workshop in 2016, and the PSCR Analytics Summit in 2016. The area of analytics is extremely broad—spanning a variety of technologies and uses, and affecting the entire public safety communications workflow.

Analytics imply processes to transform data into actionable information that can support decision making or knowledge discovery. The data utilized by analytics can be in the form of unstructured signals, structured databases, information flows, and combinations therein. Analytic technologies can be implemented in specific components of workflows or end-to-end systems. One doesn't typically think of capture, encoding, and compression as being an analytic, but these include analytic transformations of data into actionable forms. Emerging communications technologies employ both structural and semantic analyses in the capture and encoding process itself.

For the public safety community to reach its full potential, analytics must be seamlessly woven into the fabric of the network to optimize the flow of information through it. Analytics will be leveraged not only to increase knowledge, but to optimize the flow of information while conserving bandwidth by leveraging context, need, and an understanding of semantic redundancy.

The overarching goal of this effort is to foster the creation of both communities and technologies to fully utilize the power of state-of-the-art analytics to provide both real-time and forensic information to both first responders and public safety operations centers. Analytics will provide real-time situation awareness by creating an integrated understanding of both time and space from a variety of forms of video, first-responder communications, social media, sensor data, and data from connected devices. Therefore, the intent of this research area is to promote analytics tools that will help public safety organizations make use of the large amounts of data becoming available.

PUBLIC SAFETY ANALYTICS PORTFOLIO MISSION:

To support the growth of critical mass in public-safety-focused analytics R&D and critical enabling standards that will enable a robust and state-of-the-art public safety communications analytics ecosystem.

PUBLIC SAFETY ANALYTICS PORTFOLIO VISION:

A robust and affordable public safety communications ecosystem incorporating the state-of-art in analytic technologies that are accurate, effective, dependable, customizable, secure, and usable.

Security

Cybersecurity is an area which will affect every aspect of public safety communications. A cross-cutting research area at PSCR, the Security Portfolio has three, often overlapping roles: research network security (DemoNet), security-specific research projects, and security services for all internal PSCR research projects. This portfolio is influential, as security is important to every research area at PSCR.

With roots in NIST's Information Technology Lab (ITL), the Security Portfolio at PSCR leverages the expertise of ITL while focusing on the critical needs for trust in public safety communications technologies. A key output of this focus is documenting security best practices, policies, and procedures for public safety use cases; a recent example includes PSCR Security's 2018 publication, "Security Analysis of First Responder Mobile and Wearable Devices."

To move from traditional security research into innovation, the Security Portfolio funds public safety security projects at the National Cybersecurity Center of Excellence (NCCoE), where partnering with vendors offering commercial off-the-shelf (COTS) products makes application and testing of innovative solutions possible. Investment in ITL and NCCoE enables the development of innovative solutions that could be rapidly replicated by public safety and government while enhancing the knowledge of public safety stakeholders on important security topics.

While security for public safety is necessary, it is important to recognize that the benefits security must offer first responders is distinct from other groups and sectors. Traditionally, security procedures add a layer of complexity or inconvenience to users. However, for public safety operations to be completed efficiently and effectively, convenience and ease of functionality is of utmost importance.

Ultimately, PSCR serves to develop and enhance security solutions to current and future public safety communications. For PSCR to fully address concerns around interoperability, a key component of security must be realized: federated Identity Credential and Access Management (ICAM) and enhanced authentication. For this reason, PSCR's Security Team is focusing on this research area for the next three years, inclusive of network and mobile device security research.

In addition, in 2019, the Security Portfolio launched the "Expanding the SIM Card Use for Public Safety" prize challenge.

SECURITY PORTFOLIO MISSION:

To enable the public safety community to securely and effectively conduct their operations and accomplish their missions by leveraging superior technology and standards for all aspects of communications including network, devices, peripherals, applications, and user interface.

SECURITY PORTFOLIO VISION:

To serve as a leading communications research lab enhancing public safety's cybersecurity and success through innovation and collaboration.

Resilient Systems

The transition to cellular-based mobile networks will provide first responders with significantly more data than ever before and access to the smartphone and mobile web capabilities that commercial and private users take for granted.

However, emergency response services have more stringent requirements than typical users. They must respond to events in areas with little or no fixed cellular capacity, in remote environments where backhaul to the Internet or cellular core is limited or non-existent, and in coverage holes within generally well-provisioned areas. They must also continue to function—and are perhaps most needed—in disasters or other adverse circumstances where communication infrastructure is degraded or destroyed. Current networks, services, and applications are typically not designed to function under those circumstances. They are assumed to be sufficiently uncommon, and users are assumed to be willing to accept outages; it is expected that the necessary design and engineering effort required to support these users will not be made.

Emergency services need not be forced to choose between the reliability of their existing LMR systems and the new capabilities of mobile broadband data systems. Technological developments in the decades since the advent of mobile telephony, the Internet, and LMR provide the necessary building blocks for networks and applications which are both resilient and high-performance. Therefore, the purpose of PSCR Resilient Systems project is to develop, evaluate, and evangelize tools and techniques for architecting efficient, resilient networks and applications for public safety.

Related to this portfolio is the highly mobile deployable network (HMDN) project. The goal of this project is to ensure continuity of functionality in "challenged" networks, and rapidly-deployed, limited-backhaul networks are an excellent example of such challenges. However, the Resilient Systems project is also interested in fixed infrastructure networks that become compromised (especially due to loss of backhaul, internet, or EPC components), and in D2D and off-network situations.

RESILIENT SYSTEMS PORTFOLIO MISSION:

To develop, evaluate, and evangelize tools and techniques for architecting efficient, resilient networks and applications for public safety.

RESILIENT SYSTEMS PORTFOLIO VISION:

For public safety personnel networks and applications to continue to function in disasters or other adverse circumstances where communication infrastructure is degraded or destroyed.

EXTRAMURAL FUNDING

Innovation Accelerator:

Public Safety Innovation Accelerator Program (PSIAP)

The PSIAP utilizes grants and cooperative agreements to stimulate critical, external R&D for public safety communications technology, and provides access to cutting-edge technologies and applications that will enable responders to better carry out their missions to protect lives and property. As part of this effort, PSCR continues to leverage public safety, government, academia, and industry to identify innovation opportunities which will foster technology advancements for public safety communications.

To date, PSCR has awarded over $52M to 46 recipients in grants and cooperative agreements across its priority research areas. Research updates are reported quarterly to Federal Program Officers (FPOs), and award recipients present their yearly research updates during PSCR's annual Public Safety Broadband Stakeholder Meeting. Representatives from public safety, federal agencies, industry, and academia gather at this event to convene on testing updates, upcoming R&D efforts, and opportunities to get involved.

Open Innovation (OI)

PSCR's OI program represents another funding source for external research, executed through the management of prize challenge competitions under Section 105 of the America COMPETES Reauthorization Act of 2010 (Pub. L. No 111-358), as codified in 15 U.S.C. § 3719. This program leverages financial awards and incentive-based activities to solve discrete and well-defined communications problems for public safety using the following mechanisms: Crowdsourcing, Prize & Challenge Competitions, Hack-a-thons, Data Jams, Ideation, Collaborative Iteration & Design, and Team-building Activities. PSCR's OI team focuses on advancing public safety communications by leveraging the expertise and innovative solutions from a diverse array of contributors and collaborators across the globe. Their mission is to create a framework which enables work with individuals, companies, organizations, and academic institutes in more rapid, more collaborative ways than traditional procurements.

Since 2017, PSCR has awarded $560,500 in cash prizes and $55,500 in non-cash prizes. In 2018, PSCR launched and completed its first two technology-based prize challenges. These challenges were focused on the use of drones for expanding network coverage and on using VR to develop effective in-building navigation interfaces for future heads-up-displays. Through these challenges, PSCR has engaged with innovators from all walks of life and has enabled companies and partnerships to form. PSCR believes that encouraging these open partnerships between public safety, private industry, and academic institutions is strengthening the pace of—and passion for—delivering tangible solutions. Never before have there been so many people focused on communications technology R&D beneficial to America's first responders.

In 2019, PSCR's OI team is launching the largest NIST prize challenge to date, "The Tech to Protect Challenge: Coding for Emergency Responders." This nationwide innovation contest features ten discrete problem statements designed to develop new, creative technologies to address issues faced by fire, law enforcement, and EMS. The participant-proposed solutions will support first responders' use of advanced communications technologies in accomplishing their day-to-day activities, critical responsibilities in emergencies, and beyond. PSCR anticipates awarding up to $2.2M in cash prizes.

OUTPUTS

A Diverse Group of Stakeholders

The Middle Class Tax Relief and Job Creation Act of 2012 mandates that NIST convene working groups of "relevant government and commercial parties" to achieve the necessary technology requirements for first responders, with input from public safety. Prior to this mandate, and before PSCR became an official division of NIST, the PSCR program convened public safety stakeholders from across sectors to address the critical needs and requirements of first responder technologies.

Since 2010, PSCR has hosted an annual Public Safety Broadband Stakeholder Meeting which brings together representatives from public safety, federal agencies, industry, and academia. Participants hear from PSCR engineers about testing updates, upcoming R&D efforts, and opportunities to get involved. The annual Stakeholder Meeting enables PSCR to receive direct input, guidance, and feedback from their diverse stakeholder community.

Since its inception, the Stakeholder Meeting has grown significantly—from roughly 50 attendees in 2010 to over 500 in 2018. Moreover, this growing community has diversified over the years as well; at the most recent headcount, the Stakeholder Meeting saw an attendee breakdown of 36% private industry, 24% public safety/state and local, 23% federal government employees, and 17% academia. The cross-pollination between groups during the event has benefitted PSCR's research progress, partnerships, and outcomes.

Technology Roadmaps

Between 2015 and 2018, PSCR developed Technology Roadmaps to guide its R&D into several key research areas identified by first responders. Each new roadmap offers a vision of what public safety communications might look like in 20 years. It identifies software, device and network R&D investments needed to achieve that vision. The roadmaps point out opportunities for action by multiple stakeholders, including federal, state and local governments; academia; industry; and the public safety community.

- Highly Mobile Deployed Networks R&D Summit Report (February 2018)
- Public Safety User Interface R&D Roadmap (April 2017)
- Public Safety Analytics R&D Roadmap (April 2016)
- Location-Based Services R&D Roadmap (May 2015)

Stakeholder Tools and Resources

PSCR hosts roundtables and workshops which also yield outcomes beneficial to the wider public safety community. Reports have been made available via PSCR's website for the following information:

- Public Safety User Interface R&D
- Video Analytics in Public Safety
- Identifying and Categorizing Data Types for Public Safety Mobile Applications
- Public Safety Mobile Application Security Requirements
- Highly Mobile Deployed Networks Use Cases

In addition, PSCR efforts have resulted in certain tools for the public safety community. In late 2018, PSCR released the LTE Coverage Tool application and Software Development Kit (SDK), which enables first responders and public safety personnel to survey and evaluate coverage by LTE networks in environments where incidents are ongoing or planned. The DHS-sponsored research found that non-experts could quickly master the operation of this system to measure general LTE coverage quality using a standard smartphone. The tool was also made available on Android.

New Research Lanes

A notable outcome for PSCR comes from its UI/UX portfolio. Working with VR/AR to assess usability is a new research path which has been created only recently; never before was VR/AR leveraged for measurement science for public safety applications. As a measurement organization, NIST has been able to prove that these technologies can be used far beyond gaming and entertainment, and are a legitimate path to take for research and standards work.

In 2018, PSCR was recognized for the development and execution of rigorous safety protocols, training, and infrastructure to support the NIST Unmanned Aerial Systems (UAS) Flight and Payload Challenge. The challenge was focused on innovative UAS designs capable of deploying first responder communications systems into areas where there is limited to no communications infrastructure (e.g., to help combat wildland fires). The team designed a first-of-its-kind safety plan for large (4 x 6 foot) UAS demonstrations to ensure participant safety during the challenge's evaluation process. The team's meticulous planning and preparation resulted in a successful, safe event, which advanced NIST's understanding of how drones can be used to support first responders.

Summary of Opportunities and Challenges

OPPORTUNITIES

Collaborative Partnerships with Federal Programs

CTL has built strong, productive partnerships with federal programs across NIST, DOC, DHS, and NASA. These partnerships allow CTL to leverage world-class expertise and resources to augment PSCR's extensive expertise and resources to solve public safety's most pressing communications technology challenges. Examples of this highly efficient approach include cybersecurity expertise within NIST ITL, wireless network modeling expertise within CTL's WN, and prize challenge expertise at NASA's Center of Excellence for Collaborative Innovation (CoECI). These mutually beneficial partnerships will continue to ensure that PSCR's research efforts are focused, efficient, and ultimately transformative for our nation's first responder community.

Transformative Funding Opportunities

The Innovation Accelerator Program represents an extremely rare opportunity for CTL to not only identify technology gaps hampering public safety communications but to actually direct funding to scientists and researchers across the world to solve these gaps. CTL's ability to leverage various funding mechanisms including prize challenges, grants, cooperative agreements, and contracts has resulted in exceptional flexibility and agility in how the program achieves strategic research objectives and creates results for their stakeholders.

CHALLENGES

Limited Funding Timeframe

Per legislation, the Innovation Accelerator funding must be obligated by the end of FY22. It is challenging to stand up the requisite programmatic infrastructure and processes to effectively and efficiently allocate Innovation Accelerator funds on such a tight timeline. In addition, the timeline does not allow CTL to digest outcomes of current research efforts before determining which future efforts to fund.

STRATEGIC RESEARCH OBJECTIVES CREATE RESULTS

Jack Lewis demonstrates the use of a virtual reality headset and controllers with NIST's virtual office environment (shown on the screen behind him) in which first responders search for a body in a fire. The goal is to spur industry to come up with user interfaces—visual indicators, sounds, voice commands—that could be embedded in masks or smart glasses, and use the virtual environment to test their effectiveness.

Credit: Burrus/NIST

This is Not a Game: NIST Virtual Reality Aims to Win for Public Safety

Virtual reality produces entertaining video games. But it's also a serious training and testing tool. Pilots test their skill with flight simulators, and the military can practice by playing war games.

Researchers at the National Institute of Standards and Technology (NIST) now aim to make virtual reality simulations more of a reality for first responders, enabling firefighters, law enforcement officers and others to learn and practice how to best operate and communicate in emergencies.

NIST staff are developing virtual environments featuring scenarios such as firefighting in hotels. The goal is to spur industry to come up with user interfaces—visual indicators, sounds, voice commands—that are better, cheaper, proven effective, and brought to market faster than otherwise would be possible.

Such interfaces could be embedded in firefighters' masks or smart glasses worn by emergency medical technicians, for example. A visual display might show the temperature or audio might warn that oxygen is low in a backpack tank. The idea is to present helpful data in an intuitive and nonintrusive manner.

"There is currently no method like ours to test and measure user interfaces for first responders," NIST project leader Scott Ledgerwood said. "We want to enable development, testing and rapid prototyping of these interfaces in a safe, controlled and repeatable environment."

"Virtual reality is still in its infancy, and while there've been some fantastic advances in training simulation, no one that we know has really looked at it from the testing and development perspective," Ledgerwood added. "We're creating this test bed because we don't believe anyone else has the focus or capabilities to test user interfaces for first responders."

Developing any new product for first responders requires complex and resource-intensive testing. Testing interfaces in real emergencies could expose first responders to high risk. Virtual reality offers a safer venue and can help ensure that innovations have a positive impact.

The NIST project uses commercial headsets and controllers, but NIST staff develop the content. So far, the software programs feature firefighting scenarios in a hotel, a mountain home, and an office

NIST

“Virtual reality is still in its infancy, and while there’ve been some fantastic advances in training simulation, no one that we know has really looked at it from the testing and development perspective”

environment. Users can choose their locations within the scenario and operate a controller to simulate a fire hose. NIST had to hire unusual expertise for this project. Jack Lewis recently got an academic degree in video game design, is now using his creative skills to write software programs for public service purposes.

“I thought it sounded like a cool job,” Lewis said. “Not everyone gets a chance like this to make a difference.”

NIST staff are currently showcasing the concept and basic technology at events such as the recent Consumer Electronics Show.

In the near future, NIST staff plan to develop methods and criteria for evaluating interfaces to ensure that the test bed provides valuable data to its customers. NIST staff also plan to create additional virtual scenarios for a broad range of first responders and a variety of headsets and graphic engines. The environment and scenarios may also be extended through NIST grants. Virtual reality is also a topic of some NIST prize challenges.

Soon, companies will be able to visit NIST to test their experimental interfaces or even replicate the entire test bed.

“The goal is to make this virtual environment in such a way that anyone who has access to a headset could download our scenarios and use them at their own locations,” Ledgerwood said.

Source: https://www.nist.gov/news-events/news/2018/05/not-game-nist-virtual-reality-aims-win-public-safety

CHAPTER 3: TRUSTED SPECTRUM TESTING

WELCOME AND INTRODUCTION

The National Advanced Spectrum and Communications Test Network (NASCTN) was established by NIST, the National Telecommunications and Information Administration (NTIA), and the U.S. DOD in 2015. NASCTN was established for the purpose of organizing a national network of federal, academic, and commercial test facilities that would provide trusted spectrum testing, modeling, and analysis necessary to develop and deploy spectrum-sharing technologies and inform future spectrum policy and regulations. In 2018, three additional agencies joined NASCTN: the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the National Aeronautical and Space Administration (NASA). NASCTN is hosted within the Communications Technology Laboratory at NIST. Previous NASCTN projects include its award-winning 2017 DOC Gold Medal study on the Impact of LTE Signals on GPS Receivers.

SCIENTIFICALLY RIGOROUS TEST PLANS

Mission and Functional Statement

To provide, through its members, robust test processes and validated measurement data necessary to develop, evaluate and deploy spectrum sharing technologies that can increase access to the spectrum by both federal agencies and non-federal spectrum users. Key functions include:

- Develop scientifically rigorous test plans and new methodologies with independent experts
- Access to key test facilities, and commercial and federal equipment and capabilities
- Provide validated data and models for use within the spectrum-sharing community
- Operate as a trusted agent and protect proprietary, sensitive, and classified information

Structure

NASCTN has a unique structure to operate within the context of ever-changing spectrum policy frameworks. A highly dynamic and transdisciplinary core team provides the ability to constitute and host contributors from within NIST, Charter members, and from Federally Funded Research and Development Centers (FFRDCs). Most of NASCTN's projects are short-term and complete within one year.

Steering Committee:

The NASCTN Member Steering Committee provides guidance, approval, and governance for NASCTN activities. It consists of a representative from each member, and sets the strategic direction, discusses current spectrum sharing issues with respect to the mission, identifies and evaluates NASCTN processes, and approves NASCTN spectrum sharing projects based on the submitted request and recommendation of the NASCTN Screen Team.

Core Team

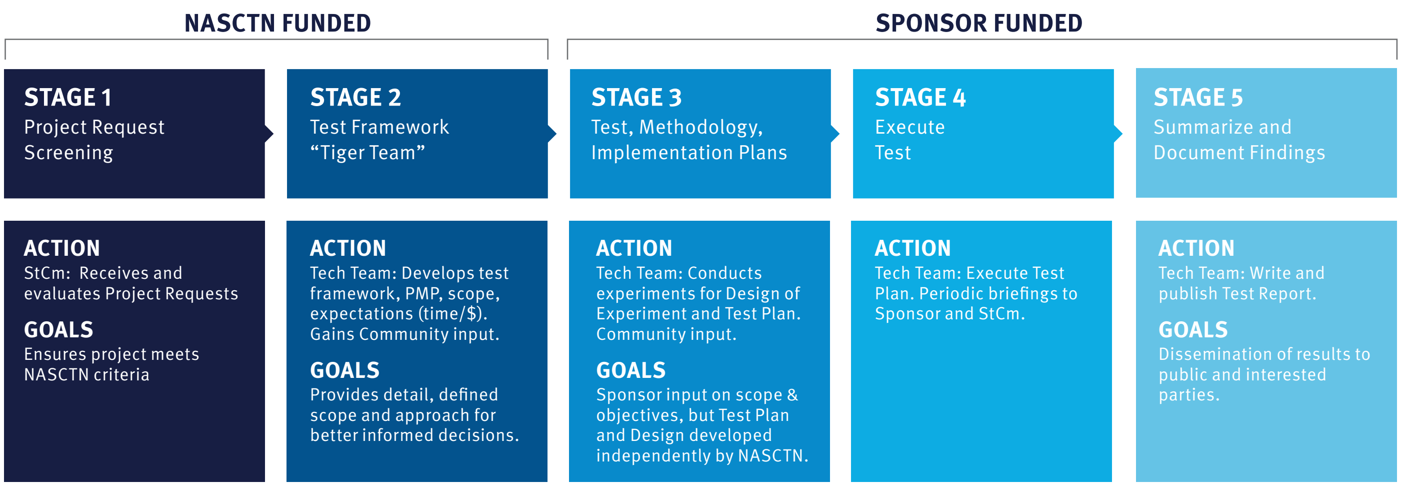
The core team resides at NIST, and is responsible for overall programmatic direction and coordination across partners. CTL staff provide technical knowledge and institutional knowledge to enable rapid start-up of new projects, and ensure technical quality and direction for ongoing projects and screen teams. The core team includes program support staff, a Chief Engineer, a Lead Data Scientist, and Lab engineering/IT support. All team members are highly-qualified personnel and possess the fundamental skill sets required across all NASCTN projects.

Technical Leads and Subject Matter Experts

Each project employs key personnel based on the requirements of the test plan. These team members come from NIST (permanent staff and associates), Professional Research Experience Program (PREP), NASCTN Charter Members, FFRDCs, and federal contractors. This framework addresses the ability to tackle large scope and small scope problems simultaneously without sacrificing NASCTN core values.

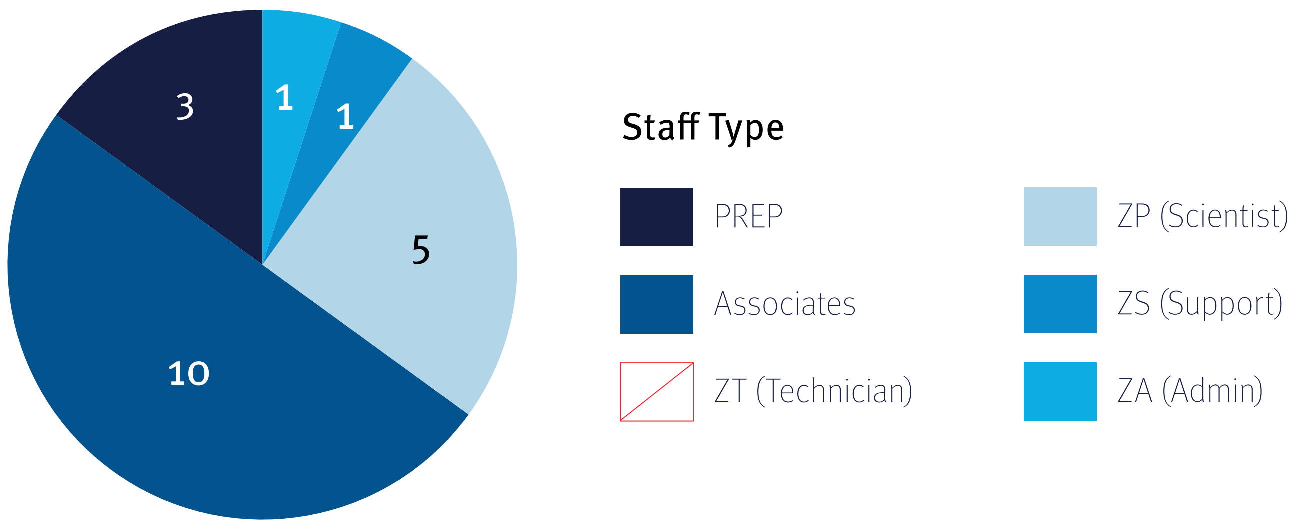
NASCTN Framework

NASCTN projects follow an open, transparent and comprehensive process for developing scientifically based test plans, facilitating access to member test ranges and laboratories, protecting controlled information, and validating test results before findings are reported. The five-stage NASCTN Framework, shown below, serves as a common architecture across NASCTN's diverse spectrum sharing projects.



STAFFING

The NASCTN staff supporting the Trusted Spectrum Testing program area are listed below by staff level.



FACILITIES UPDATE

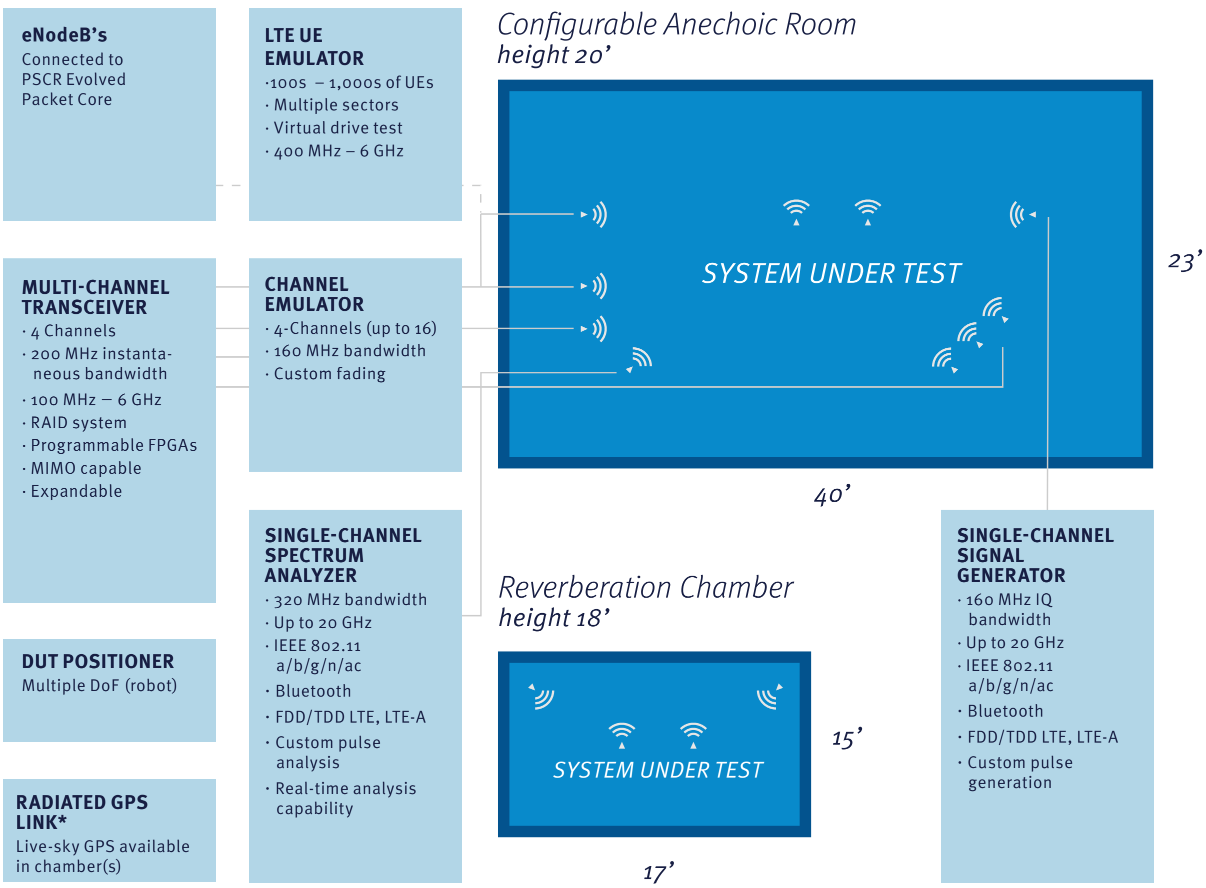
In 2018, NASCTN established laboratory space on the third floor of Building 3 (3-3A119) and began developing the capabilities to support initial and complementary test beds. This included various wireless spectrum test equipment (e.g., emulators, racks, filters, analyzers, and switches), a dedicated server for machine learning and high-intensity data analytics, and a dedicated storage array. NASCTN also maintains a secure room for classified document storage and processing.

NASCTN augments these resources with leased, loaned, and borrowed equipment, as well as unique facilities from NASCTN project sponsors, NASCTN members, and other organizations on the NIST campus (e.g., anechoic chambers, operational systems, and specialized test equipment). Key Charter Member facilities used in NASCTN projects include the NIST NBIT facility in Building 24, NASA's Wireless Intelligent Systems E3 Research (WISE3R) Lab at Langley, telemetry radars at Edwards Air Force Base, California, and coastal measurement locations at Point Loma in San Diego, California and Fort Story in Virginia Beach, Virginia, and the Radio Spectrum Measurement Science (RSMS) vehicles and portable systems from NTIA's Institute of Telecommunication Sciences (ITS).

National Broadband Interoperability Test Bed (NBIT)

NBIT supports research in wireless coexistence metrology and standards, enabling researchers to understand how radar, LTE, Wi-Fi and other systems interact in an integrated environment combining large anechoic and reverberation chambers. Unique to NBIT is the integration of a live LTE network, which enables real-world testing of this complex and increasingly ubiquitous wireless-data protocol.

NBIT's integration of large semi-anechoic (40' x 23' x 20') and reverberation (17' x 15' x 18') chambers enables a broad range of test conditions, from highly reflective ones that Multiple Input Multiple Output (MIMO) systems prefer to absorbent ones favored by traditional point-to-point systems. In addition to enabling realistic test environments, these chambers' large volumes eliminate the risk of electromagnetic interactions among device electronics (as opposed to device antennas, the focus of radiated testing) corrupting experiments. In addition, the semi-anechoic chamber can be made fully anechoic using an RF-absorbent floor covering or more reflective by hanging conductive curtains to create partial-multipath environments.



** indicates planned acquisition*

In addition to the chambers themselves, NBIT's systems include:

- A series of LTE evolved NodeB (eNodeB) base stations connected to NIST CTL's Public Safety Communication Division LTE network, with an Evolved Packet System core
- An expandable, MIMO-capable multi-channel transceiver, initially with four channels providing 200 MHz instantaneous bandwidth from 100 MHz to 6 GHz
- An expandable four-channel channel emulator with 160 MHz bandwidth from 100 MHz-6 GHz and custom fading profiles
- A single-channel signal generator with 160 MHz IQ bandwidth up to 20 GHz. Generates IEEE 802.11 a/b/g/n/ac, Bluetooth, FD/TDD LTE, LTE-A, custom pulses, and custom fading
- A single-channel spectrum analyzer with 320 MHz bandwidth up to 26 GHz. Capable of real-time analysis of IEEE 802.11 a/b/g/n/ac, Bluetooth, FD/TDD LTE, LTE-A, and custom pulse analysis

Infrastructure Challenges:

The lack of a modern, high-speed intranet and connectivity hampers NASCTN's ability to utilize existing facilities as large data sets are created daily during measurements. These data sets need to be accessible to the analysis teams. The need to protect sensitive or proprietary information is further complicated by limited pipelines. NASCTN investments are heavily focused in modern equipment to support dynamic spectrum challenges and to support communication between partners. However, key investments in network infrastructure to support large data sets created during testing are hampered by the outdated network infrastructure.

RESEARCH AREAS

Trusted Spectrum Testing:

The Defense Spectrum Organization (DSO) sponsored Aggregate LTE project was initiated as a result of the 2014 AWS-3 spectrum auction, which assigned 1755–1780 MHz frequencies to commercial wireless carriers with conditions for sharing the spectrum with existing federal systems. As carriers consider early network build-outs in this band, the Defense Information Systems Agency (DISA) DSO is engaged in a broader effort to assess interference risk between the two types of systems, with aggregate LTE user equipment emissions as one potentially influential factor.

A test plan for a new methodology for measuring aggregate interference due to a large number of factors was developed. This was the largest factor screening test undertaken in NIST history. Such factors include the collective power distributions emitted by the UEs in a cell, the number of UEs transmitting simultaneously, the spectral properties of the UEs, channel characteristics on the path between the UEs and unintended receivers, and other special conditions relevant to the test environment. Phase One of the test is set in a controlled lab environment to produce baseline reference variables for network configuration and accurate assessment of impact dependencies. Phase Two will include outdoor field measurements for estimates of certain factors.

Results of this NASCTN project may affect the business strategy and network design of commercial deployments during the time federal systems continue to operate in the 1755–1780 MHz band.

OUTPUTS

NASCTN Program Management

NIST serves as the NASCTN hosting organization and is responsible for appointing a Program Manager who oversees day-to-day operations of efforts, engages in outreach activities, and coordinates Steering Committee reviews and input. In addition, the Program Manager is also responsible for creating the mechanisms such as CRADAs, Interagency Agreements (IAA), and contracts to enable cross-agency and other required test support.

Aggregate LTE Characterizing User Equipment Emissions Project

In 2018, NASCTN launched this project to develop new methodologies and statistical measurement data to characterize LTE and groups of signals (i.e., emissions from multiple UEs transmitting simultaneously). Validated measurements will update interference models and calculations used in the FCC-NTIA AWS-3 Coordination Request Evaluation (CRE) process, which evaluates and approves commercial entry into frequencies purchased by commercial telecommunications companies.

Hybrid chamber for laboratory-based emulation of spatial wireless channels

NASCTN demonstrated a proof-of-concept hybrid chamber that combines reverberation and anechoic properties to produce controllable, spatial-channel test environments in a lower-cost system relative to anechoic-chamber based methods.

International Symposium on Advanced Radio Technologies (ISART) Conference

NASCTN joined ITS to host the ISART, a US government-sponsored conference that brings together approximately 150 participants from government, academia, and industry. The purpose of ISART is to collaborate on groundbreaking developments and applications of advanced radio technologies.

Test Plan Workshops

NASCTN develops scientifically rigorous spectrum sharing test plans. These tests plans are widely distributed throughout the government, industry, and academic spectrum community for awareness, review, and comment, often involving 50–70 participants. This collaboration ensures the broadest input of ideas into the test plan while providing best practices for other spectrum sharing testing to leverage. Noteworthy test plans that garnered significant interest from spectrum community included the LTE Impacts on GPS, Radar 1 Waveform Capture, and the Aggregate LTE Characterizing User Equipment Emissions Projects.

Test Reports & Articles

At the conclusion of every NASCTN project, a publicly releasable report is generated that captures the test execution, analysis, and the results of the spectrum sharing project. These test reports are stored in the NIST document repository. A formal brief is also generated and presented to the spectrum community to provide a forum for questions and deeper insight into the results of the project. NASCTN often generates additional research and documentation from spectrum sharing projects; for example, NASCTN performed considerable research using machine learning to analyze the radar 1 waveform captured as part of the project. This research resulted in a number of peer-reviewed journal articles, NIST Technical Notes, and has also informed the WinnForum and ESC testing.

Out-of-Band Emissions Measurements of LTE Devices Operating in the AWS-3 Band

NASCTN held a public briefing for its release of the completed “Measured Emission Spectra of Selected AWS-3 LTE Transmitters” (NIST Technical Note 1980). The project, proposed by Edwards Air Force Base, measured Out-of-Band (OoB) emissions from new LTE systems operating in bands adjacent to existing incumbent DOD Aeronautical Mobile Telemetry (AMT) systems used at government test and training ranges (TTRs). This data can be used by government organizations to determine the level of OoB emissions they can expect from LTE systems and plan mitigation strategies. In addition, the test report details test calibration procedures, frequency scan sequencing, and tuning configurations that may be recommended for consideration in future experiments of transmitter OoB emissions.

Provided Technical Support to Ligado Networks, LLC

Ligado Networks is a small business with 40 MHz of spectrum licenses in the nationwide block of 1500 MHz to 1700 MHz spectrum in the L-Band. Ligado Networks is using its 40 MHz of spectrum to develop a satellite-terrestrial network to support the emerging 5G market and IoT applications. NASCTN supported Ligado Networks by performing validated measurements to better understand the potential impact of adjacent-band LTE signals on GPS receiver performance. The tests and report were completed in 2017, and its findings are still awaiting FCC decision.

STRATCOM Electronic Warfare Battle Management Workshop

STRATCOM requested information about commercial approaches and solutions to Spectrum Sharing in pursuit of new options for Electronic Warfare Battle Management (EWBM). NASCTN coordinated this workshop to highlight technologies aimed at supporting spectrum sharing between federal and commercial users, as a result of the spectrum sell off. Topics briefed by NIST and NTIA members covered technologies from spectrum monitoring and response (ESC/SAS, DFS, XG), spectrum efficiency, measurement campaigns, and other efforts. Attending visitors included STRATCOM J853 EW Capabilities and EMS Operations Advocacy, DOD’s OUSD (R&E) office, and OUSD EW EXCOM office.

Additionally, NASCTN has conducted a variety of community outreach including:

- Range Commanders Council—Frequency Management Group (RCC FMG)
- Wireless Spectrum Research and Development (WSRD) IWG
- Variety DOD Services laboratories/test ranges (e.g., AFRL, NRL, NAVAIR, CERDEC)

Summary of Opportunities and Challenges

OPPORTUNITIES

Trusted Partner for Spectrum Policy Decision Makers:

Through the successful completion of several high-profile spectrum sharing measurement campaigns, NASCTN has solidified its reputation as a trusted partner for developing test methods and networks to inform future spectrum policy and regulations. Today, NASCTN is working with external stakeholders to identify measurement campaigns to be undertaken prior to federal spectrum auctions. By providing information to both the federal incumbent and commercial providers, they can make better informed decisions regarding the value of spectrum licenses.

CHALLENGES

Prepare in Advance of the 2024 Spectrum Auction:

All too often, spectrum sharing issues and efforts to mitigate them are identified after the auction. NASCTN is working with agencies to aid policy and investment decisions by identifying potential key measurements and new methodologies in advance of the 2024 Spectrum Auction.

Maintaining an Independent and Neutral Role:

NASCTN projects often require trusted testing methodologies given the potentially contentious environment surrounding the project measurements. Changes to spectrum policies resulting from NASCTN reports could lead to intense scrutiny. It is vital that NASCTN's overarching processes, test development, execution, and reporting maintain an independent and neutral role.

Modifications to Current Business Model:

The original process placed the responsibilities of the test plan development and preliminary trials (Design of Experiment) on NASCTN members. This cost, absorbed by the members, negatively affected resources and limited the number of proposals NASCTN could feasibly support. An update to the process maintains an independent project evaluation and an experimental approach design, but utilizes cost reimbursement for major design and experiments to the customer. Care must be taken to ensure that NASCTN maintains its independence from the funding sponsor in the test plan development, oversight activities, and quality control of the test execution.

NASCTN Releases Report on LTE Impact on GPS Receivers

The National Advanced Spectrum and Communications Test Network (NASCTN) has completed the Impacts of LTE Signals on GPS Receivers project and has released the NASCTN report LTE Impacts on GPS along with the measurement data associated with this project.

The focus of this NASCTN project, proposed by Ligado Networks in April of 2016, was the development of a test methodology to (1) investigate the impact of Long Term Evolution (LTE) signals on Global Positioning System (GPS) devices that operate in the GPS L1 frequency band and to (2) perform radiated radio-frequency measurements on a representative set of GPS devices in order to validate the test methodology.

To better understand the potential impact of adjacent-band LTE signals on GPS receiver performance, NASCTN developed a draft test plan designed to measure how the performance of GPS receivers changed as a function of increasing LTE signal power relative to a baseline with no LTE emissions.

NASCTN testing included several measurands: carrier-to-noise density (C/No), 3D position error, timing error, number of GPS satellites in view, time to first fix and time to first reacquisition.

The focus of this study was on GPS devices from four different receiver classes—general location and navigation (GLN), high-performance positioning (HPP), real-time kinematic (RTK), and GPS-disciplined oscillator (GPSDO).

A cross-section of regulators, Federal agencies and GPS manufacturers reviewed the NASCTN test plan and provided technical comments, which NASCTN used to prepare a revised test plan, which was released in July of 2016.

Over a three-month period, NASCTN performed the radiated measurements associated with this project at two facilities—a semi-anechoic chamber at National Technical Systems (NTS) in Longmont, CO and at a fully-anechoic chamber at the NIST Broadband Interoperability Testbed (NBIT) facility in Boulder, CO.

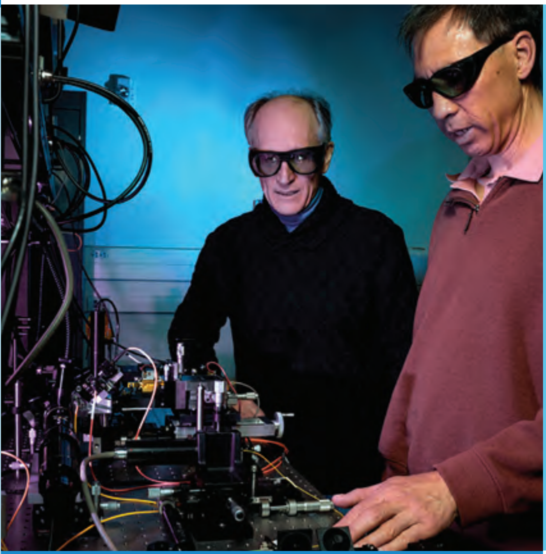
NASCTN relied on technical staff from NIST and the U.S. Army's Electronic Proving Grounds to perform and validate the measurements and collect the data. The team was multi-disciplinary, including expertise in GPS devices and simulation, radiated radio-frequency measurements, timing measurements, microwave metrology, statistical analysis and data processing.

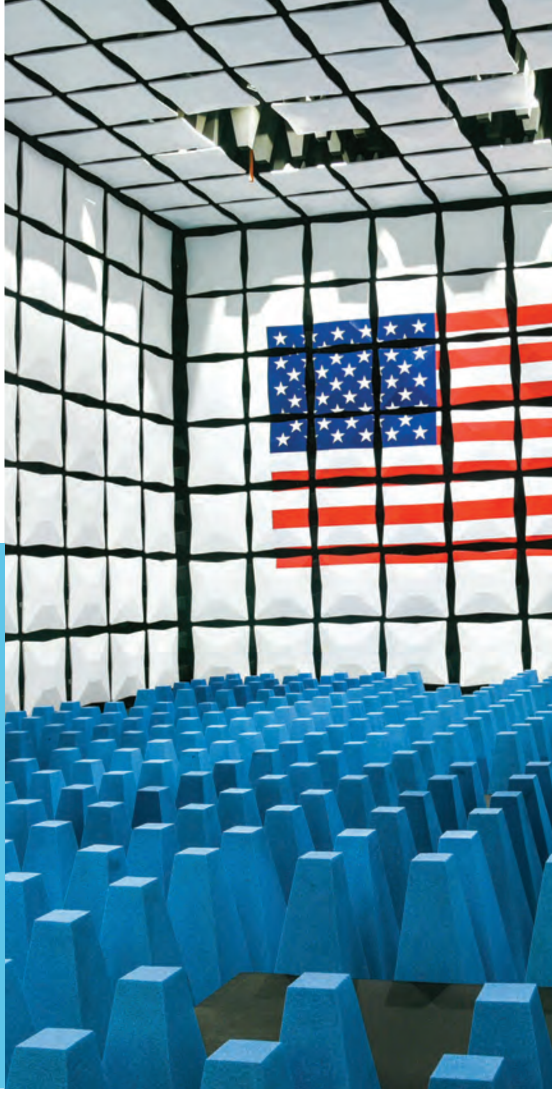
In total, NASCTN performed 1,476 hours of testing and collected over 19,000 data files for a variety of measurands that were collected from a number of GPS devices. These data were collected at a baseline condition (no LTE signals present) and over a large range of LTE signal power levels. Subsequent data processing yielded a set of 3,859 anonymized data files (780 MB) that is available along with the NASCTN report.

Due to significant interest in these measurements by regulators for assessing LTE signals on performance of GPS devices, Federal agencies, and the GPS community, NASCTN is publically releasing both the test report and the associated measurement data and may host a public meeting to give an overview of the test results and answer any questions on the testing methodology.

Source: https://www.nist.gov/news-events/news/2017/02/nasctn-releases-report-lte-impact-gps-receivers

CHAPTER 4: METROLOGY FOR ADVANCED COMMUNICATIONS





THIS RESEARCH PUSHES THE STATE-OF-THE-ART

WELCOME AND INTRODUCTION

Future generations of wireless communications will employ various technologies to efficiently utilize spectrum and extend the frequency range available for non-government use. Advances in communication metrology are needed to support the continuous development and deployment of these new communications technologies. This work also furthers NIST's core mission of developing and applying new measurement science to difficult, high-impact, national-scale problems.

CTL research within the Metrology for Advanced Communications Program spans the range between fundamental measurements at the device and circuit level, through antennas and the propagation channel, to system-level measurements. Activities also span the communications frequencies below 6 GHz as well as the millimeter-wave regime above 24 GHz.

The CTL Radio Frequency (RF) Technology and Wireless Networks (WN) divisions work closely together to develop theory, metrology, and standards for the technologies upon which the future of wireless communications depends. The divisions continue to invent new ways to accomplish their mission, including the world's first robotic-arm antenna testing system, state-of-the-art channel models for complex environments, electro-optic sampling for on-chip metrology, and a quantum field probe for electric field strength measurements.

Mission and Functional Statement

The mission of the Metrology for Advanced Communications Program is to provide metrology resources to facilitate the development and commercialization of a broad range of radio-frequency electronic and electromagnetic technologies, as well as research emerging technologies and standards that revolutionize how wireless networks are operated and used. The programmatic activities are primarily centered in the CTL Divisions of RF Technology and WN.

The RF Technology Division provides fundamental measurement science to facilitate the development and commercialization of a broad range of RF electronic and electromagnetic technologies. The measurement science developed and disseminated by the division provides for national and international measurement harmony and formal traceability via calibration services, reference standards, and measurement comparisons. This research pushes the state of the art in microwave metrology and addresses fundamental measurement problems that are of interest to a broad range of industry and government stakeholders and remain unresolved due to lack of resources. General program areas include fundamental microwave quantities, high-speed microelectronics, electromagnetic compatibility, electromagnetic field characterization, antenna metrology, electromagnetic properties of materials, and radio-frequency communications systems.

The Wireless Network Division specializes in communication networks and protocols and in the digital communications technologies that make those networks possible. Staff perform theoretical and empirical research to develop simulation models, experimental testbeds, and proof-of-concept prototypes that are used to evaluate new technologies and refine existing standard specifications for wireless networks and systems. Additionally, the division develops metrics and measurement methods to assess the performance of many types of wireless systems.

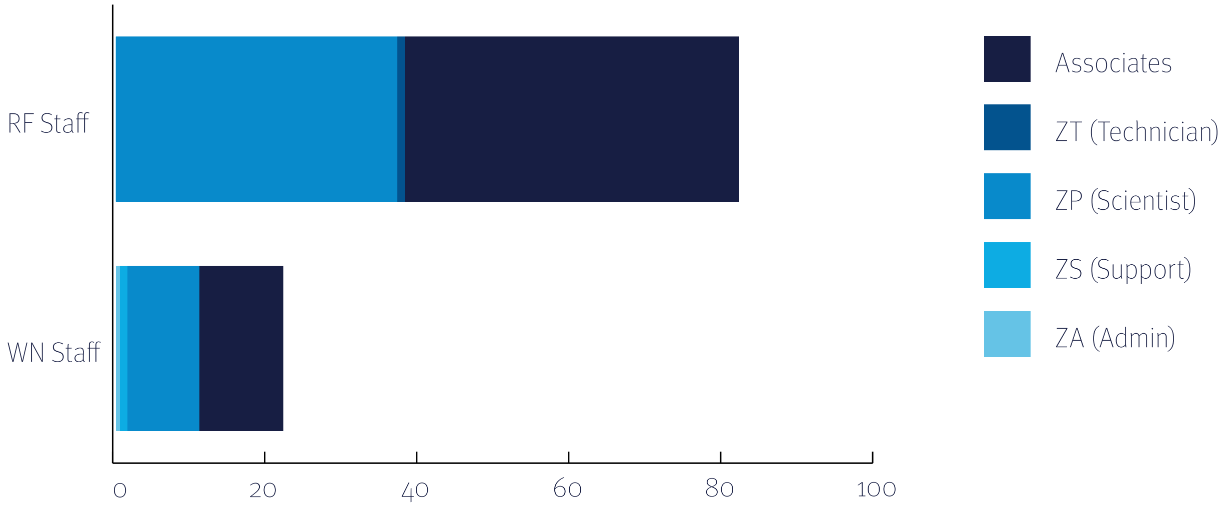
STAFFING

Staffing levels for this program are a collaboration between RF and WN Division staff. The graph below indicates the number of full-time and part-time staff working in both divisions to support the Metrology for Advanced Communications program.

FACILITIES UPDATE

CTL Antenna Communication and Metrology Laboratory

The CTL Antenna Communication and Metrology Laboratory (ACML) enables metrology research on advanced antenna systems operating in complex



Developing and applying new measurement science

electromagnetic environments. Its capabilities, anchored by the Large Antenna Positioning System (LAPS) consist of two six-axis industrial robot arms. LAPS fosters the development of next-generation 5G wireless and spectrum-sharing systems through dynamic measurements, flexible scan geometries, and high speeds. The ACML supports testing and characterization of multiple steered-beam and other antennas from ultra-high frequency (UHF, from 300 megahertz through 3 gigahertz) through the 500 gigahertz range as well as near-field scanning techniques to antenna technologies from 50 GHz up to 500 GHz.

The ACML's main anechoic chamber is a fully shielded 51' by 23' by 21' space with two six-axis robots, accommodating antenna separations of up to ten meters as required for gain extrapolation measurements at sub-gigahertz to 500 GHz range. In addition to LAPS, the ACML is home to the Configurable Robotic Millimeter-Wave Antenna (CROMMA) facility that, in contrast to legacy antenna ranges, enables configurable geometries, fast and dynamic antenna movement, beam tracking, large payload capacity and improved dynamic accuracy and repeatability from 100 GHz and beyond. These advantages are increasingly critical as spectrum use expands to include higher-frequency applications and MIMO systems, which are difficult to characterize due to positional accuracy and scan geometry limitations. The dual-robot system supports MIMO, phased-array, and other measurements with an eye on addressing an overarching need to understand the interference problems created by ever-increasing signal density in frequencies below 50 GHz.

RESEARCH AREAS

NIST's investment in metrology for advanced communications spans from the measurement of fundamental electromagnetic quantities, characterization of materials and circuit components, through propagation channels to modeling, simulation, and characterization of systems behavior and performance. Detailed on the next page, are the major programmatic themes in the divisions of RF Technology and WN.

Next Generation (5G and Beyond) Wireless Communications

Next generation (5G & Beyond) wireless technology seeks to create networks that will appear ubiquitous and limitless to the user, with increased bandwidth and lowered-access latency, giving rise to new applications, use cases, and businesses. Today, 5G networks are starting to be deployed to address new wireless challenges and accommodate the explosive growth in wireless network traffic. The development and evolution of these new networks rely on major advances in several key technology areas including massive MIMO antenna systems, use of the higher frequency bands (e.g. millimeter-wave), and efficient spectrum utilization and reuse.

Advances in communication metrology are also needed to support continuous development and deployment of 5G networks. Developing and applying new measurement science to difficult, high-impact, national-scale problems falls squarely within NIST's core mission. CTL is tackling several key areas that are important to wireless system designers, standards organizations, and network service providers including characterization of power-efficient mm-wave circuits, measurements and modeling of complicated and dynamic propagation channels, antenna measurement and modeling, and evaluation of spectrum sharing protocols.

5G mmWave Channel Model Alliance

In July 2015, CTL kicked off the 5G mmWave Channel Model Alliance to address the need for accurate channel propagation measurements and models that characterize the millimeter wave bands. To date, the alliance includes over 175 motivated stakeholders representing 758 organizations worldwide.

Alliance for 5G Networks

The next generation of wireless communications technology will allow many more devices to send information much faster, making possible everything from virtual reality to driverless cars. NIST works with industry and academia to understand how those technologies behave, so next generation wireless networks can be deployed sooner and with a better user experience.

NIST launched the 5G mmWave Channel Model Alliance to accelerate the development and use of accurate measurements and models for next-generation communications technology. By bringing together researchers from multiple stakeholders—including communications technology companies, academia and government—NIST is accelerating 5G innovation.

The widespread use of 5G technologies is expected to produce $3.5 trillion in output and 22 million jobs globally by 2035. However, technical impediments still stand in the way. The high-frequency signals used by some 5G technologies are more likely to be affected by physical barriers such as walls or buildings. The communications industry needs accurate models and measurement techniques to better understand those effects.

NIST's establishment of the alliance has brought together more than 130 participants, including representatives from Qualcomm, Intel, Samsung, Keysight and Echostar, to solve the most pressing modeling and measurement challenges facing the deployment of 5G wireless communications. The output of NIST's research and that of the alliance is being incorporated into the development of standards, specifications and best practices benefitting the entire industry.

Source: https://www.nist.gov/industry-impacts/alliance-5g-networks

To ensure the broadest participation in the alliance, participation is open to all, and no membership fee is required. The alliance has produced two white papers on millimeter-wave propagation modeling, sounder verification, and calibration, in addition to raw data measurements for select environments. NIST and other alliance members have led the development of predictive channel models used by standard developing organizations (3GPP, IEEE 802) working on 5G and future generation millimeter-wave wireless communication systems. Target deliverables for 2019 include channel propagation models for 28 and 60 GHz systems deployed in urban canyon environments to expedite the deployment of 5G fixed-mobile millimeter-wave systems. The NIST-led alliance is also hosting a publicly available repository of measurement data and models. To date, 50 data sets have been made available to characterize the millimeter-wave propagation of key indoor and outdoor scenarios of interest.

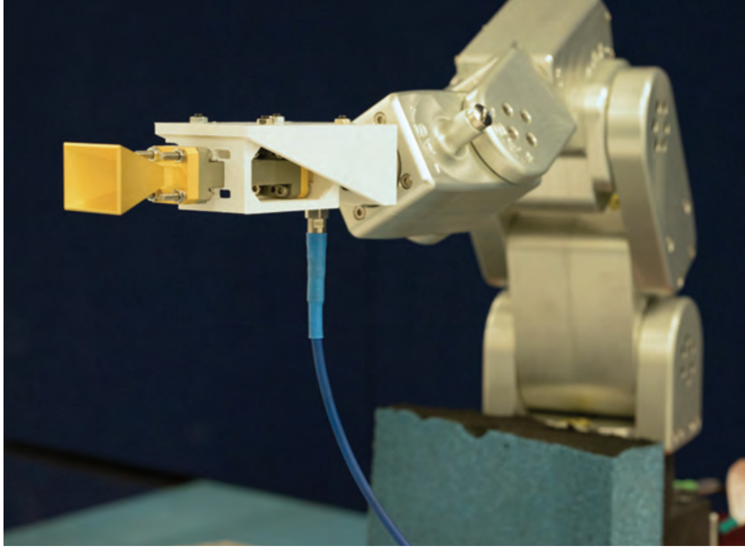
Wireless Channel Sounding and Modeling

New propagation models are needed for emerging wireless technologies that use lower bands (below about 6 GHz), IoT, and mm-wave and THz bands. Through measurement campaigns with NIST's state-of-the-art channel sounders, CTL seeks to furnish the wireless research community with advanced propagation models to help stakeholders bring finalized products to market as efficiently as possible. Previously, working groups within IEEE, 3GPP, and other standards development organizations were scrambling to define new specifications using existing channel models that were either unreliable (often retrofitted from sub 6-GHz legacy models) or insufficient (propagation is not fully understood despite significant efforts, to characterize the channel).

The CTL effort to develop accurate channel propagation models from field measurements has been supported by the development of precision channel sounder calibration and verification methods for mm-wave and sub 6-GHz systems. CTL has made significant progress in characterizing path-loss models, map-based dispersion models, Doppler frequency-spread models, multipath tracking, human blockage, in addition to delay, angle and phase information.

Over-the-Air (OTA) Metrology

"Over-the-Air Metrology" (OTA Metrology) refers to the development of measurement science that characterizes the performance of current and future mobile wireless systems and underlying technology



through measurements made in radiated (non-conductive) channels. CTL is addressing challenges related to accurately determining measurement-based performance metrics for both deployed and future wireless communication applications. The work is centered around providing traceability for, and uncertainty analysis of, new or improved measurements of wireless-enabled devices. CTL addresses both current commercial cellular technology—including smartphones, IoT devices, body wearables, and machine-to-machine applications—as well as future applications—including 5G mm-wave "New Radio" OTA tests, smart manufacturing, vehicle-to-vehicle, telemedicine, and other anticipated technologies requiring high-quality low-latency visual, tactile and audio telepresence not possible with current cellular technology.

Wireless Coexistence Metrology

In order to assess the wireless coexistence of communication systems that are sharing the same frequency band, it is critical to identify the appropriate KPIs to measure and accurately calculate the uncertainties associated with these measured KPIs. This project models and analyzes the statistical distribution of the uncertainties based on information in the medium access control (MAC) physical and hardware layers of communication systems in a coexistence scenario and verifies the results via conductive and radiated experiments in a controlled laboratory environment, such as an anechoic chamber.

The long-term goal is to provide the testing procedure design and uncertainty evaluation techniques for the forthcoming coexistence testing standards, especially the American National Standards Institute (ANSI) C63.27 standard—Evaluation of Wireless Coexistence. The developed techniques will initially be demonstrated and validated on communication systems that operate at 6 GHz and below, such as radar and LTE in the CBRS 3.5 GHz systems, and the sub-6 GHz 5G New Radio designs. Extensions to future communications systems, especially those that operate at millimeter-wave frequencies, will be explored once these methods are established and validated at lower frequencies.

The state-of-the-art NBIT facility enables CTL and its stakeholders to perform leading-edge research on radiated test methods and spectrum sharing technologies in a facility capable of replicating real-world environments. Example projects include establishing an aggregate waveform representing multiple UE connected to an LTE system or the controlled, radiated testing of systems such as airborne telemetry systems over a range of conditions. NASCTN and PSCR have made extensive use of NBIT.

Spectrum Sensing and Monitoring

The presence of large numbers of licensed and unlicensed spectrum users has increased the environmental noise floor well above conventional thermal noise levels. Nevertheless, a quantitative assessment of the existing noise floor in today's communication world is not yet available. As a result, precision measurements of low-level signals in a traceable way are critical endeavors.

A key element of quantitative noise and interference measurement is the separation of environmental noise and interference signals (due to various man-made sources) from noise internally generated by sensors or systems under test. A reliable separation is predicated on the development of traceable signal sources and receivers. While they were initially designed for quantification of thermal noise, these instruments can also be utilized to examine interference at a fundamental level.

It is critical to develop metrics to evaluate the wireless sensors and receivers in the presence of noise, interference, and coexisting signals in order to determine the performance of wireless communication systems. Knowledge of noise and interference in and between systems can facilitate investigations of co-existence tolerances and can inform adjudication processes in spectrum access, as in the push for risk-informed interference analysis by the FCC.

Citizens Broadband Radio Service

The Citizens Broadband Radio Service (CBRS) band is 150 MHz of spectrum recently made available by FCC Part 96 rules, establishing a three-tier architecture for sharing the Radio-Frequency (RF) spectrum from 3550 MHz to 3700 MHz. Commercial users of the CBRS band are expected to share this spectrum with existing incumbents, including the federal government which currently operates mission-critical radiolocation services in this spectrum. CTL contributed significantly to the development of the CBRS standards. This effort was led by the Wireless Innovation Forum; an international group of equipment vendors, broadband service providers, government agencies, and regulators. The Forum's Spectrum Sharing Committee serves as the CBRS standards body and is comprised of 52 organizations including AT&T, CommScope, CTIA, Ericsson, Federated Wireless, Google, Nokia, Sony, Qualcomm, and Verizon. Government stakeholders include DOD, FCC, and NTIA. The CBRS standards specify commercial systems known as Spectrum Access Systems (SAS) to mediate access to the RF band and provide interference avoidance with incumbents. NIST test methods and reference software validate whether these systems meet established requirements to protect incumbents, such as the U.S. Navy, from harmful RF interference.

NIST is also creating digital waveforms that may be used by the regulator to test and certify commercial 3.5 GHz sensors. Known as Environmental Sensing Capability (ESC) systems, these sensors are responsible for detecting federal incumbent signals and triggering interference protection mechanisms. The digital waveforms are derived from radar measurements conducted by NASCTN in the 3.5 GHz band.

Research components of the CBRS project include detection of radar signals in the presence of interference from CBRS devices and other emissions, modeling aggregate interference for the computation of interference protection metrics, and applying machine learning and data mining to the classification and characterization of 3.5 GHz waveforms.

Massive MIMO Measurement and Modeling

Recognizing the measurement challenges in dealing with hundreds of elements in massive MIMO systems, NIST has established the LAPS facility for testing, calibration and characterization of massive MIMO antenna arrays up to millimeter wave frequencies. NIST is also working on the development of channel models for massive MIMO systems and modeling tools to evaluate and develop beam-forming and training mechanisms.

Measurement Services for Communications

Measurement services are part of NIST's core mission to advance measurement science, standards, and technology in ways that enhance economic security and improve our quality of life. Performing measurements for paying customers informs NIST research about industry needs and demonstrates the economic value of NIST measurements. NIST research feeds into measurement services and keeps them current.

In the past, the RF Technology Division has provided measurement services that enable traceability for traditional continuous wave measurands: power, scattering parameters, noise, materials properties, and antenna parameters. The impact of these services has dwindled because these traditional measurements are widely available elsewhere. Now in CTL, the RF Technology Division is working to extend this foundational expertise to measurements that are more relevant to advanced communications, such as modulated signals, over the air tests, nonlinear materials and device characterization, connector-less and on-wafer device tests at mm-wave frequencies, and multiple element antenna arrays.

mm-wave Circuit Technologies

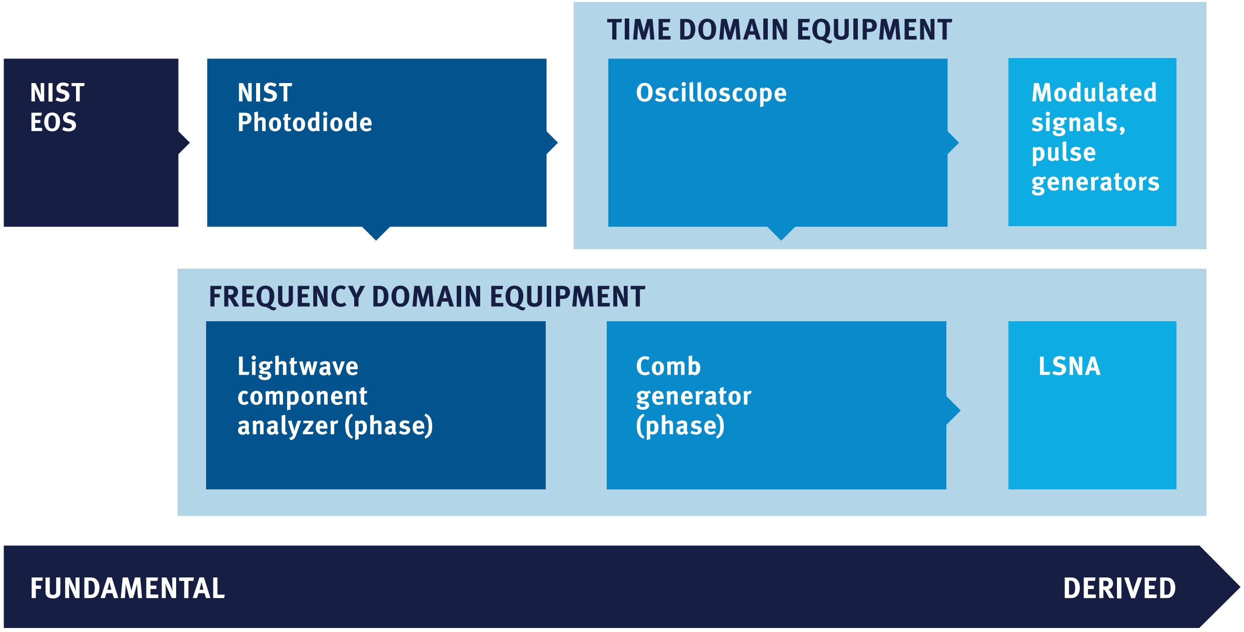
A key limiting factor on the use of the incredible bandwidth available in the mm-wave spectrum, for mobile communications, is industry's ability to develop transistor and integrated-circuit technology suitable for mobile operation at these frequencies. CTL has seen this play out over the last five years, with initial expectations that 5G would rely on mm-wave spectrum being radically scaled back. Terms like "5G under 6 GHz" are an acknowledgment that working at mm-waves presents challenges that go far beyond other generational jumps that the industry has taken in the past.

Opening up the mm-wave spectrum to commercial mobile wireless communication systems is a daunting task that requires advances in transistor technology and highly integrated hardware systems. Achieving the complexity, agility, and efficiency needed for mobile mm-wave communication systems requires maintaining high levels of linearity while achieving high power-added efficiency at mm-wave frequencies. This translates directly into battery life, and tops the list of required developments for mobile mm-wave communications. Simultaneously achieving high linearity and efficiency requires both a capable technology and accurate designs that are able to control and redirect harmonic energy at hundreds of GHz back to a transistor to boost efficiency.

CTL is working to introduce new characterization techniques and design flows that will guarantee design accuracy and first-pass design success. This requires two important measurement advances, 1) the development of large-signal mm-wave measurement capability, with harmonics above 60 GHz and 2) an uncertainty analysis of the measurement, modeling, and manufacturing processes that is capable of calculating the probability of a circuit functioning as intended in the original design.

CTL is working to develop new measurement technologies for characterizing the behavior of mm-wave devices when excited by large, modulated signals. New instruments designed in these projects promise to lead to full and direct large-signal circuit characterization without the need to extrapolate performance from measurements performed at lower frequencies. CTL has also developed the traceable fundamental measurements and statistical tools that enable NIST to characterize high-speed circuits and signals with correlated uncertainties, transformable between the time and frequency domains. This work has led to the NIST Microwave Uncertainty

Framework; a common framework for transporting measurements with correlated uncertainties to the next measurement system. This framework supports a complex traceability chain for many high-speed/high-bandwidth measurements, as shown in the Fundamental to Delivered Framework figure. As an example application, CTL used this framework to discriminate between measurement and modeling errors and variations due to manufacturing tolerances, demonstrating the need for improved models of certain HBT transistors.



OUTPUTS

5G mm-wave Channel Model Alliance

CTL engages industry, government, and academic stakeholders to identify additional measurements and metrology R&D gaps in support of the development of wireless communication systems and standards. Based on industry interviews, CTL assessed the future generation wireless communication R&D landscape and published the results in "Future Generation Wireless Research and Development Gaps Report", NIST Special Publication 1219, https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1219.pdf. CTL continues to be active in other standards and road-mapping efforts, including the IEEE "5G and beyond" Roadmap working group. Information on the working group is available at https://futurenetworks.ieee.org/roadmap.

Establishment of 5G mm-wave Channel Model Alliance and Hosting of millimeter-wave Data Repository

CTL established the 5G mm-Wave Channel Model Alliance, a group consisting of 175 participants representing over 78 companies and organizations worldwide (government, industry, academic). CTL is also hosting the millimeter-wave data repository to provide industry and the NIST stakeholder community with channel propagation measurements, datasets, and models.

Contributions to ANSI C63 Working Group

A member of the Wireless Coexistence Project served as Co-Chair to the ANSI C63.27 Working Group and led the effort to revise the standard per requests from industry and users. CTL developed text for the document, provided leadership to the group, and served as secretary for the parent subcommittee

AI May Be Better for Detecting Radar Signals, Facilitating Spectrum Sharing

When vacationers buy a stake in a beachfront timeshare, they decide in advance who gets to use the property when.

The National Institute of Standards and Technology (NIST) is helping the Federal Communications Commission (FCC) institute a similar plan for when commercial wireless providers and the U.S. Navy attempt to share a desirable 150-megahertz (MHz)-wide section of the radio frequency (RF) spectrum for communications.

In a new paper, NIST researchers demonstrate that deep learning algorithms—a form of artificial intelligence—are significantly better than a commonly used, less sophisticated method for detecting when offshore radars are operating. Improved radar detection would enable commercial users to know when they must yield the so-called 3.5 Gigahertz (3.5 GHz) Band.

In 2015, the FCC adopted rules for the Citizens Broadband Radio Service (CBRS) to permit commercial LTE (long-term evolution) wireless equipment vendors and service providers to use the 3.5 GHz Band when not needed for radar operations.

Companies such as AT&T, Google, Nokia, Qualcomm, Sony and Verizon have been eager to access this band (between 3550 and 3700 MHz) because it will expand product markets and give end users better coverage and higher data rate speeds in a variety of environments where service is traditionally weak.

NIST helped develop 10 standard specifications that enable service providers and other potential users to operate in the 3.5 GHz Band under FCC regulations while assuring the Navy that the band can be successfully shared without RF interference. These standard specifications, including the algorithm for protecting military incumbent users, were approved in February 2018 by the Wireless Innovation Forum Spectrum Sharing Committee (WINNF SSC), the public-private standards body for the CBRS. However, there are presently no official standards for determining when the military is using the band. The new study, reported in the journal IEEE Transactions on Cognitive Communications and Networking, represents the latest NIST research effort toward achieving that goal.

In current practice, radar signals from ships at sea are identified using automated detectors that look for energy rises in the electromagnetic spectrum. "However," said Michael Souryal, lead for the NIST spectrum sharing support project, "these energy detectors are not discriminating enough to consistently get it right, sometimes confusing other RF signals as radar or missing the radar signatures altogether."

Souryal and his colleagues turned to artificial intelligence (AI) for a potential solution. Eight deep learning algorithms—software systems that learn from pre-existing data—were trained to recognize offshore radar signals from a collection of nearly 15,000 60-second-long spectrograms (visual representations of the radar signals over time). These spectrograms were recorded in 2016 near naval bases in San Diego, California, and Virginia Beach, Virginia, for the National Advanced Spectrum and Communications Test Network (NASCTN).

After training, the deep learning algorithms were pitted against energy detectors to see which performed best at identifying and classifying a set of spectrograms different from the ones used to educate the AI detectors.

"We found that three of the deep learning algorithms appreciably outperformed the energy detectors," Souryal said.

The best deep learning algorithm and the spectrogram collection were used to develop 3.5 GHz Band "occupancy statistics," datasets that describe when the band is available and for how long.

Now that the NIST researchers have validated the use of the deep learning algorithms, they plan to continue refining the AI detectors by training them with higher-resolution, more-detailed radar data, which they believe should lead to even better performance.

Source: https://www.nist.gov/news-events/news/2019/02/ai-may-be-better-detecting-radar-signals-facilitating-spectrum-sharing

NIST

CTL Communications Technology Laboratory on Unlicensed Personal Communications/Spectrum Etiquette. The ANSI C63.27. Working Group is leading the effort in standardization and measurement best practices to assess the coexistence of wireless devices in a spectrum sharing scenario. The C63.27 methodologies have been adopted by small and large companies such as Medtronic Corporation and Stryker Corporation. Intertek offers services on the standard Northwest EMC as part of the Element Materials Technology Group, offering testing services (lab accredited), and Keysight Technologies is discussing coexistence testing with its clients.

Contributions to CTIA Standardized Test Methods and Uncertainties for Large-form-factor Cellular Devices

CTL has continued contributions to the development of standardized certification tests for cellular-enabled IoT devices and to the Cellular Industry Association's (CTIA's) Wireless Internet of Things Subgroup. This work resulted in the publication of the "CTIA Test Plan for Wireless Large-Form-Factor Device Over-the-Air Performance", (2017). Once the test plan becomes mandatory, a broad class of large-form-factor cellular IoT devices will be certified according to this test plan, with application to hundreds of new models of cellular-enabled devices deployed annually. The new NIST-developed test methods and uncertainties were designed to address the wireless IoT device industry's needs for practical, rapid and accurate test approaches. An important aspect of the NIST team's work was to ensure that the tests are sufficiently general to allow manufacturers the flexibility to innovate their chamber designs while maintaining rigor and providing the fundamental theory through journal publications.

IEEE P1765 Uncertainty in EVM Standard

Members of the Over the Air Metrology Project and High-Speed Metrology groups participated in the working group that consists of more than 12 voting members and 30 participants, with representatives from all major test instrumentation manufacturers, academic institutions, and other NMIs. CTL supported the development of the IEEE standard "Recommended Practice for Estimating the Uncertainty in Error Vector Magnitude of Measured Digitally Modulated Signals for Wireless Communications."

This work impacts many sectors of the telecommunications industry because many diverse wireless telecommunication organizations and standards bodies require the calculation of system-level distortion metrics such as error vector magnitude, but, to date, there is no uniform approach to deriving uncertainty in EVM. NIST has received requests for such traceable uncertainties in EVM for over 10 years. This work will provide test equipment manufacturers and other users with a uniform, traceable approach to this issue. Recommended practice will incorporate NIST and NPL research that allows independent, traceable calibration of receivers. The NIST approach makes it possible to incorporate correlated uncertainties, which are important at millimeter-wave frequencies. Most prior techniques are unable to separate the distortion introduced by a waveform generator from that of the receiver.

Contributions to IEEE 802,11ay to Support the Development of a millimeter-wave Propagation Channel Model

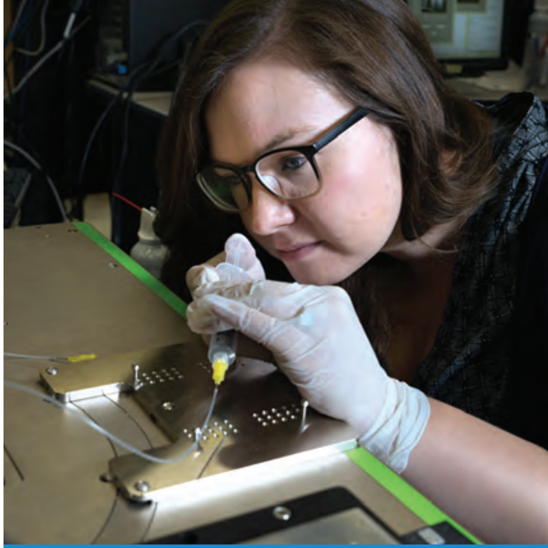
CTL developed a millimeter-wave propagation channel model to support the performance evaluation of IEEE 802.11ay (WiFi at 60 GHz) standard specifications. This model was included by Mathworks in their 2018 release of the WLAN tool box. It is also being used by Ball Aerospace to evaluate and develop phased-array antenna systems.

U.S. PATENT ACTIVITY IN 2018:

- FULL PATENT: (From Antenna Metrology Work) US PATENT NO 10,078,898 B2, Title: "NONCONTACT METROLOGY PROBE FOR MAKING AND USE OF SAME", Awarded September 18, 2018
- PROVISIONAL: (From Antenna Metrology Work) U.S. Provisional Patent Application serial number 62/721,099, Title: "A NON-CONTACT COORDINATE MEASURING MACHINE USING A PIXEL PROBE," was filed on August 22, 2018
- SPIN-OFFS: (From Rydberg Atom Electric-Field Sensing Work) Rydberg Technologies LLC in Michigan is a direct spin off from our collaborations. In fact, after NIST's success with the DARPA funding, DARPA awarded a Phase I and Phase II SBIR to develop the atom-based probe to Rydberg Technologies. They will have a commercial product in 6 months

2018 NIST Bronze Medal Award

Staff members from CTL were recognized for significantly advancing standards to enable mission-critical voice over broadband networks for public safety applications. CTL's sustained efforts have led to new products with mission-critical voice capabilities that will have significant impacts on multi-agency coordination during periods of severe network congestion and large disaster events by leveraging the broadband capabilities of FirstNet. These products will enable public safety communication across organizations on commercially available public safety devices from smartphones to tablets to laptops.



WinnForum Steering Committee

CTL has made numerous contributions to the WinnForum Steering Committee on Spectrum Sharing. Contributions include test methods and reference implementations as part of the CBRS standards.

PUBLICATIONS IN ARCHIVAL PROFESSIONAL JOURNAL/CONFERENCE PROCEEDINGS

Several hundred articles have been published in conference proceedings, archival journals, and as NIST Special Publications and Technical Notes. Formal recognitions include:

- Best Paper Award for the CTL Rydberg Atom Work—RF Field Group 672.02
- Best paper at the 2018 GSMM conference: "High-resolution antenna near-field imaging and sub-THz measurements with a small atomic vapor-cell sensing elements"
- Best paper at the 2018 EMC Europe conference: "Development and Applications of a Fiber-Coupled Atom-Based Electric Field Probe"
- Best paper at the 2018 AMTA conference: "Development of A New Atom-Based SI Traceable Electric-Field Metrology Technique"
- Second Place Best paper at the 2018 EMC Europe conference: "Uncertainties in Rydberg Atom-based RF E-field Measurements"

Best Poster Paper Award

ARFTG, June 2018, "Quantifying variance components for repeated scattering parameter measurements," authored by members of the Statistical Engineering Division (Information Technology Laboratory) and the High-speed Measurements Group.

R & D 100 Award

"For the development of a Radiation Pressure Power Meter that enables extremely high continuous laser powers to be measured as the force applied by the laser light reflects from a mirror. And improving on conventional power meters as a truly portable, lighter, faster, measurable, and traceable primary standard device." Awarded to members of the Applied Physics Division (Physical Measurement Laboratory) and the High-speed Measurements Group.

Summary of Opportunities and Challenges

OPPORTUNITIES

Optical Communications and Quantum Networks

Prior to the formation of CTL, NIST supported the optical communications industry through measurement services and standard reference materials. The NIST technology was successfully adopted by commercial testing houses, which caused the NIST program to become dormant. More challenging measurement problems resulted from the recent and significant investments in U.S. optical fiber communications infrastructure. For example, developing meaningful system-level measurements that would guide the design and operation of software defined networks poses a formidable challenge to researchers.

Furthermore, the high-bandwidth and low-latency requirements of 5G wireless communications—as well as increasing demand for mobile, high data content applications (e.g., video streaming, video gaming, and AR)—will continue to stress the fiber-optic communications network backbones. Lastly, quantum computers and networks are receiving a great deal of attention both domestically and internationally, and are the subject of a recent budget initiative in Congress. While CTL is not currently funded for activities targeted at classical or quantum optical communications, CTL is developing plans for future NIST investment in these areas while collaborating with other NIST OUs using non-base funding. For example, CTL is working with the Physical Measurement Laboratory and the Information Technology Laboratory to construct the world's first small-scale quantum network of superconducting quantum nodes. This network will function as a testbed and technology pathfinder, positioning NIST in a leadership role to tackle the measurement challenges of the future quantum internet. While working to develop such a network, NIST will develop the necessary interfaces between superconducting qubits and optical fiber networks, the supporting network protocols, and the required metrics, measurements, and characterization tools.

RF metrology will also play a key role in making superconducting quantum computing operational. Practical quantum computers will consist of 103–105 physical qubits, necessitating massive monolithic integration of both the qubits and signal conditioning/readout components. Yet on-chip microwave characterization technology is nearly non-existent at the mK temperatures required in such systems. Systematically de-bugging the inevitable microwave

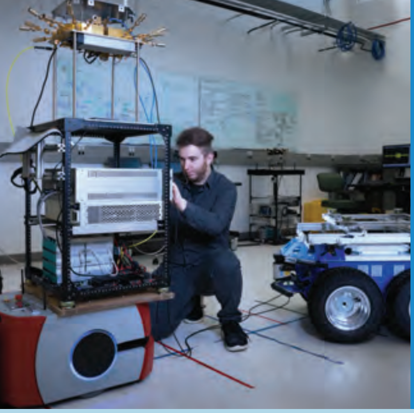
circuit problems in complex quantum integrated-circuit technologies, such as distortion in input and output signals, impedances and cross-talk between qubits, is impossible with existing on-chip measurement technology. However, these integrated circuits reside inside large dilution refrigerators at mK temperatures and signals must be transferred into and out of the refrigerator through lossy coaxial signal conditioning components including cables, isolators, couplers, attenuators, and amplifiers, making calibrations impossible with today's technology.

NIST is considering development of traceable on-chip calibration techniques at microwave frequencies for use in dilution refrigerators. This effort would leverage the full waveform-metrology technologies now used at room temperature to great effect by CTL and the microwave industry. Using this new technology, NIST could bring these room-temperature measurement techniques directly to the nascent quantum-computing industry with unprecedented accuracy. NIST expects that the availability of new measurement techniques and measurement services at NIST, and elsewhere, will greatly accelerate the development of superconducting and quantum information science.

CHALLENGES

CTL continues to face challenges associated with recruiting and retaining staff with expertise in wireless communications given the availability of private sector opportunities. CTL must seek out overlaps between industry needs and existing CTL resources—both technical expertise and facilities—to maximize impact given budget uncertainties related to the expiration of the Public Safety Trust Auction Funds.

CTL has made considerable investments in new facilities for fundamental measurements, including the ACML, the new laboratory, and office space in Wing 6. However, the ACML is housed in a 1960's vintage Building that has inadequate temperature control for the mm-wave frequencies targeted by this facility. Furthermore the data interconnects between Building 24 and the new computer server facility are inadequate for the data intensive research housed there. Measurement services, research, and offices in Wing 6 sometimes have incompatible temperature and humidity requirements and the controls must be customized for some of these activities or new space must be found.



NIST's Antenna Evaluation Method Could Help Boost 5G Network Capacity and Cut Costs

Researchers at the National Institute of Standards and Technology (NIST) have developed a method for evaluating and selecting optimal antenna designs for future fifth-generation (5G) cellphones, other wireless devices and base stations.

The new NIST method could boost 5G wireless network capacity and reduce costs.

5G systems will avoid crowded conventional wireless channels by using higher, millimeter-wave frequency bands. Transmissions at these frequencies lose a lot of energy along the way, which weakens received signal strength. One solution is "smart" antennas that can form unusually narrow beams—the area in space where signals are transmitted or received—and rapidly steer them in different directions.

Antenna beamwidth affects wireless system design and performance. NIST's new measurement-based method allows system designers and engineers to evaluate the most appropriate antenna beamwidths for real environments.

"Our new method could reduce costs by enabling greater success with initial network design, eliminating much of the trial and error that is now required," NIST engineer Kate Remley said. "The method also would foster the use of new base stations that transmit to several users either simultaneously or in rapid succession without one antenna beam interfering with another. This, in turn, would increase network capacity and reduce costs with higher reliability."

This is the first detailed measurement-based study of how antenna beamwidth and orientation interact with the environment to affect millimeter-wave signal transmission. In the technique, NIST measurements covering a broad range of antenna beam angles are converted into an omnidirectional antenna pattern covering all angles equally. The omnidirectional pattern can then be segmented into narrower and narrower beamwidths. Users can evaluate and model how antenna beam characteristics are expected to perform in specific types of wireless channels.

An engineer could use the method to select an antenna that best suits a specific application. For example, the engineer may choose a beamwidth that is narrow enough to avoid reflections off certain surfaces or that allows multiple antennas to coexist in a given environment without interference.

To develop the new method, the NIST team collected experimental data in a hallway and lobby of a NIST research building, using a special robot loaded with a customized channel sounder and other equipment. A channel sounder collects data that capture the signal reflections, diffractions and scattering that occur between a transmitter and receiver. Many such measurements can be used to create a statistical representation of the radio channel, to support reliable system design and standardization.

NIST study results confirm that narrow beams can significantly reduce signal interference and delays, and that an optimized beam orientation reduces energy loss during transmissions. For example, the time interval during which signal reflections arrive (a metric called RMS delay spread) dropped dramatically from 15 nanoseconds (ns) to about 1.4 ns as antenna beamwidth was reduced from omnidirectional (360 degrees) to a narrow 3 degrees or so-called pencil beam.

Future research will include extending the method to different environments and analysis of other wireless channel characteristics.

Source: https://www.nist.gov/news-events/news/2018/12/nists-antenna-evaluation-method-could-help-boost-5g-network-capacity

APPENDIX A:
RESPONSES TO THE PREVIOUS NRC PANEL RECOMMENDATIONS FOR CTL

ASSESSMENT OF THE COMMUNICATIONS TECHNOLOGY LABORATORY

FINDING: CTL has adequate and sufficiently stable financial resources to carry out its mission. The high portion funding that comes from appropriations provides significant stability to CTL.

RESPONSE: CTL has adequate resources to carry out its mission until the NIST Public Safety Communications Research Fund expires in 2022. These time-limited funds are targeted at helping develop cutting-edge wireless technologies for public safety users, as part of the National Wireless Initiative included in the Middle Class Tax Relief and Job Creation Act of 2012. CTL is actively pursuing multiple avenues to replace these funds, including the federal initiative process, support from other federal agencies, and expansion of its measurement service portfolio to address communications industry's most challenging test and measurement needs.

FINDING: Channel models play a key role in the design and deployment of wireless systems and in the adoption of standards. Mm-wave radio frequency technology is a promising tool for meeting future demands for wireless system capacity. Participation in the 5G Millimeter Wave Channel Model Alliance contributes to the quality and visibility of CTL's mm-wave model research.

RECOMMENDATION: CTL should maintain a position of leadership in the 5G 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.

RESPONSE: Launched in July 2015, the NIST 5G mmWave Channel Model Alliance helps accelerate the development and use of accurate measurements and models for next-generation communications technology. By bringing together researchers from multiple stakeholders—including communications technology companies, academia and government—NIST is accelerating 5G innovation.

NIST's establishment of the alliance has brought together more than 175 participants from over 75 organizations, including representatives from Qualcomm, Intel, Samsung, Keysight and Echostar, to solve the most pressing modeling and measurement challenges facing the deployment of 5G wireless communications. The output of NIST's research and that of the alliance is being incorporated into the development of standards, specifications and best practices benefitting the entire industry. Charlie Zhang, Vice President, Samsung Research America, has cited the NIST leadership of this effort as "instrumental in inspiring continued contributions from top experts in government, academia, as well as industry toward this important goal over the last couple years."

FINDING: CTL staff has identified an appropriate set of communication technology priorities and has begun building the appropriate research activities to support future communication needs. This work is centered on solving fundamental problems (with an eye toward application) and verification, measurement, and testing. However, this research agenda does not outline specific tasks to advance these problems.

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

RESPONSE: Since 2015, CTL has engaged its staff in a rigorous annual research planning process focused on the CTL program areas of public safety, trusted spectrum testing, and metrology for advanced communications. CTL's process consists of three major steps:1.) Process Review, 2) Program Review, and 3) Resource Allocation.

During the Process Review, the CTL Leadership Team, consisting of CTL Director, Executive Officer, Division Chiefs, and NASCTN Program Manager, review lessons learned from prior years, suggestions, or unique circumstances that may impact the next year's efforts. Inputs are considered and incorporated into the process and approved by the Lab Leadership Team (LLT).

The Planning Process is then released to the staff and a question and answer session is held to address any concerns. During the Program Review process, each active project submits a Project Review Summary and a Project Plan including a proposed budget. New projects submit an abbreviated proposal for initial consideration. This allows evaluation of new proposals without requiring a full package. If further development of the idea is warranted after review by the LLT, a full proposal is requested. Program Champions digest project plans in order to create a Program Portfolio consisting of recommendations to fully fund, partially fund, or not fund each submission within their program. This is a collaborative effort between all involved in the Program. During a Program Review meeting, Champions present previous year's successes and failures, propose plans for the next FY, field questions, engage in discussion, etc.

Resource Allocation occurs at the Laboratory level with the Laboratory Leadership Team recommending a finalized list of Projects to the OU Director for approval. The OU Director has final approval authority. The CTL budget is finalized and released and is briefed at the start of year CTL Town Hall Meeting.

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.

RESPONSE: Since 2015, CTL has made significant investments in upgrading its antenna metrology facilities and 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 Public Safety Communications Research Division. CTL has also aggressively pursued multiple avenues for quickly staffing its programs. In addition to traditional federal hiring mechanisms, CTL has brought in contractors as well as federal employees from other agencies on detail. CTL has also used the NIST Professional Research Experience Program to attract staff at all levels—from senior professionals to undergraduate student interns.

FINDING: CTL has put in place opportunities to engage with stakeholders and receive outside technical reviews.

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.

RESPONSE: In addition to the NIST 5G mmWave Channel Model Alliance, CTL sponsors the annual Public Safety Broadband Stakeholder Meeting that brings together representatives from public safety, federal agencies, industry, and academia. Participants hear from PSCR engineers about testing updates, upcoming R&D efforts, and opportunities to get involved. PSCR invites industry leaders and public safety partners to present on cutting edge technology trends, features, and functionalities. The annual Stakeholder Meeting enables PSCR to receive direct input, guidance, and feedback from their diverse stakeholder community. In 2018, the meeting attracted over 500 stakeholders, featured concurrent conference tracks across seven research areas, provided access to over 30 onsite demos, and hosted the final stages for live prize challenge related to virtual reality devices.

In addition, CTL staff gave talks and served on industry panels at leading communications conferences and venues, including Telecom Infra Project Summit, IEEE 5G World Forum, IEEE International Conference on Communications, Critical Communications World, IEEE International Microwave Symposium, and the Automatic Radio Frequency Techniques Group.

COLLABORATION AT THE BOULDER TELECOMMUNICATIONS LABORATORIES

FINDING: CAC is in the very early stages of planning and development. The current co-leadership structure may make setting and implementing priorities challenging.

FINDING: PSCR is an example of successful collaboration between ITS and CTL, providing essential public communication services to the federal government and the public safety community.

FINDING: NASCTN, as described, would respond to important national needs, but its processes are still in their formative stages; therefore, it has not yet demonstrated its ability to meet these needs or to effectively coordinate use of federally supported test facilities.

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

RESPONSE: NIST CTL and NTIA ITS leadership continue to build upon collaborations across both laboratories. Evidence of the success is NTIA involvement in both NASCTN and PSCR programs. More recently, CTL and ITS leadership have worked together to revise NASCTN model and expand its membership.

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

RESPONSE: The NIST Public Safety Communications Research Program is viewed as a successful collaborative program. Metrics of this success include multiple award-winning projects with teams consisting of NIST staff from both CTL as well as other NIST organizations.

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.

RESPONSE: NASCTN is fully functional and has successfully completed several projects since its inception in 2015. NASCTN has expanded its membership to include NOAA, NASA, and NSF in addition to DOD and NTIA. Completed projects include measurements on the impact of user equipment (UE) aggregate long term evolution (LTE) emissions on federal systems in the AWS-3 Band, LTE impact on GPS receivers, as well as effects of LTE out-of-band emissions in the AWS-3 Band. These NASCTN projects brought together both commercial and federal agencies working towards a common measurement framework. Outcomes of these projects enabled DOD test ranges to invest in protective equipment and processes. Finally, these successful projects have led to acceptance of NASCTN as a neutral body for key data inputs to LTE and GPS policy discussions.

NATIONAL TELECOMMUNICATIONS RESEARCH NEEDS AND THE FUTURE ROLE OF THE BOULDER TELECOMMUNICATIONS LABORATORIES

FINDING: Advances in communications and networking technologies will have significant positive social and economic impact provided that the associated increasing demand for wireless communications can be met. New spectrum (both licensed and unlicensed) to support increased use of mobile and the Internet of Things devices has been slow in emerging. There is a need for neutral, technical expertise to determine when spectrum is underutilized, review technology for shared use, and evaluate interference and enforcement.

RESPONSE: NASCTN has established itself as a neutral body for the development of independent test methodologies and trusted test data that can be used to evaluate spectrum-sharing technologies and inform spectrum policy and regulations. NASCTN develops scientifically rigorous test plans, provides access to key test facilities, validates data analysis and test results, and most importantly operates as a trusted agent to protect proprietary, sensitive, and classified information.

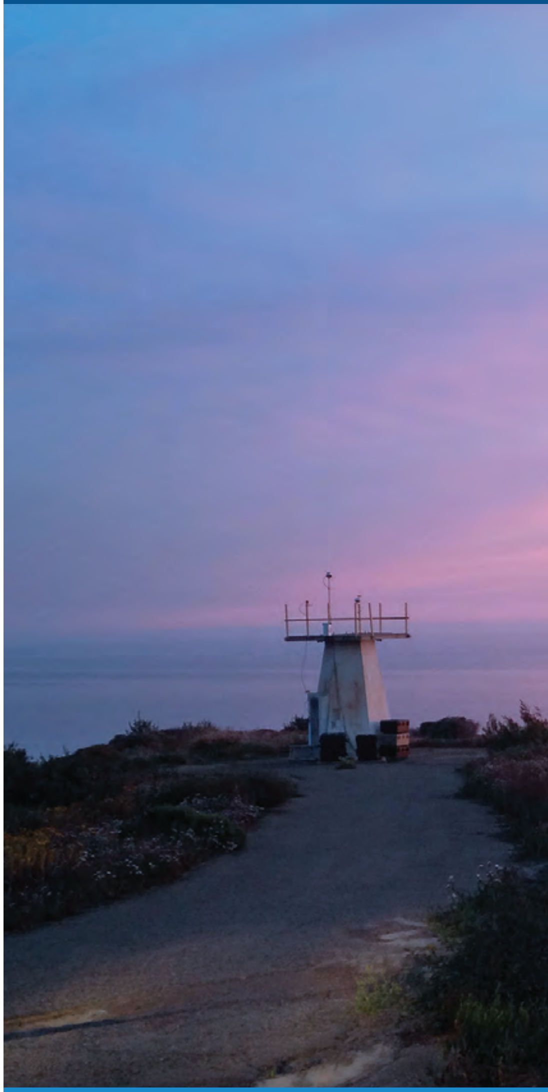
RECOMMENDATION: The DOC should develop short- and long-term application and basic research plans that would provide the country with the necessary knowledge base in spectrum areas and enhance the capability for spectrum sharing and repurposing analysis. The DOC plans should include opportunities for 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.

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.

RESPONSE: CTL staff serve in leadership and/or advisory roles across federal agencies, standards development organizations, as well as industry consortium. These organizations include, but are not limited to: NSF Millimeter-Wave Research Coordination Network Steering Committee, NIST 5G mmWave Channel Model Alliance, Telecom Infra Project (TIP), White House Office of Science and Technology Policy, U.S. Government Accountability Office, National Spectrum Consortium, and Wireless Spectrum R&D Interagency Working Group.

RECOMMENDATION: The Boulder telecommunications laboratories should fully engage in the current and emerging work in 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.

RESPONSE: CTL, leveraging its partnerships across NIST and industry, is fully engaged the major international standards efforts, including IEEE 802, 3GPP, Telecom Infra Project, and the Internet Engineering Task Force. As evidence of their impact, a CTL team was recognized with a 2018 NIST Bronze Medal for their contributions to 3GPP standards for mission critical voice for public safety. Since 2011, the group worked to create dozens of standards that were ultimately accepted and met all public safety mission critical voice requirements, while including numerous ancillary features. Companies that have implemented these standards include Qualcomm, Motorola, Telstra, SONIM, Kodiak, and Nokia among others. CTL is now recognized amongst the standards communities for its science-based approach to standards development leading to accelerated standards adoption.



APPENDIX B: GLOSSARY OF ACRONYMS

ACML — Antenna Communication and Metrology Laboratory

AMT — Aeronautical Mobile Telemetry

ANSI — American National Standards Institute

AR — Augmented Reality

ARFTG — Automatic Radio Frequency Techniques Group

CAC — Center for Advanced Communications

CBRS — Citizens Broadband Radio Service

CoECI — Center of Excellence for Collaborative Innovation

COTS — Commercial Off-The-Shelf

CRADA — Cooperative Research and Development Agreements

CRE — Coordination Request Evaluation

CROMMA — Configurable Robotic Millimeter-Wave Antenna

CTIA— The Wireless Association

CTL — Communications Technology Laboratory

D2D — Device to Device

DHS — Department of Homeland Security

DISA — Defense Information Systems Agency

DOC — Department of Commerce

DOD — Department of Defense

DSO — Defense Spectrum Organization

EMC — Element Materials Technology Group

EMS — Emergency Medical Services

EOS — Electro-Optic Sampling

EPC — Evolved Packet Core

ESC — Environmental Sensing Capability

EVM — Error Vector Magnitude

EWBM — Electronic Warfare Battle Management

FCC — Federal Communications Commission

FFRDCs — Federally Funded Research and Development Centers

FPO — Federal Program Officers

FY — Fiscal Year

GPS — Global Positioning Services

GRP — Gross Rating Point

HBT — Heterojunction Bipolar Transistor

HMDN — Highly Mobile Deployable Network

HQ — Head Quarters

HUD — Heads Up Display

IAA — Interagency Agreements

ICAM — Identity Credential and Access Management

IEEE — Institute of Electrical and Electronics Engineers

IIoT — Industrial IoT

IMS — Innovations in Measurement Science

IMS — IP Multimedia System

IoT — Internet of Things

ISART — International Symposium on Advanced Radio Technologies

IT — Information Technology

ITL — Information Technology Lab

ITS — Institute of Telecommunication Sciences

IWF — Interworking Function

KPIs — Key Performance Indicators

LAPS — Large Antenna Positioning System

LBS — Location-Based Services

LiDAR — Light Detection and Ranging technology

LLT — Lab Leadership Team

LMR — Land Mobile Radio

LTE — Long-Term Evolution

MAC — Medium Access Control

MCPTT — Mission Critical Push to Talk

MCV — Mission Critical Voice

MIMO — Multiple Input/ Multiple Output

MOA — Memorandum of Agreement

NASA — National Aeronautics and Space Administration

NASCTN — National Advanced Spectrum and Communications Test Network

NBIT — National Broadband Interoperability Test Bed

NCCoE — National Cybersecurity Center of Excellence

NIH — National Institutes of Health

NIST — National Institute of Standards and Technology

NPL — National Physical Laboratory

NRC — National Research Council

NSF — National Science Foundation

NTIA — National Telecommunications Information Administration

OI — Open Innovation

OoB — Out-of-Band

OTA — Over-the-Air

OUSD — Office of the Under Secretary of Defense

PREP — Professional Research Experience Program

ProSe — Proximity Services

PSCR — Public Safety Communications Research

PSIAP — Public Safety Innovation Accelerator Program

PSO — Public Safety Organizations

QoE — Quality of Experience

QoS — Quality of Service

QPP — Priority and Preemption

R&D — Research and Development

RDT&E — Research, Development, Testing, and Evaluation

RF — Radio Frequency

SAS — Spectrum Access Systems

SBIR — Small Business Innovation Research

SDK — Software Development Kit

SIM Card — Subscriber Identity Module Card

STRS — Scientific and Technical Research Services

TIP — Telecom Infra Project

TTRs — Test And Training Ranges

UAS — Unmanned Aerial Systems

UE — Multiple User Equipment

UI/UX — User Interface/User Experience

UI — User Interface

VR — Virtual Reality

WISE3R — Wireless Intelligent Systems E3 Research

WLAN — Wireless LAN (Local Area Network)

WN — Wireless Networks Division

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