Telecommunications Research and Engineering at the Communications Technology Laboratory of the Department of Commerce: Meeting the Nation's Telecommunications Needs

DETAILS

64 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-37980-9 | DOI: 10.17226/21828

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TELECOMMUNICATIONS RESEARCH AND ENGINEERING AT THE COMMUNICATIONS TECHNOLOGY LABORATORY OF THE DEPARTMENT OF COMMERCE

Meeting the Nation's Telecommunications Needs

Committee on Telecommunications Research and Engineering
at the Department of Commerce's Boulder Laboratories

Computer Science and Telecommunications Board

Division on Engineering and Physical Sciences

The National Academies of
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THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

This study was supported by National Institute of Standards and Technology. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project.

International Standard Book Number-13: 978-0-309-37980-9
International Standard Book Number-10: 0-309-37980-6

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Printed in the United States of America

Suggested citation: National Academies of Sciences, Engineering, and Medicine. 2015. *Telecommunications Research and Engineering at the Communications Technology Laboratory: Meeting the Nation's Telecommunications Needs.* Washington, DC: The National Academies Press.

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Preface

The 2006 National Research Council report *Renewing U.S. Telecommunications Research* observed that "the telecommunications industry remains of crucial importance to the United States as a society, that a strong telecommunications research capability continues to be essential to the health and competitiveness of this U.S. industry internationally, and that the health of this industry strongly affects the U.S. economy in many ways."[1] In recent years, use of radio-frequency (RF) communications has grown tremendously, making it especially important to use the RF spectrum more efficiently.

The Department of Commerce (DOC) operates two laboratories concerned with communications technologies collocated at its Boulder, Colorado, campus (referred to collectively in this report as the Boulder telecommunications laboratories). The National Telecommunications and Information Administration (NTIA) operates a telecommunications research and engineering laboratory, the Institute for Telecommunication Sciences (ITS). ITS serves as a principal federal resource for solving the telecommunications concerns of federal agencies, state and local governments, private corporations and associations, standards bodies, and international organizations. ITS helps carry out NTIA's mission by performing research and engineering to support government and private industry in managing the radio spectrum and making effective use of new technologies. Much of the ITS annual operating budget comes from federal and private research sponsors rather than NTIA's direct appropriation. In 2014, the National Institute of Standards and Technology (NIST) established the Communications Technology Laboratory (CTL) to merge several current NIST laboratories into a single laboratory and to promote standards and metrology in the area of communications technologies. CTL develops appropriate measurements and standards to enable interoperable public safety communications, effective and efficient spectrum use and sharing, and advanced communication technologies. In June 2013, NTIA announced an agreement with NIST to establish a national Center for Advanced Communications (CAC) to better coordinate telecommunications-related research and engineering activities of ITS and NIST (now CTL). Figure P.1 outlines the organizations of the Boulder telecommunications laboratories.

This study originates in part from language in House Report 112-463, which accompanied Fiscal Year 2013 Commerce Justice, Science, and Related Agencies Appropriations, which directs NTIA to engage the National Academy of Sciences, Engineering, and Medicine to "analyze the research and activities of ITS and make recommendations regarding the extent to which ITS research is addressing future telecommunications challenges and spectrum needs."[2] Subsequently, NIST, on behalf of itself and NTIA, asked that the Academies carry out assessments of both ITS and CTL. Two separate task orders were issued calling for these assessments to be performed by a single study committee, the Committee on Telecommunications Research and Engineering at the Department of Commerce's Boulder Laboratories. This report provides the Academies' assessment of CTL. A separate report provides the Academies'

[1] National Research Council, *Renewing U.S. Telecommunications Research*, The National Academies Press, Washington, D.C., 2006, p. 4.

[2] Commerce, Justice, Science, and Related Agencies Appropriation Bill, House Report 112-463, 2013, p. 15, http://thomas.loc.gov/cgi-bin/cpquery/R?cp112:FLD010:@1(hr463).

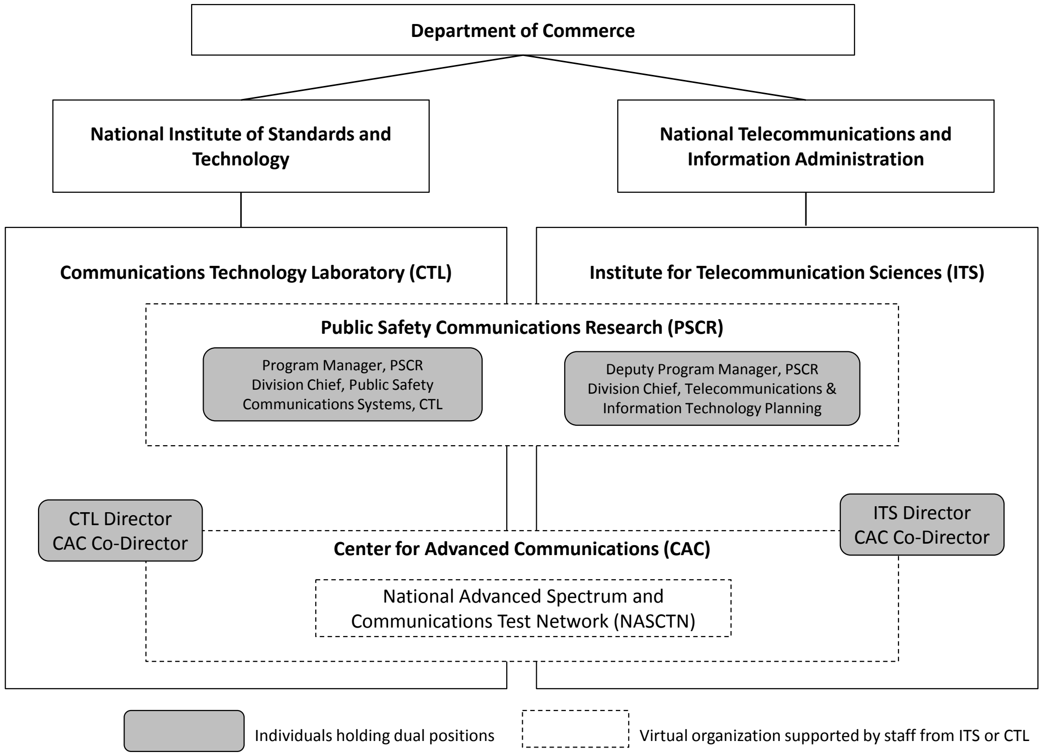

FIGURE P.1 The Boulder telecommunications laboratories.

assessment of ITS.[3] Both reports contain sections examining (1) collaborative efforts between the two laboratories, including CAC, National Advanced Spectrum and Communications Network (NASCTN), and Public Safety Communications Research (PSCR), and how these programs support NIST and NTIA missions and (2) national priorities in telecommunications research and the role in which the Boulder telecommunications laboratories can play. Appendix A provides the committee's statement of task.

The study committee visited the Boulder telecommunications laboratories on April 22, 2015, meeting with staff from CTL to understand the current activities of the laboratory, its strengths and weaknesses as an organization, and its plans for the near future. The committee also met with additional stakeholders, including industry and government organizations who have used the Boulder telecommunications laboratories resources (listed in Appendix C). The assessment included in this report stems from these visits and discussions and the committee's own expertise.

Douglas Sicker, *Chair*
Committee on Telecommunications Research and Engineering at the Department of Commerce's Boulder Laboratories

[3] National Academies of Sciences, Engineering, and Medicine, *Telecommunications Research and Engineering at the Institute for Telecommunication Sciences: Meeting the Nation's Telecommunications Needs*, The National Academies Press, Washington, D.C., 2015.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Vanu Bose, Vanu, Inc.,
Martin Cooper, Dyna, LLC,
David Liddle, U.S. Venture Partners,
Paul Milgrom, Stanford University,
David Morse, Corning Incorporated,
Tom Sorley, City of Houston, Texas, and
Andrew Viterbi, University of Southern California.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Louis Lanzerotti, New Jersey Institute of Technology, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Summary

The Department of Commerce (DOC) operates two telecommunications[1] research laboratories located at its Boulder, Colorado, campus: the National Telecommunications and Information Administration's (NTIA's) Institute for Telecommunication Sciences (ITS) and the National Institute of Standards and Technology's (NIST's) Communications Technology Laboratory (CTL).

The Boulder telecommunications laboratories currently play an important role in the economic vitality of the country and can play an even greater role given the importance of access to spectrum and spectrum sharing to the wireless networking and mobile cellular industries. Research advances are needed to ensure the continued evolution and enhancement of the connected world the public has come to expect. In addition to familiar portable communication and computing devices, anticipated deployment of a variety of new, connected "smart" devices will demand more access to spectrum and advanced networked communication technologies. The economic value of spectrum as a natural resource is illustrated by the $41 billion in revenue from the 2014-2015 advanced wireless services (AWS)-3 auction. New wireless applications such telehealth, machine-to-machine communications, and augmented reality will fuel further demand for wireless communications. The Boulder telecommunications laboratories serve an important role in communications research and engineering for the nation. Key areas include spectrum measurement and propagation modeling; applied research on wireless network access technologies; and applied research, testing, and evaluation of newly developed technologies. ITS and CTL also provide technical support to other federal agencies and the private sector, principally for spectrum measurement and analysis of spectrum sharing and service coexistence. ITS and CTL participate in several formal collaborative structures. The Public Safety Communication Research Program (PSCR), a long-standing (and well-regarded) collaboration between NIST and NTIA, is also collocated with ITS and CTL in Boulder. NTIA and NIST established the new Center for Advanced Communications (CAC) in 2014 to coordinate ITS and CTL programs on spectrum research and other communications work central to the goals of the DOC and established the National Advanced Spectrum and Communications Test Network (NASCTN) in 2015 to organize a network of test facilities to support spectrum-related testing, modeling, and analysis.

The Committee on Telecommunications Research and Engineering at the Department of Commerce's Boulder Laboratories visited the Boulder telecommunications laboratories on April 20-22, 2015, to receive briefings from and hold discussions with ITS and CTL staff to learn about current activities of each laboratory, their strengths and weaknesses, and plans for the near future. The sections below provide the committee's assessment of CTL, followed by discussion of two crosscutting topics—opportunities for collaboration and satisfying long-term national communications network infrastructure (both wired and wireless) research needs and long-term implications for both laboratories. The committee suggests a two-

[1] The term *telecommunications* is used throughout this report to mean technology-mediated communications and data transfer. Numerous applications, outside of what was historically termed telecommunications (telephony), today take advantage of a vast and complex communications network infrastructure that encompasses the Internet, traditional telephony, wireless technologies, communications satellites, and many other modes of communication. An expanded definition of telecommunications that is inclusive of a wide array of communications technologies and infrastructure and the applications that take advantage of it is imperative when considering the national research needs for advanced communications infrastructure.

prong strategy for developing technical expertise and research goals in telecommunications. First, CTL will need to further define the near-term research strategy it developed as part of its launch. Second, the DOC will need to develop short- and long-term applied and basic research plans to support national goals in areas such as spectrum sharing, service coexistence, and spectrum repurposing to ensure the most efficient use of its laboratories in achieving these goals.

ASSESSMENT OF THE COMMUNICATIONS TECHNOLOGY LABORATORY

CTL is a newly organized laboratory within NIST, formed mid-2014, and consists of the Boulder Laboratory Director Office, the Communications Test Coordination Office, the Public Safety Communications Research Division, the RF Technology Division, and the Wireless Networks Division (located at NIST in Gaithersburg, Maryland). According to its functional statement, CTL "promotes the development and deployment of advanced communications technologies, through the conduct of leading edge R&D." (See Box 1.2 for a full functional statement.) Because it is new and its planned work represents a departure from that carried out by the elements of which it was composed, the committee's assessment is focused on its available resources and future plans rather than past work.

Capabilities and Performance

In contrast to ITS, CTL is directly funded in large part from the DOC budget; 82.8 percent of the budget comes directly from NIST, while only 17.1 percent comes from other agencies via fees and through cooperative research and development agreements (CRADAs). As such, CTL is positioned to identify and carry out work directly relevant to its mission and national interest, including the following: building the capabilities to support NASCTN, developing situational awareness measurement and analytics for public safety communications, and metrology[2] for next-generation wireless networks. The commitment to metrology for next-generation wireless networks is essential because this will seed the laboratory with expertise in areas such as spectrum sharing, coexistence, and channel propagation and modeling, which are needed to characterize multipoint-to-multipoint wireless communications.

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

Strategy

It is important for a laboratory like CTL to stay engaged with the research and development (R&D) community at large and, in particular, be attuned to the research and technology needs of the private sector. The committee was encouraged by CTL's development of the 5G Millimeter Wave Channel Model Alliance,[3] which may serve as a model for further engagement with relevant R&D communities so that they can truly serve as an informed and engaged resource for the government as spectrum sharing technologies advance. While technical advances in millimeter-wave (mm-wave) radio frequencies are valuable in advanced new wireless communications because of the large amounts of unused mm-wave spectrum, other technologies will be important, including multiple input, multiple output (MIMO)

[2] *Metrology* is the science of measurement, including both theoretical and practical aspects of measurements.
[3] *5G* refers to emerging fifth-generation wireless communication systems and is considered the next major phase of mobile telecommunications standards. Millimeter wave is the extremely-high-frequency spectrum from 30 to 300 GHz.

techniques to increase spectrum capacity; spectrum sharing and management techniques; interference at boundaries and enforcement; bi-directional transmission on the same channel; and channel bonding techniques, including bonding between licensed and unlicensed services. Several of these are noted in CTL's technical plan.[4] However, CTL's technical plan is a list of broad potential research areas and lacks sufficient specific tasks and research goals. CTL will need to quickly develop a more specific and deeper research plan.

CTL identified a handful of challenges, including staffing and equipment, most of which stemmed from the newness of the organization. The committee anticipates that an increase in technical staff would further CTL's research agenda in positive ways. Furthermore, CTL will need to replace or update aging equipment at the Boulder laboratories.

Another way in which NIST can ensure that CTL understands the needs of the private sector is to utilize outside review. Outside technical reviews ensure that technical work aligns with national priorities and industry needs. As a new organization building its technical plans and capacity, frequent, perhaps even annual, review may be warranted.

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.

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.

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.

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.

[4] Laboratory Planning Communications Technology Laboratory FY2015, Program Coordination Office, National Institute of Standards and Technology, U.S. Department of Commerce, 2014 v1.

COLLABORATION AT THE BOULDER TELECOMMUNICATIONS LABORATORIES

Given that ITS and CTL are both operated by the DOC, are collocated in Boulder, Colorado, and have related missions, it is only natural that they collaborate on key areas of research.[5] Current collaborations include PSCR, a long-standing and highly successful collaboration between ITS and NIST, and two newly created collaboration mechanisms, CAC and NASCTN.

For many years, ITS and NIST have provided unique technical testing services and support in the arena of public safety communications and other technical services. Establishment of PSCR has further facilitated the cooperative use of ITS and CTL capabilities to serve the needs of public safety. PSCR is the only provider of objective, non-vendor–driven testing and evaluation services to the public safety community.

CAC, established in 2013 to coordinate research programs between ITS and CTL, is a virtual organization with no staff, funding, or resources of its own. Better coordination of ITS and CTL can leverage telecommunications-related research and engineering capabilities, ensure non-duplication of work, and, at the same time, propel each laboratory to develop and take ownership of its own areas of expertise and capability. The committee notes that it is important to ensure that both laboratories focus on work that reflects their strengths, although the committee is unsure if a formal organization is needed (versus a process to manage coordination across the Boulder telecommunications laboratories). However, CAC could facilitate this collaboration by serving in a centralized program management role to further national priorities in communications and spectrum use and coordinate research programs outlined by ITS and CTL.

The committee understands the desire to ensure that each laboratory is adequately represented within the new CAC. However, there is significant concern that the current structure of CAC—in which the directors of CTL and ITS are co-leaders of CAC, with no one individual in charge—may make it difficult to set and implement priorities. (PSCR is operated by a program manager from NIST and a deputy program manager from ITS.) CTL and ITS leaders will need to build a collegial relationship with one another and work to build a similar relationship within each research and technical division. This task, while not necessarily technical in nature, will be important if the collaborative goals of CAC—or any other collaboration—are to be met.

NASCTN was established in 2015 to increase commercial and federal access to spectrum by helping to accelerate the design and deployment of spectrum-sharing technologies through accurate testing and modeling. The intent is to create an environment of trust to support impartial testing and evaluation of new spectrum sharing technologies and, ultimately, promote balanced policy decisions that are driven by scientifically sound tests and evaluations. NASCTN is meant to enable sound policy decisions based on effectively engineered sharing solutions produced by member laboratories. NASCTN processes are still in their formative stages and therefore have not proven themselves to be capable of meeting the desired intake and project allocation role.

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.

[5] The committee recognizes that there are potential inefficiencies associated with the Department of Commerce (DOC) operating two separate laboratories with missions related to advanced telecommunication research and radio spectrum and that merging the laboratories might yield administrative efficiencies and a greater critical mass in resources and talent. Barriers to such a merger include distinct, although overlapping, mission statements, distinct technical and management cultures, and funding that currently comes from different federal appropriation line items. These questions could be addressed by the DOC as part of the recommended research planning activity.

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.

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

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.

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

Today, there are more wireless connections to the Internet than wired, and the proportion will continue to increase as the volume of wireless Internet connections continues to grow very rapidly.[6] Future demand for wireless communication will come from both conventional wireless networks' endpoints (cellphones, tablets, laptops, and radio and TV receivers) and an expansion in the number and type of new connected devices, including vehicles, sensors of many types, appliances, thermostats, and other familiar objects, even light bulbs (the IoT). Meeting these demands will depend on better understanding of technical challenges in three principal areas: (1) spectrum use, management, and enforcement; (2) system-level optimization and related issues; and (3) public safety and, more generally, mission critical communications research (these are explored in-depth in Chapter 4).

Spectrum management—and associated technologies and standards—are major features of today's communication landscape. With an ever-increasing demand for spectrum, an increase in the desire to share, disagreements about use, and interference between devices are inevitable. The ramifications of spectrum management on economic activity and national security are immense because spectrum resources are fundamental to wireless network capacity. The government plays a key role in managing spectrum through the Federal Communications Commission (FCC), which regulates commercially used spectrum, and NTIA, which manages federal agency use. ITS has, and with the addition of CTL, should continue to have, a significant impact on analyzing and measuring proposed approaches to more efficient spectrum management (Box 4.1 provides examples of challenges that arise when technical analysis is not provided). In the process, the laboratories have an opportunity to develop novel approaches to spectrum management, which can become a fundamental asset to the country.

The Boulder telecommunications laboratories are in an excellent position—provided they are sufficiently funded and staffed—to provide independent and objective evaluations of proposed sharing standards and to test equipment and systems for compliance with emerging standards-based sharing protocols, because few other organizations can provide this capability. This will benefit U.S. regulatory agencies, the FCC and NTIA, in their pursuit to preserve existing services while enabling new services to operate with limited and increasingly valuable spectrum resources. In undertaking research, the Boulder telecommunications laboratories will need to balance the need for cutting-edge research with the need for

[6] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update 2014-2019 White Paper, February 3, 2015, http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white_paper_c11-520862.html.

application-based knowledge in spectrum use, ensure that their research portfolio is broad enough to ensure that its researchers are able to anticipate changes in the direction of commercial technology, and position themselves to provide technology for measuring interference and develop new ways to manage interference.

The Boulder telecommunications laboratories have opportunities to take on additional responsibilities and leadership with regards to techniques and standardized approaches to spectrum measurement and, more generally, the technology standards needed for telecommunications. Interoperability standards are of critical importance to both the data-communications and cellular mobile communications industries. They enable a large number of vendors to supply the components necessary to assemble the vast and complex wired and wireless network infrastructure critical to connecting citizens and business in the United States and throughout the world. Interoperability standards are an essential ingredient in today's dynamic and growing online economy. Both ITS and CTL currently work with network and mobile standard-setting organizations in a limited way, but this engagement will need to be reassessed to ensure that their participation aligns with their missions. There are areas where CTL and ITS involvement is strong and aligns with DOC missions; however, there are other areas where they are participating in efforts not aligned with national needs.

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.

RECOMMENDATION: The Department of Commerce (DOC) should develop short- and long-term application and basic research plans that would provide the country with the necessary knowledge base in spectrum areas and enhance the capability for spectrum sharing and repurposing analysis. The DOC plans should include opportunities for various users of spectrum to identify their needs and long-term objectives. A research agenda should consider the most efficient use of DOC's—and the relevant laboratories'—resources and develop an effective organizational structure and funding strategies to ensure that research goals are met and resources are effectively used.

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.

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.

1

History of the Boulder Telecommunications Laboratories

A 2006 National Research Council report observed that "the telecommunications industry remains of crucial importance to the United States as a society, that a strong telecommunications research capability continues to be essential to the health and competitiveness of this U.S. industry internationally, and that the health of this industry strongly affects the U.S. economy in many ways."[1] Recent years have seen particular emphasis on radio-frequency (RF) communications and more efficient use of the RF spectrum.

To contribute to this significant technical area, the DOC operates two telecommunications research laboratories collocated in Boulder, Colorado: NTIA's Institute for Telecommunication Sciences and the NIST's Communications Technology Laboratory.

ITS began in the 1940s as the Interservice Radio Propagation Laboratory (later the Central Radio Propagation Laboratory (CRPL)) of the National Bureau of Standards (NBS). Following a 1960s consolidation with other federal laboratories and subsequent split, it was established as a separate laboratory within the DOC and became part of NTIA when that agency was formed in 1977. ITS is collocated with NIST's Boulder, Colorado, laboratories, which also conduct telecommunications-related research in such areas as quantum information, electromagnetics, and optoelectronics. As ITS evolved, so did its mission. Radio propagation studies have been the core of the ITS mission since its creation, but it has expanded and contracted over time in somewhat overlapping directions. These include an early expansion into systems engineering and operations research involving wireless systems and into the study and analysis of wireline systems that are critical to public interest. At one point, the laboratories had a greater role in policy formation rather than simply providing technical advice to policy makers.

ITS's current mission is provided in Box 1.1, and its core area is still radio propagation studies and radio channel model development. However, related areas of research and expertise include enhanced spectrum utilization, radio environment, improvement and optimization of wireline networks, and public safety communications. ITS no longer actively engages in policy research per se; rather, it focuses on providing objective scientific and engineering study to support policy making.

CTL was formed in mid-2014 within NIST and consists of the Boulder Laboratory Director Office, the Communications Test Coordination Office, the Public Safety Communications Research Division, the RF Technology Division, and the Wireless Networks Division (located at NIST in Gaithersburg, Maryland). CTL's functional statement can be found in Box 1.2. Given its recent start, CTL's early efforts were focused on operational basics, including acquiring space, hiring personnel, and developing programmatic plans.

CTL has a similar starting point as ITS. When CRPL moved to Boulder in the 1950s, the Radio Physics and Radio Engineering Measurements and Standards divisions were created within the NBS. In 1978, these divisions were renamed the Electromagnetic Fields and Electromagnetic Technology divisions. When NBS became NIST in 1988, the Electromagnetic Fields and Electromagnetic Technology divisions were moved into the Electronic and Electrical Engineering Laboratory. The Electromagnetic

[1] National Research Council, *Renewing U.S. Telecommunications Research*, The National Academies Press, Washington, D.C., 2006, p. 4.

BOX 1.1
ITS Mission Statement

The Institute for Telecommunication Sciences (ITS) is the research and engineering laboratory of the National Telecommunications and Information Administration (NTIA), an agency of the U.S. Department of Commerce (DOC). ITS performs basic research in radio science, which provides the technical foundation for NTIA's policy development and spectrum management activities.

ITS research enhances scientific knowledge and understanding in cutting-edge areas of telecommunications technology. The Institute's research capacity and expertise is used to analyze new and emerging technologies and to contribute to standards creation. Research results are broadly disseminated through peer-reviewed publications as well as through technical contributions and recommendations to standards bodies. ITS staff represent U.S. interests in many national and international telecommunication conferences and standards organizations. Through leadership roles in various working groups, ITS helps to influence development of international standards and policies to support the full and fair competitiveness of the U.S. communications and information technology sectors. ITS research helps to drive innovation and contributes to the development of communications and broadband policies that enable a robust telecommunication infrastructure, ensure system integrity, support e-commerce, and protect an open global Internet.

ITS also serves as a principal Federal resource for solving the telecommunications concerns of other Federal agencies, state and local Governments, private corporations and associations, and international organizations. These problems fall into the areas of communications technology use (including RF, PSTN and IP/IT).

Cooperative research agreements based on the Federal Technology Transfer Act of 1986 are the principal means of aiding the private sector. This Act provides the legal basis for and encourages shared use of Government facilities and resources with the private sector in advanced telecommunications technologies. These partnerships aid in the commercialization of new products and services.

SOURCE: Reprinted from National Telecommunications and Information Administration, Institute for Telecommunication Sciences, "ITS Mission and History," http://www.its.bldrdoc.gov/about-its/its-mission-history.aspx, assessed October 26, 2015.

Fields Division includes microwave metrology, broadband microwave technology, fields and interference metrology, and antenna metrology groups. In 2012, the Electronic and Electrical Engineering Laboratory and the Physics Laboratory were combined to create the Physical Measurement Laboratory (PML). CTL combines several research groups from the RF Technology Division of the PML and the Wireless Networks Division of the Information Technology Laboratory.

In 2013, NIST and NTIA signed a memorandum of understanding to create CAC, and the agreement was revised in 2014 to establish that CAC will be co-directed by the ITS and CTL directors.[2] Its mission can be found in Box 1.3. CAC has been slow in organizing in part because ITS was without a director for

[2] Memorandum of Understanding between the National Institute of Standards and Technology and the National Telecommunications and Information Administration for the Intent to Establish a Center for Advanced Communications, May 24, 2013, http://www.nist.gov/public_affairs/releases/upload/NIST-NTIA-MOU-CAC.pdf.

BOX 1.2
CTL Functional Statement

The Communications Technology Laboratory promotes the development and deployment of advanced communications technologies, through the conduct of leading edge R&D on both the metrology and understanding of physical phenomena, materials capabilities, complex systems relevant to advanced communications; performs research in high-speed electronics, wireless systems metrology, antennas, advanced optics, network design and optimization, and public safety communications; performs research supporting a multi-level testbed facility, including the development of precision instrumentation, validated test-protocols, models, and simulation tools necessary to support the testing and validation of new communications technologies; leverages key research and engineering expertise and capabilities within NIST Boulder and NTIA's ITS labs to establish a "Center for Advanced Communications" to provide opportunities for collaborative R&D and access to test-bed resources; has authority and responsibility for the management of the NIST Boulder facilities.

SOURCE: Reprinted from National Institute of Standards and Technology, Program Coordination Office, "Laboratory Planning: Communications Technology Laboratory, FY 2015," 2014.

BOX 1.3
Mission of the Center for Advanced Communications

The parties contemplate that the mission of the center will include the following:

- Enhancing mission effectiveness of both agencies by better coordinating research and testing functions of NIST and NTIA in the area of advanced communication technology;
- Promoting interdisciplinary research, development, and testing in advanced communications-related areas such as radiofrequency technology, digital information processing, cybersecurity, interoperability, and usability; and
- Providing a single focal point for engaging both industry and other government agencies on advanced communication technologies, including testing, validation, and conformity assessment.

SOURCE: Reprinted from the Memorandum of Understanding between the National Institute of Standards and Technology and the National Telecommunications and Information Administration for the Intent to Establish a Center for Advanced Communications, May 24, 2013, http://www.nist.gov/public_affairs/releases/upload/NIST-NTIA-MOU-CAC.pdf.

approximately a year until April 2015, when Keith Grenbam was appointed. Given that ITS did not have a director until recently, much of CAC's current work has been managed by the CTL director, Kent Rochford. The current agreement only runs through 2016 but provides that "if this limited amount of collaboration is successful, the parties may seek to increase the work of the CAC further."[3]

[3] Memorandum of Agreement between the National Telecommunications and Information Administration and the National Institute of Standards and Technology for the Establishment and Operation of the Center for Advanced Communications, U.S. Department of Commerce, Office of the General Counsel, April 11, 2014.

SCOPE OF REPORT

The committee was asked to review CTL's CAC-related programs (the committee's statement of task is provided in Appendix A). Although the committee does explore CAC, the focus in Chapter 2 is more on CTL and how its current research agenda addresses future telecommunication needs. Chapter 3 focuses on collaborative efforts between the two laboratories, including CAC, NASCTN, and PSCR, and how these programs support NIST and NTIA missions.[4] Chapter 4 explores national priorities in telecommunications research and the role in which the Boulder telecommunications laboratories can play, and outlines key areas in which the laboratories could engage to advance federal and industry interests in telecommunications. Box 4.2 examines the capacity of ITS and CTL compared to international telecommunication laboratories, although these laboratories have different missions than the Boulder telecommunications laboratories.

2

Assessment of the Communications Technology Laboratory

The Communications Technology Laboratory was formed in mid-2014 within NIST and consists of the Boulder Laboratory Director Office, the Communications Test Coordination Office, the Public Safety Communications Research Division, the RF Technology Division, and the Wireless Networks Division (located at NIST in Gaithersburg, Maryland). Given its recent start, CTL's early efforts were focused on operational basics, including acquiring space and hiring personnel and developing programmatic plans.

CTL's current annual budget is $20.7 million; approximately 82.8 percent of this comes directly from NIST, with the balance reimbursed by federal agencies or CRADAs with private firms. At present, the Department of Homeland Security, the Defense Advanced Research Projects Agency, FirstNET, the U.S. Army, the Department of Energy, and the National Security Agency fund projects at CTL.[1] The majority of the current research staff has expertise in electrical engineering, and most of the technical staff have Ph.D.s.

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.

CTL'S RESEARCH PLANS

CTL's current funding is being applied to establish CTL and build the CAC collaboration. CTL has identified four areas in which it would like to build capability: (1) personnel and facilities to support NASCTN, (2) situational awareness measurement and analytics for public safety communications, (3) metrology for next-generation wireless networks, and (4) optical communications metrology. Funding is in place to support the first three initiatives, and CTL is seeking funding in fiscal year (FY) 2016 for the fourth initiative. Chapter 4, on collaborations between the Boulder telecommunications laboratories, discusses CTL's work to support CAC, NASCTN, and public safety.

CTL's commitment to developing metrology for next-generation wireless networks is commendable, as this will seed the laboratory with expertise in a likely area of future high demand. Relevant topics include the metrology needed to support expansion of spectrum sharing and coexistence and channel propagation and modeling expertise. Much of CTL's current work focuses on mm-wave technologies. To advance this work and maximize its impact, CTL sponsors the new 5G Millimeter Wave Channel Model Alliance[2] with participation of government, industry, and academic researchers. To facilitate the formation of the Alliance, CTL convened a kick-off meeting in Boulder in July 2015. At the meeting, the alliance created a steering committee and six working groups that will meet virtually several times a year.

[1] The committee was asked to review customer needs; however, limited information was provided to the committee regarding CTL's current customers or CRADAs.

[2] For more information on the 5G Millimeter Wave Channel Model Alliance, see https://sites.google.com/a/corneralliance.com/5g-mmwave-channel-model-alliance-wiki/home, assessed September 3, 2015.

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.

RECOMMENNDATION: 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 millimeter-wave work with other standard and industry bodies.

While technical advances in mm-wave spectrum are valuable in advanced new wireless communications, other technologies will be of importance, including MIMO, spectrum sharing and management techniques, interference at boundaries, bi-directional transmission on the same channel, and channel bonding techniques, including bonding between license and unlicensed services. Several of these are noted in CTL's technical plan.[3] However, CTL's technical plan is a list of broad potential research areas and lacks sufficient specific tasks and research goals. CTL will need to quickly develop a more specific and deeper research plan. The committee notes that although the anticipated work is important, the current spectrum-related research being conducted at CTL—with the exception of mm-wave channel modeling—does not seem to be at the cutting edge compared to that being conducted in commercial and academic laboratories, especially related to spectrum sensing, spectrum-agile hardware, sharing algorithms, and next-generation dense networks. A more specific research plan would help identify areas where deeper work is needed by CTL (and where work might be best done at commercial or academic laboratories). Because the range of possible research is so large, this plan should be developed with careful consideration of what is being done elsewhere in order to define what CTL can do that needs doing (within its charter), what its people are capable of doing (at the state-of-the-art level), and what only NIST can do.

CTL identified a handful of challenges, most of which stemmed from the newness of the organization. The committee anticipates that an increase in technical staff would further CTL's research agenda in positive ways. For example, CTL identified optical communications metrology as a fourth priority but noted that they have not yet built the capacity to perform this work. Several advances in optical metrology would support next-generation communications. For example, CTL could work to develop fundamental parameters that would support interoperability at 400 GB/s Ethernet (and beyond, over time) by the IEEE 802.3 Ethernet Working Group. In addition, the Boulder laboratories are aging, and CTL does not currently have the most current technical equipment. To advance their stated research goals, CTL will need to quickly hire and train personnel to establish state-of-the-art skills in their areas of focus, and they will need to upgrade their aging facilities and instrumentation. This should be done with a specific research agenda in mind, so that personnel and facilities provide capabilities consistent with the highest state-of-the-art research.

FINDING: CTL staff have identified an appropriate set of communication technology priorities and have 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.

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[3] National Institute of Standards and Technology, Program Coordination Office, "Laboratory Planning: Communications Technology Laboratory FY2015," 2014.

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.

STAKEHOLDER ENGAGEMENT

It is important for a laboratory like CTL to stay engaged with the R&D community at large and in particular be attuned to the research and technology needs of the private sector. The committee is encouraged by CTL's development of the 5G Millimeter Wave Channel Model Alliance, which may serve as a model for further engagement with relevant R&D communities so that CTL can truly serve as an informed and engaged resource for the government as spectrum sharing technologies advance. CTL should also seek out additional opportunities for engaging with the private sector, including increased participation in key standard-setting organizations, such as the IEEE 802 LAN/MAN Standards Committee (standardizing lower-layer Internet network interfaces), the European Telecommunications Standards Institute's 3rd Generation Partnership Project (3GPP; standardizing cellular infrastructure and end devices), and the Internet Engineering Task Force (IETF; standardizing higher-layer Internet protocols.

Another way in which NIST can ensure that it understands the need for the private sector is to utilize outside review. Outside technical reviews ensure that technical work aligns with national priorities and industry needs. NIST has put in place several procedures to review CTL's work and make recommendations regarding its program. One example is the work of the NIST Visiting Committee on Advanced Technology (VCAT), which is made up of external scientific and engineering experts. CTL presented to VCAT in fall of 2014 and the committee's report is supportive of its current plans.[4] NIST also commissions regular reviews of its laboratories by the National Academies of Sciences, Engineering, and Medicine on an approximate 3-year cycle (but has not yet reviewed CTL under this regular process). As a new organization that is building its technical plans and capacity, a more frequent review through some mechanism may be warranted.

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.

[4] U.S. Department of Commerce, *2014 Annual Report,* Visiting Committee on Advanced Technology of the National Institute of Standards and Technology, March 2015, http://www.nist.gov/director/vcat/upload/2014-VCAT-Annual-Report_final.pdf.

3

Collaboration at the Boulder Telecommunications Laboratories

Given that ITS and CTL are collocated in Boulder, Colorado, and have similar missions under the DOC, it is only natural that they collaborate and have established mechanisms to enhance such collaboration. This chapter describes PSCR, a highly successful long-term collaboration between ITS and elements of NIST (now all consolidated in CTL), and two newly created collaboration mechanisms, the CAC and the NASCTN.

PUBLIC SAFETY COMMUNICATIONS RESEARCH PROGRAM

For many years, ITS and NIST have provided unique technical testing services and support to the public safety community in the area of public safety communications and other technical services. The first interagency agreement between ITS and NIST to perform public safety services was signed in 1999, and a rebranding in 2007 designated the relationship with PSCR. The relationship has furthered the cooperative use of the capabilities of both ITS and CTL to serve the needs of public safety. Key PSCR work includes the following:

- *Public safety broadband communications.* A significant challenge faced by the public safety communications community is how to ensure interoperability across more than 8,000 public safety jurisdictions. PSCR leads discussions related to the development of requirements and standards, conducts testing and evaluation, cybersecurity research, and modeling and simulation. The FCC recently created the public safety 700 MHz spectrum allocation, providing an opportunity to create a unified broadband communications plan for public safety. PSCR provides a multi-vendor, neutral test environment for manufacturers and first responders to demonstrate their equipment.
- *Public safety audio and video quality.* Clear voice and video are key to situational awareness for first responders. PSCR develops performance parameters for testing and evaluating manufacturers' equipment and participates in appropriate standards organizations in order to incorporate its findings into key technology standards.
- *Compliance assessment program.* Vendors of public safety radio and communications equipment have begun incorporating technology standards (which PSCR helped establish); however, purchasers were unable to verify compliance with these standards. PSCR, in partnership with the DHS Office of Interoperability and Compatibility, created an assessment program that allows voluntary testing to verify compliance at recognized laboratories.

PSCR provides the only objective, non-vendor-driven testing and evaluation services to the public safety community. Their demonstrated value stimulated a large influx of funding generated by the 2014-

2015 AWS-3 auction.[1] PSCR has begun developing research roadmaps to articulate requirements and plans for the use of these funds.[2] The first of these, "Location-Based Services R&D Roadmap,"[3] was released in May 2015.

The committee notes that PSCR's organizational structure, with a program manager from CTL and a deputy program manager from ITS, works well to coordinate efforts across these two independent laboratories. The committee also commends PSCR's leadership for building an environment that engenders trust and communication across the two laboratories.

CENTER FOR ADVANCED COMMUNICATIONS

In 2013, NIST and NTIA signed a memorandum of understanding to create the CAC in Boulder[4] to coordinate research programs between ITS and CTL. CAC offers several potential benefits to both laboratories. Better coordination of ITS and CTL can leverage telecommunications-related research and engineering capabilities of each laboratory, ensure non-duplication, and, at the same time, enable each organization to better accomplish its mission. Coupling under CAC could further support a prioritizing of projects that could be independent (supportive of each entity's strengths) or that might be able to leverage resources of common goals such as public safety, spectrum research, and other communications work, which is central to the mission of the DOC.

In order to capitalize on this opportunity, the CAC management team must make specific efforts to couple CTL foundational research to ITS application work. At present, CAC is a virtual organization with no staff, funding, or resources of its own. Some possible activities that would support interactions and collaborations between CTL and ITS staff include formation of working groups around emerging areas of interest such as spectrum efficiency, spectrum sharing, and spectrum measurement and verification techniques. Assignment of leads in the working groups coming from both CTL and ITS, modeled after the existing collaboration in the public safety arena, can help to strengthen working relationships between the groups and could result in significant technological advances.

The co-directors of CAC are charged with conducting formal assessments of all NIST and NTIA advanced communications projects to determine if cross-agency participation could enhance these projects. This could be done at regular intervals, and projects could be moved between the various organizations—CAC, CTL, and ITS—to ensure effective use of resources and expertise among the laboratories. The success of CAC will also lie in identifying a small set of core efforts and setting up a process to fund and address them.

In a 2014 memorandum of understanding (MOU), the DOC made changes to the initial organization of CAC.[5] Under the 2013 MOU, CAC's director would be appointed by NIST, with input from NTIA.

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[1] Roger C. Sherman, Chief, Wireless Telecommunications Bureau, "Putting Auction 97 in the History Books," Federal Communications Commission, January 29, 2015, https://www.fcc.gov/blog/putting-auction-97-history-books.

[2] With this level of funding, there is a risk that PSCR work dominates the Boulder telecommunications laboratories. This could serve to undermine the valuable commercial communications work and the public safety communications that leverages those commercial technologies.

[3] Ryan Felts and Marc Leh, Corner Alliance, Inc., Dereck Orr and Tracy A. McElvaney, Public Safety Communications Research Division, Communications Technology Laboratory, "Location-based Services R&D Roadmap, NIST Technical Note 1883," May 2015, http://dx.doi.org/10.6028/NIST.TN.1883.

[4] Memorandum of Understanding between the National Institute of Standards and Technology and the National Telecommunications and Information Administration for the Intent to Establish a Center for Advanced Communications, May 24, 2013, http://www.nist.gov/public_affairs/releases/upload/NIST-NTIA-MOU-CAC.pdf.

[5] Memorandum of Understanding, 2014.

The 2014 MOU designates that the directors of ITS and CTL would serve as co-directors of CAC.[6] The committee understands the desire to ensure that each laboratory is adequately represented within the new CAC. However, there is substantial concern that co-leadership may make setting and implementing priorities challenging, especially given the virtual nature of CAC. This model relies on a good working relationship between the counterparts, which can take significant time to build. Additionally, a change in leadership could limit the ability of CAC to move forward, just as ITS's lack of a director resulted in the slow launch of CAC.

Collaboration across research divisions will also require an increase in working knowledge of the counterpart's expertise and a working trust. The committee notes an absence of this between the two research laboratories (with PSCR being a notable exception). Laboratory leaders will need to build a collegial relationship with one another and work to build a similar relationship within each research and technical division. This task, while not necessarily technical in nature, will be an important piece if the collaborative goals of CAC are to be met. Furthermore, laboratory leaders may need to incentivize the sharing of resources and collaboration among staff.

NATIONAL ADVANCED SPECTRUM AND COMMUNICATIONS TEST NETWORK

NASCTN had its genesis in 2009 when the Department of Defense (DOD) developed the idea for a single entity to address the increasing commercial demands on spectrum occupied by DOD systems. In 2010, this initial concept gained support through the Presidential Memorandum "Unleashing the Wireless Broadband Revolution"[7] and NTIA's "Ten Year Plan and Timetable to Make Available 500 Megahertz of Spectrum for Wireless Broadband."[8] During the National Executive Council on Space-Positioning, Navigation and Timing deliberations on the company LightSquared in 2011, then Deputy Secretary of Defense Ashton Carter and Deputy Secretary of Transportation John Porcari affirmed the need for an independent and impartial organization, environment, and process for testing and evaluating new spectrum-sharing technologies to support policy decisions.[9] Momentum built in 2012 with the publication of the President's Council of Advisors on Science and Technology (PCAST) report *Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth*[10] and a 2013 Presidential memorandum directing NIST and NTIA to establish a plan to accelerate the development and deployment of spectrum-sharing technologies.[11] The NASCTN transition team consisting of NIST, NTIA, and DOD staff was established in Boulder, Colorado in 2013. The NTIA director, NIST director, and DOD chief information officer signed a memorandum of agreement (MOA) establishing NASCTN on March 11,

[6] CAC has been slow in organizing in part because ITS was without a director until April 2015. Given that ITS did not have a director until recently, much of CAC's current work has been completed by the CTL director.

[7] Presidential Memorandum, "Unleashing the Wireless Broadband Revolution, Memorandum for the Heads of Executive Departments and Agencies," The White House, June 28, 2010, https://www.whitehouse.gov/the-press-office/presidential-memorandum-unleashing-wireless-broadband-revolution.

[8] National Telecommunications and Information Administration, *Ten Year Plan and Timetable to Make Available 500 Megahertz of Spectrum for Wireless Broadband (President's Spectrum Plan Report)*, October 29, 2010, http://www.ntia.doc.gov/report/2010/ten-year-plan-and-timetable-make-available-500-megahertz-spectrum-wireless-broadband-pre.

[9] "Letter to NTIA on LightSquared Testing," January 13, 2012, available at http://www.gps.gov/news/2012/01/lightsquared/.

[10] President's Council of Advisors on Science and Technology, *Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth*, 2012, https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf.

[11] Presidential Memorandum, "Expanding America's Leadership in Wireless Innovation, Memorandum for the Heads of Executive Departments and Agencies," The White House, June 14, 2013, https://www.whitehouse.gov/the-press-office/2013/06/14/presidential-memorandum-expanding-americas-leadership-wireless-innovatio.

2015. Although a part of the formation of the organization as noted above, at the time of this report, the Department of Transportation has not joined this group.

NASCTN was established to increase commercial and federal access to the spectrum by helping to accelerate the design and deployment of spectrum-sharing technologies through accurate testing and modeling. The intent is to create an environment of trust to support impartial testing and evaluation of new spectrum sharing technologies and, ultimately, balanced policy decisions that are driven by scientifically sound tests and evaluations. NASCTN is structured as a one-stop shop for coordinating access to federally owned, federally operated, or federally funded spectrum test facilities. NASCTN is meant to enable sound policy decisions based on effectively engineered sharing solutions produced by member laboratories.

NASCTN will rely on network of technical staff, resources, capabilities, and facilities made available by NIST, NTIA, and DOD and future NASCTN members; NIST will provide a program manager. Test facilities will initially be made available by NIST, NTIA, and DOD. The current NASCTN members are soliciting potential additional members. From the NASCTN website, key functionalities of the enterprise include the following:

- Creating a trusted capability for federal, academic and industry spectrum users to facilitate spectrum sharing studies; optimize access to engineering capabilities; and engage federal, academic, and industry spectrum users' in active collaboration;
- Performing outreach and engagement activities within their respective communities in order to identify spectrum-related testing and evaluation needs, and to disseminate information about the availability and access requirements of engineering capabilities;
- Protecting controlled information (e.g. proprietary, classified, and commercially sensitive) against unauthorized uses and disclosures, pursuant to applicable statutes, regulations, and agreements, while facilitating sharing of member controlled information;
- Facilitate access to available spectrum test data, analyses, and reports that can be made available to federal, academic, and industry spectrum users to assist in testing, technology assessments, and other research; and
- Facilitating coordination, rapid access, and engagement of member engineering capabilities.[12]

The potential value of NASCTN, as described above, is obvious to the committee; however, despite the NASCTN transition team moving to Boulder in 2013, the NASCTN processes are still in their formative stages and, therefore, have not proven themselves to be capable of meeting the desired in-take and project allocation role. CAC is in a similar position; collaboration between ITS and CTL is imperative but it has yet to be seen if the current model will be successful. CAC must determine the best way to manage across two technical laboratories with very different cultures. The committee is unsure if the current management model of CAC will be sufficient, but the leadership could explore ways to better manage this collaboration.

CAC can function as a coordinating organization to ensure that work is not duplicated across CTL and ITS and ensure that both laboratories focus on work that reflects their strengths, although the committee is unsure if a formal organization is needed (versus a process to manage coordination across the Boulder telecommunications laboratories). However, CAC could facilitate collaboration by serving in a centralized program management role to further national priorities in communications and spectrum use and coordinate research programs outlined by ITS and CTL. Furthermore, laboratory leadership will need to make a concerted effort to build an environment that encourages and facilitates collaboration in Boulder.

[12] Reprinted from National Institute of Standards and Technology, Communications Technology Laboratory, "National Advanced Spectrum and Communications Test Network (NASCTN)," http://www.nist.gov/ctl/nasctn.cfm, accessed September 10, 2015.

The committee is encouraged by the collaborative nature of PSCR. The success of PSCR provides an excellent example of the advantages of CTL and ITS coordinating their expertise and resources. The PSCR model can also be used to enhance NASCTN efforts and processes. The sharing of personnel and laboratory equipment, capabilities, and resources has been very successful at PSCR. However, lack of funding support for ITS personnel and capabilities may pose another obstacle for collaborative work. For example, it appears that funding for PSCR is increasingly coming from NIST, whereas funding from NTIA for ITS has been slowly decreasing. Because of this, ITS has not kept up with changing technologies, and NIST has not been able to leverage its expertise nearly as much in the emerging LTE and broadband technology areas. If ITS resources for PSCR, CAC, and NASCTN are to be of value it needs to invest in new staff and physical resources (e.g., at Table Mountain Field Site and Radio Quiet Zone) to ensure that ITS can meet the research demands of current and future technology deployments in a manner similar to NIST.

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 and, 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.

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

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.

4

National Telecommunication Research Needs and the Future Role of the Boulder Telecommunications Laboratories

To understand the role that the Boulder telecommunications laboratories currently play and can play in the economic vitality of the country, it is important to understand the role of spectrum in the wireless networking and mobile cellular industries and the influence that ITS has in making spectrum available to government and industry. ITS has and with the addition of CTL, will continue to have, a significant impact on analyzing and developing approaches to spectrum management. The influence of spectrum management on economic activity and national security is immense because spectrum resources are fundamental to wireless network capacity.

NEED FOR OBJECTIVE SPECTRUM METROLOGY, MEASUREMENT, AND RESEARCH

The 2014-2015 AWS-3 band auction, a band that was formerly controlled almost exclusively by the federal government, netted the federal government $41.3 billion. Other auctions have raised significant funds as well, including $13.7 billion for the AWS-1 auction in 2006 and $18.9 billion for the 700 MHz auction in 2008.

The rapid rise in the price of spectrum is due to the exponential increase in the number of Internet-connected wireless devices and the rising data demands for the applications that run on these devices, combined with the constrained supply of viable spectrum for these devices. Mobile data used in the United States doubled from 2012 to 2013 and is expected to increase by 650 percent by 2018 with the increased use of smart phones and tablets. For instance, a smart phone uses 49 times more data over a basic handset with more than a 300 percent increase in data anticipated by 2018. Tablets consume 127 times more than a basic handset, with a 370 percent increase expected by 2018.[1] The Internet of Things (IoT) is another driving force behind the increased demand for spectrum. IoT revolves around increased machine-to-machine communication; it is built on cloud computing and networks of data-gathering sensors; it is mobile, virtual, and always on. Its real value is at the intersection of gathering data and leveraging it. Cloud-based applications are the key to using leveraged data. Cloud-based applications interpret and analyze the data coming from all of these IoT sensors.

The economic value of spectrum as a natural resource is reflected in the $41.3 billion auctioning of the AWS-3 band. To put the value of spectrum into perspective for the wireless carriers, consider that U.S. carriers invested $33 billion in capital expenditures in 2013.[2] Note that when spectrum availability is lacking, cellular networks compensate for this by deploying more infrastructure (frequency reuse) to

[1] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update 2014-2019 White Paper," February 3, 2015, http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white_paper_c11-520862.html.

[2] For background on CTIA's Wireless Industry Survey, see "Investment" at http://www.ctia.org/your-wireless-life/how-wireless-works/wireless-quick-facts, accessed June 2014.

increase wireless data capacity. They are also now planning on utilizing the unlicensed spectrum, which has caused deep concern among Wireless LAN (WLAN) product and service providers, because that unlicensed spectrum has been relatively fairly shared using 802.11 Listen Before Talk protocols to date. Although the costs are high, wireless products and services produce more than $400 billion per year of economic impact for the United States. This economic impact will no doubt increase as new wireless applications such telehealth, machine-to-machine communications, and augmented reality take off in the coming years, placing even greater demands on spectrum use.

New spectrum (both licensed and unlicensed) to support increased use of mobile and IoT devices has been slow in emerging. The need for expertise to help determine when spectrum is underutilized and when to free it up is essential to insure speedy and reliable transition of exclusive federal spectrum to joint commercial use. This has resulted in higher capital costs for service providers as they compensate for spectrum deficiency with greater infrastructure expenditures. Likewise for license-free devices, such as 802.11 Wi-Fi, which have grown at a remarkable rate. Wi-Fi traffic in the United States is growing at 68 percent per annum, while Wi-Fi households, currently at 63 percent, are forecast to reach 86 percent by 2017.[3]

In general, the most useful bands in the electromagnetic spectrum are currently already devoted to supporting other services.[4] Making room for new wireless services requires transitioning legacy users out of their spectrum to other parts of spectrum by using more efficient technologies before new services can be accommodated in the band.[5]

In 2013, a Presidential memorandum noted that sharing spectrum that is currently exclusively allocated for federal use will be a partial solution to current spectrum shortage.[6] In fact, the 2014-2015 AWS-3 auction sold spectrum that was made available from freeing up federal government spectrum allocations, particularly spectrum allocated to DOD radar. ITS participated in studies that led to the transition of this band, and they continue to lead the transition of other federal bands to support commercial use. The Boulder telecommunications laboratories are among the few government facilities with the necessary skills and specialized equipment capable of performing the measurement and analysis needed for transitioning spectrum from exclusive federal use to shared commercial use. They have extensive experience in propagation and interference measurements and analyses and better access to federal facilities (especially classified or controlled facilities) to explore these issues than commercial industry. However, little fiscal support (under $2 million over the course of 2 years to ITS) has been given to support these activities.

The legislation to authorize the AWS-3 auction[7] gave the federal government only 2 years to develop specifications and transition plans for billions of dollars of government assets to be relocated or altered to facilitate sharing between federal and commercial systems. The committee applauds the rapid transition of federal spectrum to shared commercial use as a very positive economic step. However, the details on how this sharing would be accomplished were not in place by the time the legislation took effect. As a result, federal agencies scrambled to set up mechanisms for sharing this $41 billion asset with the auction winners. The wireless service providers that purchased these spectrum rights took risks with this auction. Better spectrum research and engineering in advance could have helped reduce this risk, thereby increasing auction prices. The basic mechanism of how, when, and where commercial services providers

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[3] Telecom Advisory Services, LLC, *Final Report—Assessment of the Economic Value of Unlicensed Spectrum in the United States*, February 2014, http://www.wififorward.org/wp-content/uploads/2014/01/Value-of-Unlicensed-Spectrum-to-the-US-Economy-Full-Report.pdf.

[4] For a discussion of current uses of spectrum, see Appendix C, "The Value and Use of Wireless Technology."

[5] This is an expensive proposition for the legacy users, requiring the purchasing of new equipment and services to support deployment.

[6] Presidential Memorandum, "Expanding America's Leadership in Wireless Innovation, Memorandum for the Heads of Executive Departments and Agencies," The White House, June 14, 2013, https://www.whitehouse.gov/the-press-office/2013/06/14/presidential-memorandum-expanding-americas-leadership-wireless-innovatio.

[7] H.R. 3630, Middle Class Tax Relief and Job Creation Act of 2012, Title V6.

will be able to use the AWS-3 spectrum is still being developed—months after the auction and very close to when the service providers legally could be able to begin their deployment.[8]

The AWS-3 transition issues point to a fundamental problem—the lack of neutral and sound technical knowledge to validate spectrum sharing. (Additional examples of failure in spectrum allocation can be found in Box 4.1.) The R&D for transition mechanisms and means for validating fair sharing in the laboratory and in the field should have been done well before the legislation that authorized the AWS-3 auction, anticipating that these bands might be transitioned. Long-term R&D planning by the Boulder telecommunications laboratories could have mitigated the risks associated with such a transition for both commercial and federal entities. Now the laboratories are in catch-up mode to help find answers to the key issues that would allow sharing of the band. These laboratories are the best option to answer many of the key issues associated with the transition.

A similar need for a neutral, unbiased analysis and validation of sharing mechanisms is happening in the 5 GHz unlicensed band. The WLAN (i.e., IEEE 802.11 or Wi-Fi) system suppliers and service providers are concerned about the efforts of cellular service operators and system suppliers to re-route some of their mobile network traffic into the unlicensed bands. Naturally, both sides are competing for "fair use" of this 5 GHz unlicensed spectrum and are making claims regarding fair sharing or the lack of it, many of which are speculative and without rigorous science, engineering, and practical, realistic testing mechanisms in place. The Boulder telecommunications laboratories could provide this service for the public good.

The problem of providing long-term R&D to support rapid transition of spectrum is, to a great extent, outside of the Boulder telecommunications laboratories' control. For example, the ITS budget consists of only 30 to 50 percent from federal sources that could be applied to far reaching "what could happen" scenarios. Not only is it a relatively small percentage, the absolute dollars are small relative to the economic value of the spectrum. A limited amount of money was set aside for answering questions related to the 3.5 GHz and AWS-3 transition before the auctions, especially when compared to the value of the spectrum or even the interest lost on the auction revenues due to a delayed deployment. Furthermore, the 2012 legislation prevents significant R&D spending on transition of bands until the R&D is paid for by the auction. Hence, the revenue source that could have been paying for the transition was not available to ITS or other federal entities to speed up the transition of spectrum. While significant technical and economic risks of delays existed, adequate R&D funding was not provided to mitigate these risks.

Likewise, the 5 GHz band is currently being discussed as a candidate for sharing between federal systems and commercial users.[9] However, very little R&D resources are being provided to the Boulder telecommunications laboratories to answer pressing problems related to managing interference between federal and commercial users in this band. Given the economic risks if more spectrum is not made available, a sustained investment will help maintain U.S. competitiveness in the telecommunications arena, especially given that other nations are investing significantly in telecommunications research (see Box 4.2).

Despite significant federal commitments to expand spectrum availability, little funding is available to make significant commitments to expand spectrum availability, and little funding has been made available to the individual laboratories that can provide the research and technical expertise to assist in resolving complicated questions. Moving forward, a substantive change in the mission and funding model of the Boulder telecommunications laboratories may be needed, moving from a reactive technical organization to a pro-active research organization.

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[8] NTIA's transition plans can be viewed at NTIA, "AWS-3 Transition," http://www.ntia.doc.gov/category/aws-3-transition, accessed September 10, 2015.

[9] ITS and CTL have developed initial research plans for the 5 GHz band, but a significant investment and focus on hiring the appropriate talent will be needed for the Boulder telecommunications laboratories to provide needed technical knowledge in a timely manner.

BOX 4.1
Need for Technical Review

There are numerous, often infamous, examples of times when a rigorous technical analysis could have helped in either expediting the transition of spectrum assets or in properly assessing the potential for or reality of harmful interference. In many cases, decisions were tentatively made to proceed with a new use of the spectrum only to find that the use had a more negative effect than anticipated. In other cases, although the incumbent was clearly operating outside its allocated spectrum, the incumbent was deemed "too big to fail," rendering the new use of the spectrum technically and/or politically infeasible. Finally, in other cases, a suboptimal solution was implemented simply to insure that there would not be any harmful interference to an incumbent service. Understanding the technical details surrounding the current utilization of the spectrum and the potential limitations associated with its use are extremely important. If a detailed technical understanding exists up front, policy decisions can be more appropriately applied to determine how a specific area of spectrum can or cannot be utilized.

Some of these failures were not driven by technical mistakes, per se, but by failure to properly resolve disputed parameters and thresholds among the parties involved. These types of failures often result in overly conservative parameters being selected by the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration to satisfy the incumbent party's concerns. This inevitably leads to less efficient use of the radio spectrum both today and in the future.

Examples of High-Profile Failures in Spectrum Allocation

The FCC Technological Advisory Council's white paper on spectrum efficiency metrics[1] summarized nine high-profile failures, including the following:

- The prospect of overload interference to legacy Satellite Digital Audio Radio Service (SDARS, aka SiriusXM) receivers from mobile devices in the Wireless Communications Service (WCS) required application of strict technical rules and effectively created 5 MHz guard bands on each side of the SDARS allocation.
- Many C-band satellite earth station receivers operating at 3700-4200 MHz are susceptible to signals from well inside the 3650-3700 MHz band that was transferred from federal to commercial use, risking the possibility that much of the federal transferred spectrum would be useless.
- The use of the 20 MHz advanced wireless services (AWS)-3 band (2155-2175 MHz) for time-division duplex operation was blocked because cellular handsets in the lower adjacent AWS-1 F-block (2145-2155 MHz) were designed to operate across the AWS-3 spectrum, consistent with international (but not U.S.) allocations and, thus, were unable to reject interference from nearby AWS-3 handset transmissions.

- The AWS-1 downlink spectrum at 2110-2155 MHz is upper-adjacent to the broadcast auxiliary service (BAS) at 2025-2110 MHz. AWS-1 licensees were required as the newcomers to correct any harmful interference to the BAS operations. Because BAS equipment had not been designed with sharp filters, AWS-1 operations were found to cause harmful interference to BAS, requiring the AWS-1 licensees to pay to design, purchase, and install new filters for BAS equipment.
- TV receiver performance was a significant issue for the access of unlicensed devices in unused portions of the TV bands (i.e., the TV white spaces). The roll-off of the TV filters is the dominant factor limiting the amount of energy that a TV white space device may emit on allowed TV channels and, therefore, the limiting factor to potential applications for the devices.
- Receiver performance relative to adjacent channel and intermodulation characteristics was a major element in the issue of re-banding the 800 MHz spectrum to avoid interference between Nextel and public safety operations on interleaved channels.
- LightSquared's proposed deployment of ancillary terrestrial component base stations as part of a hybrid terrestrial–satellite service has raised significant concerns about potential harmful interference to the GPS service operating in the upper-adjacent spectrum due to the potential for receiver overload—that is, power transmitted in LightSquared's licensed frequencies causing degradation of GPS devices that did not filter out this energy sufficiently well.
- The original 800 MHz band-plan for Nextel and public safety land mobile radios had the Nextel and public safety channels interleaved under the assumption that there would be no harmful interference between the two. The use case for Nextel radically changed, as it became more of a professional's cell phone service. Ultimately a new band plan was required to separate the services and add a guard band in order to eliminate the harmful interference.

Each of these failures could have been minimized or eliminated if the proper technical analysis had been conducted. This is the type of work where the Institute for Telecommunication Sciences excels—where it could have been engaged to provide technical analysis and establish appropriate and balanced technical parameters.

It is recognized (and communicated to the committee during interviews) that ITS has already provided very valuable assistance in the AWS-3 auction by providing technical analysis of the interference potentials that could arise in a shared-use environment, and ITS is serving as an independent and trusted third party in negotiating the operating parameters. Although ITS provided technical efforts prior to the AWS-3, the committee does not yet know how sufficient this was, especially given its short timespan to prepare a technical analysis.

[1] Federal Communications Commission, Technological Advisory Council, "Spectrum Efficiency Metrics," White Paper, 2011, Appendix C.

BOX 4.2
Comparison of the Boulder Telecommunications Laboratories with International Research Laboratories

The committee was asked to assess how well the performance of ITS compares to similar research organizations with similar functionalities. Given that there are few, if any, similar domestic research laboratories, the work of the National Institute of Standards and Technology's (NIST's) Communications Technology Laboratory (CTL), the National Telecommunications and Information Administration's (NTIA's) Institute for Telecommunication Sciences (ITS), and the Center for Advanced Communications (CAC) was compared with five international organizations that perform similar types of technical work. The chief motivation behind the technical work in other countries is quite different from that in the United States when you examine mission statements and institutional behaviors. The five organizations reviewed were the following:

- Communications Research Centre (CRC), Canada;
- Electronics and Telecommunications Research Institute (ETRI), Republic of Korea;
- Information and Communications Research Laboratories (ITRL), Taiwan;
- Institute for Information Sciences and Technologies (INS2I), France; and
- National Institute of Information and Communications Technology (NICT), Japan.

A common theme for the five other countries is that the organizations exist to increase economic benefit to their countries and specifically to enhance the expertise and competitiveness of their indigenous telecommunications industries. Several of the organizations keep metrics on how many companies are spawned in their countries by their work. In general, there appears to be a much tighter collaboration and interaction between the private sector enterprise companies or entities and the government organizations. This is generally not the case for the U.S. organizations—"economic" themes do not appear in ITS, CTL, or CAC's mission statements.

Another theme that is apparent, especially in the French and Canadian organizations, is the contribution by those organizations to a national industrial policy in those countries. In general, the U.S. government has shied away from establishing a national industrial policy in the field of telecommunications. Rather, the United States has focused on international standards and policies to ensure a level and fair playing field for the U.S. communications and information technology sectors. Indeed, while ETRI and NICT have dozens of active participants in IEEE 802 standards activities, NIST and NTIA participate in a very limited fashion—only one or two individuals and on a part-time basis.

In terms of research areas, U.S. and foreign organizations examine similar topics. However, there is more emphasis in the international organizations on commercialization and transfer of research and technology into their domestic industries. In some cases, especially in France, the international organizations perform more fundamental or basic research than the U.S. organizations. A sample of technical papers would indicate that the quality of research at the U.S. and foreign organizational laboratories is comparable.

The laboratory size was drastically different as well. The combined headcount for CTL, ITS, and CAC is less than 200, while the French INS2I alone has a staff of more than 4,000, and the Korean ETRI has almost 2,000.

EMERGING RESEARCH AREAS RELEVANT TO THE MISSIONS OF ITS AND CTL

Today, there are more wireless connections to the Internet than wired, and the proportion will continue to increase as the volume of wireless Internet connections continues to grow very rapidly.[10] Future demand for wireless communication will come from both conventional wireless networks' endpoints (cellphones, tablets, laptops, and radio and TV receivers) and an expansion in the number and type of new connected devices, including vehicles, sensors of many types, appliances, thermostats, and other familiar objects, even light bulbs (the IoT). Meeting these demands will depend on better understanding of technical challenges in three principal areas: (1) spectrum use, management, and enforcement; (2) system-level optimization and related issues; and (3) public safety and, more generally, mission-critical communications research.

Frequency Use, Management, and Enforcement

There are three ways to increase the capacity of a communications network: (1) increase amount of spectrum available by adding more spectrum or through reducing the coverage area of each transmitter (sectorizing or cell splitting); (2) improve sharing among existing users while limiting the impact of interference; or (3) improve the underlying transmission technology. Additionally, as spectrum becomes increasingly crowded, understanding how to enforce regulatory restrictions will be essential, especially at spectrum boundaries.

Availability of Frequency Bands

Examples of areas where ITS and CTL should consider developing or extending their expertise and physical resources include the following:

- *Propagation modeling, approaches to sharing, and the use of MIMO techniques in mm-wave bands*—hot research topics and of great current interest at the FCC.[11] Nearly all of the best "beachfront property" (microwaves, frequencies below 3 GHz) has been allocated and assigned, but large amounts of spectrum are available in bands corresponding to millimeter wavelengths (or tens of gigahertz). Accurate, comprehensive, and low-cost techniques to measure and monitor spectrum utilization need to be developed and certified. The Boulder telecommunications laboratories should also explore cutting-edge research areas in new spectrum, such as the use of terahertz wireless data transmission.
- *Understanding the characteristics of the noise floor over time in various interesting areas of the spectrum*—including sensitive areas supporting satellite communications, cellular communications, various military use bands, etc. This would need to be done in a variety of geographic environments and under various environmental circumstances. The implications of these noise observations would be of enormous value in understanding the degree to which

[10] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update 2014-2019 White Paper," February 3, 2015, http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white_paper_c11-520862.html.

[11] Federal Communications Commission, Notice of Inquiry, FCC 14-154, In the Matter of: Use of Spectrum Bands Above 24 GHz For Mobile Radio Services; Amendment of the Commission's Rules Regarding the 37.0-38.6 GHz and 38.6-40.0 GHz Bands; Implementation of Section 309(j) of the Communications Act—Competitive Bidding, 37.0-38.6 GHz and 38.6-40.0 GHz Bands; Petition for Rulemaking of the Fixed Wireless Communications Coalition to Create Service Rules for the 42-43.5 GHz Band, October 17, 2014, https://apps.fcc.gov/edocs_public/attachmatch/FCC-14-154A1.pdf.

targeted wireless services are being impacted today and how they are likely to be impacted in the future.

- *Understanding the out-of-band characteristics of receivers for a wide variety of device classes*. If we are to move to ever-denser spectrum use, an understanding the receiver-based inhibitors to "more efficient" spectral use in various spectral areas will be of enormous import.
- *Related to the previous bullet, a focus on enhancing the understanding of the technology underpinnings for the proposed Interference Limits Policy*[12] with its focus on establishing a Harms Claims Threshold[13] would be of significant value. This technique promises to be a great boon in sorting out the long-standing receiver-related interference issue because there are still significant challenges in translating the current theory into a practical approach to interference management.
- *Understanding the commercial spectral environments around major military bases and, conversely, government (especially DOD) usage of spectrum around major cities*, would be enormously helpful. This would particularly valuable in supporting the sharing (or not) of spectrum in environments where there is a current shortage (either temporal, e.g., during a military exercise, or recurring, as occurs during "rush hour" in major transportation hubs).

Sharing and Interference Studies

In an environment with many types of devices operating in ever closer proximity, the risk of inadvertent harmful interference significantly increases. What people often forget is that, at some level, every transmitting device interferes with every receiving device. ITS has traditionally performed studies of applications in which interference has to be avoided. In the future, it will be important for the Boulder telecommunications laboratories to have expertise and resources to understand dense, interference-limited networks that operate in both licensed and unlicensed frequency bands. The distinction between base stations or access points and terminals will be blurred in the future with the proliferation of personal "My-Fi" and "Sat-Fi" access points as well as Wi-Fi tethering using smartphones. Device-to-device communications and ad hoc networks are emerging application areas that will significantly add to the interference challenges.

Today, given the ubiquity and high economic value of network services, there are a wealth of theoretical models and a large body of practical measurements relating to interference of signals in the various licensed cellular bands. For similar reasons, the physical layer and medium access layer of Wi-Fi (IEEE 802.11) and Bluetooth standards anticipate interference among devices operating with these protocols. In the future, spectrum sharing, new cellular standards, and the anticipated proliferation of new devices will substantially complicate interference environments. Examples of research challenges include the following:

- *Improving the understanding of some of the limits associated with unlicensed use of the spectrum.* This is particularly important in specific areas—that is, the "tragedy of the commons"[14] problem that has been long discussed and is increasingly being seen in various "high-density" traffic areas. The Boulder telecommunications laboratories are uniquely positioned to provide further support

[12] *Interference limits policies* are methods to describe the environment in which a receiver must operate without necessarily specifying receiver performance.

[13] *Harms claim thresholds* are a type of interference limits policy where in-band and out-of-band interfering signals levels must be exceeded before a radio system can claim that it is experiencing harmful interference.

[14] The "tragedy of the commons" comes from the practice of having a central commons or shared property at the center of many towns. Having an area that is shared by all is a great concept until the commons becomes over shared to the degree that it is no longer productively usable by anyone because everyone is using it at the same time.

of U-NII work because they have the expertise, access to classified information (relevant to DOD work), and structures to partner with industry.

- *Expanding contributions into the area of cross-usage-sharing models*—for example, radar and terrestrial communications, or various government and commercial satellites services and terrestrial communications. There are many uses of the spectrum today that need to be carefully considered in sharing models.
- *Applying resources to better understand various non-communications sources of harmful interference,* including electrical power lines, new lighting systems, and high-performance wired data systems.
- *Understanding the aggregate impact of multiple sources of low-level transmissions that appear as "white noise" in specific bands.* This issue is of particular concern as the era of the IoT begins to emerge. With millions, or even billions, of often uncoordinated devices all communicating, or even just sending "pings" to identify that they are present and available, the aggregate effect could be profound.
- *Contributing in the area of propagation models.* Today, there are an ever-increasing number of models and, with them, an ever-increasing level of debate on when to apply which model and why one model provides very different answers than other models. Ultimately, there is a need for a consolidated propagation modeling tool that will select the model or models that are appropriate to represent the environment in question and produce the needed model for a given set of circumstances.

Enforcement

The trends of increased device deployment and shared access to spectrum suggest that harmful interference will arise with greater frequency. Traditionally, interference was avoided through the use of conservative frequency planning and liberal use of guard bands; however, spectrum sharing may result in more liberal access to frequencies, which would in turn raise concerns over the identification and remediation of an interfering system. Due to this, there will be an increased desire on behalf of spectrum users (particularly the incumbents) to have a means of assessing and responding to such events when they arise. Furthermore, many of the frequency bands where spectrum sharing is likely to happen are bands assigned to federal users; therefore, it is logical that NTIA and NIST would be interested in understanding and potentially responding to these interference events. The committee sees a logical role for the Boulder telecommunications laboratories to engage in the area of spectrum monitoring and enforcement, such as defining methods of measurement, assessment, and thresholds.

New Spectrum-Efficient Technologies

Emerging technologies that have particular relevance to the mission of ITS and CTL include the following:

- *Massive MIMO,* which combine use of millimeter wavelength devices and MIMO to create extremely large numbers of antennas forming small beam-forming antenna arrays, can be used to enable very-high-performance broadband communications systems currently being explored for use in fifth-generation (5G) cellular systems and other applications;
- *Adaptive modulation and coding,* in which the condition of radio channels is sensed and transmission techniques are adjusted to most efficiently utilize the available spectrum resources;
- *Improved base modulation schemes* with higher-order QAM (quadrature amplitude modulation) extending the spectrum efficiency (i.e., the number of bits per Hertz being transmitted and received);

- *Channel bonding and, especially, non-contiguous channel bonding* to enable very wide spectrum channels to be assigned for very-high-speed broadband deployments;
- *Dynamic spectrum sharing,* which is being explored in commercial, government and mixed commercial/government environments, increasing the need for protocols that reduce or eliminate adjacent channel interference and imposing significantly greater sophistication in spectrum management techniques; and
- *Full duplex bi-directional operation on a single frequency channel*—a technology that is just emerging from the university research environment for which the potential applications and performance improvements are still poorly understood.

System-Level Issues

Much of the current work completed by the Boulder telecommunications laboratories focuses on narrow aspects of the wireless communication systems. While important, work should also consider system-level properties, including information assurance, power consumption, and hardware implications of spectrum congestion.

Information Assurance

One of the key systems-level issues of communication integrity is information assurance—the ability to have secure and reliable communications. As critical infrastructure systems become more dependent on wireless technology, these systems become vulnerable to new "attack vectors" through exploitation of the openness of the wireless communication channel. Potential topics include the following:

- *Evaluation of quantum communications and physical layer security techniques that rely on propagation paths rather than cryptography.* Both laboratories have relevant expertise and insight into propagation measurement and could provide a valuable independent evaluation function as these kinds of security systems emerge in the market.
- *Intentional interference.* FirstNet is a nationwide public safety network that is based on LTE cellular. It is well known that it can be neutralized though interference, intentional or unintentional, on the control channels. LTE jammers can be easily ordered over the Internet from China. Similar issues will affect Dedicated Short Range Communication (DSRC), the expected communication mode for smart cars and highways. ITS's ability to perform interference analysis is well known, but future work to determine vulnerabilities must take this interference analysis a step further to understand the ramifications on overall system performance and cost.
- *Wireless protocol and device vulnerabilities.* As radios become increasingly programmable, they can easily be hacked to exploit the vulnerabilities of wireless communication protocols, a problem that will be exacerbated by the rapid movement to the IoT. This proliferation of wireless devices brings with it an extraordinarily broad attack surface, if not properly organized and controlled.

Low-Power (Green) Wireless Communications

One of the biggest technical challenges with cellular and Wi-Fi-equipped devices (such as smartphones, tablets, and laptops) is battery life, which is even more of a challenge with IoT devices that have much smaller batteries and are expected to operate for years. One possible solution to energy consumption is to improve the energy efficiency the hardware, signal processing, and software in radios.

An alternative is energy harvesting from the environment in which the devices are located. This is a fertile field for innovation.

Hardware Considerations

In order to support a growing density of devices and users, spectrum is reused by reducing the size of cells and deploying more (and lower power) wireless access points and cellular base stations that must be connected to the backbone network (so-called backhaul). Two challenges include how to drive the overall cost of system deployment down sufficiently to make this approach affordable, including the often civil engineering-centric backhaul, and how to make it easier to upgrade this infrastructure as new wireless technologies are developed and introduced.

Location-Aware Services to Support Public Safety

As new technologies emerge, public safety communications tools will need to be integrated into the new environment. PSCR has provided significant work in testing for these new environments and will continue to contribute significantly as FirstNET is further developed and deployed. However, while the work is important, little is done in terms of cutting-edge R&D. PSCR is currently developing several research roadmaps to determine allocation of the funds provided to PSCR from the AWS-3 auction. The committee is encouraged by the first of these, which identifies location services as a key area of research.

Better contextual awareness and more accurate proximity-based services for smart phones offer great potential benefits for public safety applications. Technologies under development can provide a very accurate estimate (e.g., to within 10 cm) of the location and position of a device, both indoors and outside, using a precise fix on the location of Wi-Fi access points and precision timing of its radio transmissions. For example, if such technologies were deployed, everyone in a burning building could be located precisely through their smart phones.

Advanced atomic clock and gyro-based solutions of the future could also make it possible to locate a device, and hence a person, continuously from the time the device is manufactured. These timing and location-based technologies can be critically important, not only in locating and saving lives in burning buildings, but also in providing precise timelines using location logs for events—for example, leading up to a crime and including apprehension of the criminal by the arresting officer. These important technologies need to be carefully understood and tested, and the resources at NIST, and to some degree ITS, could be enormously valuable in this area.

NEED FOR STANDARDS DEVELOPMENT PARTICIPATION

Interoperability standards are of critical importance to both the data network and telecommunications industries. They enable a large number of vendors to supply the components necessary to assemble the vast and complex wired and wireless network infrastructure critical to connecting citizens and businesses in the United States and throughout the world. Interoperability standards are an essential ingredient to today's dynamic and growing online economy. These standards are developed in voluntary standards development organizations, such as the Institute of Electrical and Electronics Engineers, IETF, the International Organization for Standardization, and the International Telecommunication Union, by the stakeholders interested in designing, building, and deploying networks of all types—from long-range, high-capacity optical networks (e.g., IEEE 802.3 400 gigabit per second Ethernet) to pervasive low-cost, yet high-performance local area wireless networks (e.g., IEEE 802.11 WLANs, Wi-Fi). New standards are being contemplated for emerging spectrum-sharing applications, including sharing in the 3.5 GHz band (radar and communications), the 5.9 GHz DSRC band (auto and WLAN), and sharing of the unlicensed 5 GHz band (WLAN and mobile cellular radio access network).

The Boulder telecommunications laboratories have had limited participation in the well-known world-class networking and cellular industry standards settings bodies such as the IEEE 802 LAN/MAN Standards Committee (developing technologies commonly known as Ethernet, Wi-Fi, etc.), 3GPP, or IETF. Yet each of these organizations is responsible for producing the technical specifications that have enabled the current Internet and mobile cellular infrastructures that connect billions of end users, and they are aggressively working to develop the next generation of specifications that will result in new products and services over the next 10 years.

As noted above, the demand for shared-spectrum applications will only increase with time. The Boulder telecommunications laboratories are in an excellent position to act as an independent organization to evaluate the efficacy of proposed sharing standards and to test equipment and systems for compliance to these emerging classes of fair-sharing standards-based protocols. This will benefit our regulatory agencies, the FCC and NTIA, in their quest to preserve existing services while nurturing a more efficient utilization of our increasingly scarce spectrum resources. Furthermore, the vendors involved in deploying all aspects of wireless networks (services, infrastructure, network elements, hardware devices, and test equipment), in particular, can take advantage of the compliance testing and evaluation services the Boulder telecommunications laboratories could provide to them. One of the unique advantages of the laboratories is vendor independence. They are not beholden to any party that stands to benefit from the test results; hence, they can afford to be truly unbiased in their testing, providing valuable feedback to the community regarding how well the interoperability standards meet their multi-vendor interoperability objectives.

FINDING: Advances in communications and networking technologies will have a 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 IOT devices has been slow in emerging. Neutral technical expertise is needed for determining when spectrum is underutilized, reviewing technology for shared use, and evaluating interference and enforcement.

RECOMMENDATION: The Department of Commerce (DOC) should develop short- and long-term application and basic research plans that would provide the country with the necessary knowledge base in spectrum areas and enhance the capability for spectrum sharing and repurposing analysis. 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 the laboratories' resources and develop an effective organizational structure and funding strategy to ensure research goals are met and resources are effectively used.

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

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

Appendixes

A

Statement of Task

An ad hoc committee under the auspices of the National Research Council will assess telecommunications research and engineering programs at the Department of Commerce's (DOC's) Institute for Telecommunication Sciences (ITS), part of the National Telecommunications and Information Administration) and the newly formed NIST Communications Technology Laboratory (CTL). The labs, both located in Boulder, Co., are to be combined as a jointly managed Center for Advanced Communications (CAC). The review will respond to a congressional request to "analyze the research and activities of ITS and make recommendations regarding the extent to which ITS research is addressing future telecommunications challenges and spectrum needs" and help NIST assess the impact of existing telecommunications research and engineering efforts and ensure that future efforts for the CAC are successfully positioned.

The assessment of and potential scope of recommendations concerning NTIA ITS activities will include the following:

Capabilities—How well ITS's capabilities compare to state-of-the-art research and engineering programs worldwide and how well the capabilities of ITS align with perceived skillsets required to meet industry demand.

Performance—How well the performance of ITS compares to similar research organizations with similar functionalities.

Resources—To what extent ITS laboratory facilities, equipment, and human resources are adequate for supporting high quality, future-focused technical research programs currently and in the future and whether current financial resources are sufficient for ITS to achieve its stated objectives and desired impact currently and in the future.

Customer needs—The technical research and engineering needs of potential customers, the extent to which extent ITS capabilities and projects are meeting this need, and areas where available services cannot meet needs.

Strategy—How ITS might address unmet customer needs through future projects and the associated costs/risks and benefits/advantage; how well the pipeline of projects for ITS addresses future telecommunications challenges and spectrum needs; and whether current processes for assessing and prioritizing potential research projects lead to projects that appropriately address future telecommunications and spectrum needs.

The assessment of NIST CTL activities will include the following:

Capabilities and performance—How the current NIST CAC-related programs compare to state-of-the-art programs worldwide.

Customer needs—What the CAC technical program should include to best meet the needs of potential customers.

Strategy—Best practices to assess and prioritize potential CAC research projects to address future telecommunications and spectrum needs.

The assessment will primarily be based on information gathered during a two-and-one-half day site visit to the two Boulder labs. It will also reflect a review of program documentation and interviews and briefings to obtain input from past, current, or potential federal and industry sponsors of Department of Commerce telecommunications research and engineering.

The committee will not make recommendations concerning the level of funds appropriated for the Boulder labs.

B

Committee Biographies

DOUGLAS C. SICKER, *Chair*, is currently the department head and professor of engineering and public policy with a joint appointment in the School of Computer Science at Carnegie Mellon University and holds the Lord Endowed Chair of Engineering. Dr. Sicker also serves as the executive director of the Broadband Internet Technical Advisory Group (BITAG) and the chief strategist of CMMB Vision. Previously, he was the DBC Endowed Professor in the Department of Computer Science at the University of Colorado, Boulder, with a joint appointment in, and director of, the Interdisciplinary Telecommunications Program. Dr. Sicker recently served as the chief technology officer and senior advisor for spectrum at the National Telecommunications and Information Administration (NTIA). He also served as the chief technology officer of the Federal Communications Commission (FCC), and prior to this he served as a senior advisor on the FCC National Broadband Plan. Earlier, he was director of global architecture at Level 3 Communications, Inc. In the late 1990s, Dr. Sicker served as chief of the Network Technology Division at the FCC. Dr. Sicker received his Ph.D. in telecommunications from the University of Pittsburgh. Dr. Sicker's research interests include wireless systems, network security and privacy, and internet policy.

JENNIFER BERNHARD is currently a professor in the Department of Electrical and Computer Engineering and the associate dean for research in the College of Engineering at the University of Illinois, Urbana-Champaign. Dr. Bernhard has been a faculty member in the Electromagnetics Laboratory in the Department of Electrical and Computer Engineering at the University of Illinois since 1999. Her research group focuses on the development and analysis of multifunctional reconfigurable antennas and their system-level benefits as well as the development of antenna synthesis and packaging techniques for electrically small, planar, and integrated antennas for wireless sensor and communication systems. In addition to the National Science Foundation (NSF) CAREER Award, the Institute of Electrical and Electronics Engineers (IEEE) Antennas and Propagation Society H.A. Wheeler Prize Paper Award, and other research recognitions, she has been honored with a number of teaching and advising awards. In 2008-2009, Dr. Bernhard was a member of the Defense Science Study Group, sponsored by the Defense Advanced Research Projects Agency (DARPA). In 2010, she co-chaired the NSF Workshop on Enhancing Access to the Radio Spectrum. She also served on the President's Council of Advisors on Science and Technology (PCAST) Working Group on Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth in 2011-2012. She is a fellow of the IEEE, and in 2008, she served as the president of the IEEE Antennas and Propagation Society. Dr. Bernhard received her Ph.D. in electrical engineering from Duke University.

ELSA GARMIRE is the Sydney E. Junkins Professor of Engineering at Dartmouth College. She was president of the Optical Society of America in 1993. Dr. Garmire received her B.A. from Harvard University and her Ph.D. from the Massachusetts Institute of Technology (MIT), both in physics. After postdoctoral work at the California Institute of Technology (Caltech), she spent 20 years at the University of Southern California, where she was eventually named William Hogue Professor of Electrical Engineering and director of the Center for Laser Studies. She went to Dartmouth in 1995, where she served 2 years as dean of Thayer School of Engineering. In 2007 to 2008, Dr. Garmire spent a year as a Jefferson Science Fellow at U.S. State Department in the Office of International Communications and Information Policy, specializing in international spectrum allocation. Author of more than 250 journal papers and holder of nine patents, she has been on the editorial board of five technical journals. She is a member of the National Academy of Engineering (NAE) and the American Academy of Arts and Sciences, and a fellow of IEEE, the American Physical Society (APS), and the Optical Society of America; she has served on the boards of three other professional societies. In 1994 she received the Society of Women Engineers Achievement Award. She has been a Fulbright senior lecturer and a visiting faculty member in Japan, Australia, Germany, and China. She has been chair of the NSF Advisory Committee on Engineering Technology and served on the NSF Advisory Committee on Engineering and the Air Force Science Advisory Board. Dr. Garmire was elected to the NAE in 1989 for contributions to nonlinear optics and optoelectronics and for leadership in education.

DAVID GOODMAN has been a professor emeritus in the Department of Electrical and Computer Engineering at New York University (NYU) since 2008. He was previously a professor and department head (1999-2001) and director of the Wireless Internet Center for Advanced Technology, an NSF center at NYU, Auburn University, Virginia Tech, and the University of Virginia. His research has made fundamental contributions to digital signal processing, speech coding, and wireless information networks. In 2006 and 2007, he was a program director in the Computer and Network Systems Division of NSF. Prior to joining NYU, he founded and directed the Wireless Information Network Laboratory at Rutgers University. In 1995, he was a research associate at the Program on Information Resources Policy at Harvard University. In 1997, he chaired the National Research Council (NRC) committee studying the evolution of untethered communications. From 1967 to 1988 he was at Bell Laboratories, where his final position was head of the Radio Research Department. Dr. Goodman is a member of the NAE and a foreign member of the Royal Academy of Engineering, a fellow of IEEE, and a fellow of the Institution of Engineering and Technology. In 1997, he received the ACM/SIGMOBILE Award for "outstanding contributions to research on mobility of systems users, data, and computing." In 1999, he won the RCR Gold Award for the best presentation at the Conference on Third Generation Wireless Communications. In 2003, he received the Avant Garde award from the Vehicular Technology Society of the IEEE. Three of his papers on wireless communications have been cited as Paper of the Year by IEEE journals, and another one earned the Award for Advances in Communication, "given to an outstanding paper published in any IEEE Communications Society publication in the previous 15 calendar years." Dr. Goodman received his Ph.D. in electrical engineering from Imperial College, University of London.

HELENA MITCHELL is the executive director of the Center for Advanced Communications Policy. She holds the rank of principal research scientist for the Georgia Institute of Technology. Helena guides the development of the technology policy agenda. Dr. Mitchell and her staff create programs and services to stimulate movement into new and advanced technology areas by institutions of the University System of Georgia and its partners. In tandem, she is the principal investigator (PI) on several major grants, including NSF, state agencies, the private sector, and the U.S. Department of Education ($5 million) "Rehabilitation Engineering Research Center on Mobile Wireless Technologies for Persons with Disabilities." Her areas of specialty include spectrum management, educational technologies, regulatory and legislative policy, DTV, emergency/public safety communications, and universal service to rural and vulnerable populations. Dr. Mitchell is a member of the School of Public Policy faculty. She was the former GRA Eminent Scholar for Distance Learning and continues to oversee the Innovative and Dynamic Educational Applications for Learning (IDEAL) virtual research center which spans technology integration into educational, community, and business environments. Her research contributed to the role of public policy in addressing technology's impact on education. Dr. Mitchell came to Atlanta from the FCC, where she was the associate chief, strategic communications, for the Office of Engineering and Technology. There, she developed and executed a wide range of programs to increase FCC dialog with advanced technology companies in new product development. Dr. Mitchell was the former chief of the

Emergency Broadcast System (EBS) of the FCC. She wrote major rulemakings that expanded EBS to include cable, satellite, and advanced communications systems. Her work resulted in the adoption of the new Emergency Alert System and selection as the FCC Organization of the Year. Dr. Mitchell has held other positions in senior management, higher education, broadcasting, and in the private sector. She has spoken, written, and taught at the graduate level on domestic and international telecommunications, policy, technical bridging, and funding agendas. She has and continues to be a grants woman and recipient of funding. Dr. Mitchell takes pride in mentoring students from high school through Ph.D. programs. She serves on a wide variety of advisory councils and board of directors. Dr. Mitchell holds a Ph.D. from Syracuse University.

HARLIN McEWEN is chairman of the Communications and Technology Committee of the International Association of Chiefs of Police (IACP) and has more than 5 decades of experience as both an advocate for public safety telecommunications issues and as a career law enforcement officer and administrator. Chief McEwen started his career as a patrol officer in 1957 and, after progressing through the ranks, served as a chief of police for more than 20 years, last serving as chief in the City of Ithaca, New York, where he was instrumental in implementing modern technology and computerization and advancing training and professionalism of the force. During his years of service, he served as coordinator of the Tompkins County Mobile Radio District, as deputy commissioner of the New York State Division of Criminal Justice Services, and director of the Bureau for Municipal Police, where he was responsible for overseeing the training and registration of all police officers and peace officers in New York State, as well as for the development and implementation of the New York State Law Enforcement Agency Accreditation Program. In February 1996, Chief McEwen was sworn in by Federal Bureau of Investigation (FBI) Director Louis Freeh as a deputy assistant director of the FBI. During his tenure at the FBI, he was responsible for oversight of the development and implementation of the National Crime Information Center 2000 system and the Integrated Automated Fingerprint Identification System and also traveled extensively throughout the United States and internationally, speaking at law enforcement and criminal justice conferences on matters relative to the FBI Criminal Justice Information Services. Chief McEwen participated as a member of the Steering Committee on the Public Safety Wireless Advisory Committee and as a member of the Steering Committee of the FCC Public Safety National Coordinating Committee. He was a leader in creating the National Public Safety Telecommunications Council (NPSTC). Chief McEwen previously served as communications advisor to the Major Cities Police Chiefs Association, the National Sheriffs' Association, and the Major County Sheriffs' Association. He serves on numerous advisory committees and is also an advisor to the FBI, the National Institute of Justice, the Department of Homeland Security, and various other organizations. Chief McEwen is a member of the board of directors and fellow in the Radio Club of America and was the first recipient of the RCA/NPSTC Richard DeMello Award. He is the recipient of the prestigious FBI Medal of Meritorious Achievement, the IACP Lone Star Distinguished Award, and in 2006 was named as Honorary President of the IACP.

PAUL NIKOLICH is a private consultant whom has been serving the data communications and broadband industries developing technology, standards, and intellectual property and establishing new ventures as an executive consultant and angel investor since 2001. He is an IEEE fellow and has served as chairman of the IEEE 802 LAN/MAN Standards Committee since 2001. As 802 chairman, he provides oversight for 75 active 802 standards and the 50 concurrent 802 activities in wired and wireless communications, networking with more than 800 active members and managing the relationships between IEEE 802 and global/regional standards bodies such as ISO, ITU, regulatory bodies, and industry alliances. He is a member of the IEEE Communications Society, the Computer Society Standards Activities Board, and an active leader in the IEEE, the IEEE Computer Society, and the IEEE Standards Association board of governors. He is a partner in YAS Broadband Friends, LLC, and holds several patents, serves on the technology advisory boards of companies developing emerging communications technology. Mr. Nikolich has held technical leadership positions at large and small networking and technology companies beginning in 1978 (e.g., Broadband Access Systems, Racal-Datacom, Applitek, Motorola, Analogic). He received a B.S. in electrical engineering, a B.S. in biology, and an M.S. in biomedical engineering from Polytechnic University in Brooklyn, N.Y. (now New York University Polytechnic School of Engineering).

JEFFREY H. REED is the Willis G. Worcester Professor in the Bradley Department of Electrical and Computer Engineering at Virginia Tech. He currently serves as founding director of Wireless@Virginia Tech, one of the largest and most comprehensive university wireless research groups in the United States, which he founded in 2006 and served as its first director. In 2010, he founded the Ted and Karyn Hume Center for National Security and Technology and served as its interim director. Dr. Reed's area of expertise is in software radios, smart antennas, wireless networks, and communications signal processing. He has authored, co-authored, or co-edited 10 books and proceedings, contributed to 6 books, and authored or co-authored more than 300 journal and conference papers. His book on software defined radio is considered one of the earliest and most comprehensive books on the subject. In September 2014, his book on cellular networks was published by Wiley and IEEE Press and is a comprehensive review of fundamentals and cellular network operations. Dr. Reed has had numerous commercial research sponsors, including Samsung, Motorola, LG, TI, GM, and Intel; government sponsors, including DARPA, the Office of Naval Research, the Army Research Office, the Joint IED Defeat Organization, the Department of Justice, and the U.S. Customs Department; and government contractors, including ITT, SAIC, General Dynamics, Aerospace, IDA, and Raytheon. He is currently the PI on an NSF project to examine enforcement and regulatory technologies for spectrum sharing between commercial wireless and government users. Dr. Reed has been PI or co-PI on 97 different sponsored research contracts. He is co-founder of Cognitive Radio Technologies, a company that is commercializing of the cognitive radio technologies produced at Virginia Tech for commercial and military applications; Federated Wireless, a company that is commercializing 5G wireless systems; and for Power Fingerprinting, a company that specializes in security for embedded systems, including Android platforms. He co-founded these companies with his former Ph.D. students. He has also served as a consultant for approximately 30 organizations and more recently was engaged in consulting regarding the AT&T–T-Mobile merger and the band plan strategy for the upcoming 600 MHz auctions and is currently advising on the spectrum screening issues before the FCC. He has served on the technical advisory boards for approximately six companies and as an in informal advisor on national policy regarding wireless issues. Dr. Reed served on the PCAST Working Group on how to transition federal spectrum for commercial economic benefits. In 2014, Dr. Reed was selected to be a member of Commerce Spectrum Management Advisory Committee, the advisory group on spectrum issues for the Department of Commerce. In 2004, he received the Outstanding Industry Contributor Award from the SDR Forum. During 2004, he also received an award from the SDR Forum for his pioneering 2001 publication that provides a mathematical foundation to cognitive radio based on game theory. In 2005, Dr. Reed became a fellow to the IEEE for contributions to software radio and communications signal processing and for leadership in engineering education. He is a Distinguished Lecturer for the IEEE Vehicular Technology Society and is on the editorial board for the *Proceedings of the IEEE*. In 2013, he received the International Achievement Award from the Wireless Innovations forum for the impact of his accumulated research. In 2014, Dr. Reed served as co-general chair for the IEEE Dynamic Spectrum Access Network (DySPAN) conference. He received his Ph.D. in electrical and computer engineering from the University of California, Davis.

RICHARD (RICK) L. REASER, JR., is head of the Spectrum and E3 Department at Raytheon Space and Airborne Systems where he plans and coordinates Spectrum Access System (SAS) use of electromagnetic spectrum and Electromagnetic Environmental Effects (E3) efforts through technical and administrative processes consistent with applicable laws and regulations to meet customer product needs. He currently serves on the Commerce Spectrum Management Advisory Committee (CSMAC). Mr. Reaser joined Raytheon in August 2006. Prior to joining Raytheon, he was deputy system program director and chief engineer for the $32 billion Navstar Global Positioning System. He served as deputy director of spectrum management in the Office of the Secretary of Defense and held spectrum positions in the White House and State Department. He was technical advisor to the U.S. Ambassador to the World Radio Communications Conference (WRC) 2000 and was a U.S. spokesperson at WRC-2003. He negotiated landmark navigation and communication signal and spectrum agreements between the United States, the Russian Federation, France, Japan, and the European Union. He also represented Department of Defense interests in 2002 Ultra Wideband (UWB) and 2003 Mobile Satellite Service (MSS) Ancillary Terrestrial Component (ATC) FCC rulemakings. Mr. Reaser has held a variety of engineering and management assignments in military space communication, navigation, imagery dissemination, and infrared detection programs. He has Level III Defense Acquisition Workforce Improvement Act certifications in program management, system engineering, and test. He retired from the Air Force after 28 years of service at the rank of Colonel. Mr. Reaser earned his bachelor's degree in engineering mechanics from the U.S Air Force Academy. He holds master's degrees in systems technology (command, control, and communications) and national resource strategy from the Naval Postgraduate School and National Defense University, respectively.

DENNIS ROBERSON has been vice provost and a research professor with the Illinois Institute of Technology (IIT) since June 2003, where he established a new undergraduate business school, a wireless research center (WiNCom), IIT's corporate relations initiative, and is currently responsible the latter two efforts and IIT's Research efforts, strategic plan assessment, and its technology commercialization office and externally focused entrepreneurial efforts. Professor Roberson is also president, CEO, and member of Roberson and Associates, LLC, a technology and management consulting firm serving a variety of government and commercial customers since 2008. From April 1998 to April 2004, Professor Roberson was executive vice president and chief technical officer of Motorola, Inc. From 1971 to 1998, he held senior executive positions with NCR Corporation, AT&T, Digital Equipment Corp. (now part of Hewlett Packard), and IBM. Professor Roberson is a director of Advanced Diamond Technologies, Cleversafe, Caerus Institute, OnKol, and SonSet Solutions. He also chairs the FCC's Technology Advisory Council and serves on the Commerce Department's CSMAC. He has served as an invited expert for the development of the PCAST Spectrum Policy Report, the board of directors of FIRST Robotics, the National Advisory Council for the Boy Scouts of America, the board of Singapore's Agency for Science, Technology and Research, and as an International Advisory Panel member for the Prime Minister of Malaysia. He holds bachelor of science degrees in physics and electrical engineering from Washington State University and a master's of science in electrical engineering from Stanford University.

C

Briefers to the Committee

Institute for Telecommunications Sciences (ITS)

Keith Gremban, Director
Brian Lane, Executive Officer
Dale Hatfield
Wayde Allen, Spectrum and Propagation Measurement Division
Michael Cotton, Telecommunications Theory Division
Julie Kub, Telecommunications Engineering, Analysis and Modeling Division
Eric Nelson, Division Chief, Spectrum and Propagation Measurement Division
Margaret Pinson, Telecommunications Theory Division
Patricia Raush, Division Chief, Telecommunications Theory Division
Frank Sanders, Division Chief, Telecommunications Engineering, Analysis and Modeling Division
Andrew Thiessen, Division Chief, Telecommunications and Information Technology Planning & Deputy Program Manager, Public Safety Communications Research, Center for Advanced Communications
Steve Voran, Telecommunications Theory Division
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Kent Rochford, Director
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Michael Kelley, Division Chief, Radio Frequency Technology Division
Dereck Orr, Division Chief, Public Safety Communications Research Division and Program Manager, Public Safety Communications Research, Center for Advanced Communications
Kate Remley, Wireless Systems Metrology
Bill Young, RF Technology Division

ITS Customer Interviews

Jeb Benson, Department of Defense
David Campbell, Department of Homeland Security
Philip Corriveau, Intel
Steve Fowler, U.S. Army
Steve Gunderson, U.S. Navy
Christian Jacobson, U.S. Air Force
Robert Scully, National Aeronautics and Space Administration

D

The Value and Use of Wireless Technology

Wireless is a short-cut terminology for electromagnetic (EM) waves transmitted through free space (without wires). EM waves are fundamental in nature. As waves, they are sinusoidal fields defined by their frequency, which can have any value from very slow vibrations to ultra-rapid vibrations. The EM waves engineers create are radiated by vibrating electrons, electrically driven to emit at the characteristic frequencies needed for wireless technology. Table D.1 gives the range of frequencies used for wireless and provides names for the ranges of frequencies that engineers use. The wavelengths of EM waves are related to the reciprocal of their frequencies. Those EM waves with wavelengths between 1 m and 1 mm are called microwaves. Millimeter waves are the name given to the highest frequencies used for wireless, with wavelengths from 0.10 to 1 cm. The terms *airwaves* and *radio waves* are sometimes used for EM waves, and the entire range of EM frequencies available for applications is called spectrum. Governments all over the world control their own airwaves by allocating separate bands of spectrum for separate applications.

EM waves can be used to transmit information if the waves are modulated (their characteristics changed with time). Radio waves, particularly microwaves and millimeter waves, form the basis of today's wireless technology. For certain applications, light waves can also be used to establish short-range wireless links, although most of their high-speed applications require transmission in optical fibers/waveguides.

Communication requires modulating the EM waves, resulting in a spread of frequencies (*bandwidth*) that carry the information surrounding the carrier frequency that defines the unmodulated wave. Because the bandwidth is a well-defined fraction of the carrier frequency, it can be seen that higher carrier frequencies can have larger bandwidth and can transmit more information. Modulated EM waves form the basis of today's wireless telecommunication systems. Today, much of the modulation has a digital format.

CONTROL OF THE AIRWAVES

The first public awareness of the importance of wireless telecommunication was the distress signals broadcast by the sinking Titanic in 1912. These signals were picked up by a nearby ship, beginning the famous rescue operation. The resulting publicity demonstrated to the world that safety required specific frequencies to be reserved for specific applications, such as SOS emergencies. Thus began government control of airwaves. The military buildup due to World War I caused wireless frequencies to be reserved primarily for government use. In the United States, the federal assignment of frequencies to commercial entities began in 1922, when 833 kHz was defined as the frequency to be used for "Entertainment" and 619 kHz as the frequency for "Market and Weather." These frequencies were in the kHz regime because wireless systems at that time could only operate at very low frequencies. As technology rapidly improved, higher frequencies could be used. By the following year, the spectrum (range of available frequencies) was assigned out to 1350 kHz (1.350 MHz).

TABLE D.1 Spectrum Frequency and Wavelength Ranges for Different Wireless Applications

Range	Designation	Frequency	Wavelength
Long wave	Low frequency (LF)	30 - 300 kHz	10 km - 1 km
Mid wave	Medium frequency (MF)	300 - 3000 kHz	100 m - 100 m
Short wave	High frequency (HF)	3 - 30 MHz	100 m - 10 m
Ultra shortwave			
Meter range	Very high frequency (VHF)	30 - 300 MHz	10 m - 1 m
Decimeter range	Ultra high frequency (UHF)	300 - 3000 MHz	100 cm - 1 cm
Centimeter range	Super high frequency (SHF)	3 - 30 GHz	10 cm - 1 cm
Millimeter range	Extremely high frequency (EHF)	30 - 300 GHz	10 mm - 1 mm

NOTE: Shaded areas are microwave.

Because EM waves easily travel across boundaries between countries, beginning in the 1920s, governments around the globe have negotiated within the International Telecommunications Union (ITU)[1] to allocate different frequency ranges for different applications while providing for compatibility**.** Radio services that have been allocated spectrum include fixed service (e.g., from one cell tower to another), mobile service (e.g., aeronautical and marine communications), land mobile service (cell phones), and broadcast service (TV), as well as standard frequency and time signals, discrete frequencies that require exclusivity for radio astronomy, and amateur radio. Through extensive negotiation, the entire radio spectrum has been divided into specific blocks of frequencies for each application; most often, several blocks at different carrier frequencies can service the same application. These blocks of frequencies are then allocated by most countries.

Spectrum Auctions

In the U.S. spectrum is allocated by the Federal Communication Commission (FCC) for non-governmental applications and by the National Telecommunications and Information Administration (NTIA) allocates spectrum for governmental applications. When the same band is shared for different applications, both entities need to agree. Initially, there was enough spectrum for everyone, and allocations were made by determining the best use for each band based on both availability and the state of the relevant technology at the time. However, in 1994 the rapid growth in personal communication systems and the impending explosion of mobile cell phone usage forced re-consideration of band allocation within the spectrum. The FCC introduced the idea of auctioning these frequency allocations to the highest bidders, with the understanding that profits could be returned to the federal budget.

[1] The International Telecommunication Union coordinates the shared global use of radio spectrum. Internationally harmonized global spectrum allocations allow manufacturers to develop worldwide markets, as demonstrated through the widespread adoption and commercial success of IEEE) standards for wireless local area networks (WLANs) in 1999, and more recent agreements that all WLANs operate in the same globally allocated spectrum. WLAN succeeded because there was universal international agreement for the use of the 2.4 GHz industry, science, and medical (ISM) band and 5 GHz Unlicensed National Information Infrastructure (UNII) bands, which allowed major manufacturers to devote significant resources to create products that could be sold and used globally. Without international spectrum agreements, new wireless technologies will founder for lack of a global market. Countries whose engineers participate in the standard-setting of ITU have more political clout to persuade the global community to choose standards that are consistent with the technology used in their country.

The first auction assigned 50 to 100 kHz bandwidth blocks within the 901-941 MHz range of carrier frequencies nationwide. Ten national licenses were provided for a total bandwidth of 0.78 MHz, for which the FCC and the U.S. government received $617 million. A few days later, the FCC auctioned off the blocks of higher bandwidth near the 218 MHz carrier frequency to 297 metropolitan service areas with the idea that these blocks could be reused by different metropolitan areas. The FCC planned for them to be used for interactive video and data services. In fact, these blocks were broken up by the carriers to enable them to handle multiple mobile phones operating simultaneously in the same cell. Almost $214 million was raised.

The rapid adoption of cell phones by the general population made apparent the value of owning spectrum bandwidth assignments. Only 4 months later, a similar auction assigning carrier frequencies of 1.8-.9 GHz (known as the A and B blocks) with 60 MHz bandwidth each sold for more than $7 billion. One year later (1995) more than $10 billion was raised in an auction to assign the higher 1.9 GHz frequency (the so-called C-block). The rapid rise in commercial value points to the rapid growth in bandwidth requirements for the burgeoning cell phone industry; the second year of FCC spectrum auctions brought in $17 billion dollars. A few of the relevant later auctions are described below.

The FCC Auction 8 in 1996 assigned frequencies for satellite TV (DBS, or Direct Broadcast Satellite). A very high carrier frequency of 12.2-12.7 GHz was chosen to provide the needed bandwidth: 28 channels at 24 MHz for a total bandwidth of 672 MHz. This was designed for direct-to-home satellite service to permit delivery of digitally compressed TV signals to individual households by means of an external receiving antenna. The external antenna was required because waves at this high frequency do not readily pass through walls. MCI paid $682 million for the nationwide license, less than the bidding on lower-frequency spectrum because of the limited market due to the need for an external antenna and the growing availability of directly connected cable.

By 2000, Auction 30 was designed for outdoor fixed point-to-point and point-to-multipoint communications, such as between cell towers. The 39 GHz carrier frequency was designated with 14 channels each with bandwidth of 100 MHz. Usage of these frequencies requires highly directional antennas to counteract propagation losses while enabling point-to-point communication.

As TV moved from analog to digital, more bandwidth previously used for analog TV transmissions could be repurposed for wireless telecommunications applications. The frequency band from 470-806 MHz had originally been reserved for broadcasting TV. In 2008, bands with carrier frequencies between 698 and 806 MHz were auctioned off, bringing in a record $19 billion.

By 2012, concerns about improving homeland security pointed to the need for a network on a single frequency band over which all first-responders could wirelessly communicate; at the time, different responders typically used different frequency bands. Congress created the First Responder Network Authority (FirstNet) with the mission to provide a single interoperable platform for emergency and daily public safety communications. FirstNet will build, operate, and maintain the first high-speed, nationwide wireless broadband network dedicated to public safety. The spectrum license issued to FirstNet is for two 10 MHz channels of paired spectrum at 758-768 MHz and 788-798 MHz, plus guard bands at 768-769 MHz and 798-799 MHz to reduce interference from adjacent channels.

To pay for FirstNet, the FCC arranged Auction 97 to allocate mid-band spectrum between 1700 and 2100 MHz frequencies (1.7-2.1 GHz). This so-called AWS-3 band has become very valuable, because increasing numbers of Americans use Internet-enabled wireless devices to do more things that require faster networks, such as watching streaming video. The auction set a new record, netting $41.3 billion for 12-year licenses. This AWS-3 band already had incumbent users, and new users would have to share it. Box D.1 outlines the requirements on new licensees designed to protect incumbent operations. Furthermore, the licensees will have to wait before they can use their new spectrum because DOD is using some of the frequencies for missile guidance systems, drone training programs, and similar activities. DOD expects these programs to take 5-10 years to relocate to other spectrum bands. As noted in Chapter 4, he Boulder telecommunications laboratories can provide considerable value to operation of this new shared allocation and have the potential to act as an independent agent to resolve disagreements between parties that share the same spectrum band, determining whether or not the AWS-3 requirements have been met.

Auction 97 was authorized to raise money for the federal government, including the funding of FirstNet. The FCC set a goal of raising at least $10.6 billion for the sale of 1,600 licenses. Because the auction generated $41 billion, FirstNet has been fully funded. The aim of this newly defined band is for all safety officers (police and fire fighters) to migrate to this new band.

Not all bands in this spectrum are equally valuable for all applications. The lower frequencies can be transmitted through walls and are useful for mobile phones, for example. But they have smaller bandwidth so they cannot carry large amounts of information. They also require larger antennas than do the higher frequencies. Higher carrier frequencies designated with larger bandwidths can carry more information, but walls and other obstacles may block it. The highest frequencies—millimeter waves (mm-band) (30 GHz and above)—are also attenuated by foliage and absorbed in the atmosphere. The propagation distance through the atmosphere generally decreases as the frequency goes up. This has advantages because the frequencies can be reused easily with the limited propagation range in this band. Thus, millimeter-waves may be useful for line-of-sight transmission for short distances. While they use smaller antennas, the electrical components become more expensive at higher frequencies. However, the cost per bit of information will decrease. Furthermore, licenses for services at higher frequencies are typically less expensive than at lower frequencies because they are not suitable for mobile phone applications. Also, mm-wave bands can be made available quickly because there are no incumbent users. All these factors point to an expected increase in mm-wave wireless telecommunications.

Typical systems split the carrier frequency into a number of channels, each with a specific transmission bandwidth that determines the rate of information that can be transmitted. Ten times the frequency can mean either ten times the bandwidth per channel or 10 times the number of channels. As transmission frequencies move into the multi-gigahertz range, larger bandwidth channels are possible, and continuous innovations in technology promise to deliver ever-increasing bandwidths and capabilities.

BOX D.1
Requirements on AWS-3 Licensees

Incumbency Issues. The AWS-3 bands are currently being used by Federal and non-Federal incumbents for a variety of government and non-government services. AWS-3 licensees are subject to various requirements related these incumbent users, including Federal and non-Federal relocation, sharing, and cost-sharing obligations, coordination requirements, and protection of Federal and non-Federal incumbent operations.

License Period. Initial licenses for AWS-3 spectrum will be granted for a twelve-year term, with subsequent renewal terms of ten years.

Construction Requirements. There are buildout requirements for the AWS-3 licenses offered in Auction 97. An AWS-3 licensee must provide reliable signal coverage and offer service to at least 40 percent of the population in each of its license areas within 6 years after license grant, and provide reliable signal coverage and offer service to at least 75 percent of the population in each of its license areas by the end of the initial twelve-year license term

Partitioning and/or disaggregation of AWS-3 licenses is permitted.

SOURCE: Reprinted from Advanced Wireless Services (AWS-3) Fact Sheet. http://wireless.fcc.gov/auctions/default.htm?id=97&job=auction_factsheet November 4, 2015.

APPLICATIONS IN UNLICENSED BANDS

Some of the spectrum is set aside for unlicensed applications, meaning one does not need a license to use the spectrum as long as one abides by defined constraints associated with the specific bands. These include the ISM radio bands, reserved internationally for the use of EM energy for industrial, scientific and medical purposes, and the U-NII band, used extensively for wireless local networks.

Industrial, Scientific, and Medical Band

The ISM band is a part of the radio spectrum that can be used without a license in most countries.[2] In the U.S., the bands were initially used for machines that used or emitted radio frequencies but not for radio communications.

- *Industrial applications.* Radio frequency energy is used for a variety of industrial welding, heating, and drying applications, including ceramics, foam, fiberglass, composites, textiles, food tempering and pasteurizing, wood, and paper. Industrial RF heaters can have powers in the 100 kW range. As just one example, RF energy is useful for sealing plastics. An RF heat sealer heats a plastic part to the point at which it can bond with another plastic part or to another surface. The technique is faster and cleaner than conventional thermal welding and also produces a stronger bond. There are more than 100,000 RF heat sealers in operation in the United States used in a variety of industries. The power generated by an RF heat sealer ranges from about 1.5 kW to more than 60 kW—a power level comparable with the highest power radio and television transmitters. However, the power is concentrated into the area that needs sealing. Nonetheless, there is considerable possibility of RF signals leaking from the equipment into the airwaves where it may interfere with RF communications applications in the same frequency band. In most cases, this equipment is qualified and monitored for non-intentional radiation during the course of its use, but the Boulder telecommunications laboratories should be aware of these possible sources of microwave interference.

  RF generators also excite plasmas for materials processing such as plasma vapor deposition (PVD), chemical vapor deposition (CVD), and plasma-enhanced chemical vapor deposition (PECVD) and etching. These processes are used for applications such as semiconductor manufacturing, integrated circuit (IC) fabrication, thin-film heads for disks, CDs, hard disk coatings, and other industrial uses. RF is also used in the development of IC devices at geometries from 0.5 to 0.25 microns for digital random-access memory, logic, application-specific integrated circuits, and other such devices. Other major application for RF-generated plasmas is industrial-scale plasma welding and cutting.
- *Scientific applications.* There is a multitude of scientific users of radio spectrum including radio astronomers and Earth scientists using remote sensing.[3] Satellite-based sensing is used extensively in weather prediction and for meteorological and climate-sensing applications, typically at frequencies spread across the EM spectrum, sometimes up to 60 GHz. Remote sensing can also be terrestrial or from airplanes. Measurement of absorption and scattering of RF beams can provide water vapor profiles, snow and ice coverage, cloud liquid water, and rain rate to monitor the state of the environment.

[2] International Telecommunication Union, Article 1, Section 1.15.

[3] National Academies of Science, Technology, and Medicine, 2015, *A Strategy for Active Remote Sensing Amid Increased Demand for Radio Spectrum* (The National Academies Press, Washington, D.C.) explores the continued need for spectrum for scientific research and encourages NASA to engage with regulatory agencies, including the NTIA, to limit interference and develop sharing mechanisms.

Some scientific applications require specific RF frequencies that may not be within ISM bands but must be protected from interference. Radio astronomy is an example. In order for radio astronomers to detect the faint signals from cosmic sources, certain scientifically important RF bands are kept clear of radio transmissions. Nevertheless, there is still some interference due to legal, high-power transmitters outside but close in frequency to the radio astronomy band. This is because all practical transmitters radiate a very small fraction of power outside their designated frequency, which can swamp the signals radio astronomers are trying to detect. Any frequency for which the atmosphere is transparent can be used for radio astronomy. However, other frequencies are assigned to other services which might cause interference. For example, Jupiter's most interesting radiation is between 15 MHz and 30 MHz. To study Jupiter's radiation in this band, the radio astronomer has to contend with transmissions from all over the world as well as computer- and television interference in the nearby 88 - 108 MHz FM broadcast band. The radio astronomer has to learn to distinguish between all kinds of noise and that coming from Jupiter. In the future, their work may become harder if their bands are not protected from emerging commercial demands on broad airwave access. Other scientific applications include microwave spectroscopy. For example*, many electron paramagnetic resonance (EPR) spectrometers operate near 9.8 GHz.*

- *Medical applications.* High frequency microwaves can be used to create therapeutic localized heating, particularly at frequencies absorbed by water. Unlike other forms of electromagnetic frequencies that cause a "surface effect," wherein the skin feels the heat application, RF energy can penetrate the body and be absorbed in deep body locations with a lower amount of heat sensation. RF medical devices transmit radio waves to increase the temperature of tissue. A sharp heat boundary is created between the affected tissue and that surrounding it allowing for surgeons to operate with a high level of precision and control, without much sacrifice to the adjacent normal tissue. The lower operating temperatures of RF, as compared to traditional electrosurgical or laser surgery tools, enables surgeons to remove, shrink, or sculpt soft tissue while simultaneously sealing blood vessels. RF works particularly well on connective tissue, which is primarily comprised of collagen and shrinks when exposed to heat.
- *Commercial use of ISM band.* Because ISM frequencies are available for unlicensed devices without paying for access, They are often used for commercial applications, including short-range communication devices. Communications equipment operating in these bands must accept any interference generated by ISM equipment, and users do not have regulatory safeguard from ISM equipment operation. More recently, because of high demand for usage for wireless connections to the Internet through mobile devices, the ISM bands have also been used through local access points to provide an alternative to connection via a traditional cell tower or access point. These connections must follow the existing rules for non-interference with other users of the ISM bands.

The ISM bands at 2.45 GHz and 900 MHz are important for historical reasons and have become the frequency most used by cordless phones, Bluetooth-enabled devices, baby monitors, and RF remotes. The 2.45 GHz band is also assigned to the microwaves generated by tubes within microwave ovens because this frequency is strongly absorbed in water, making it useful for microwave heating within the oven. The electrical components within the transmitters and receivers at this frequency are highly developed and inexpensive.

The other major commercial ISM application at the present time is RFID (radio frequency identification) readers, although most of these operate at lower frequencies than 2.4 GHz in order to restrict their read ranges. RFID is a technology that incorporates the use of electrostatic or electromagnetic coupling in the RF portion of the electromagnetic spectrum to uniquely identify an object, animal, or person. An early demonstration of reflected-power RFID tags took place at the Los Alamos National Laboratory in 1973. The portable system operated at 915 MHz and used 12-bit tags. This technique is used by the majority of today's UHF-ID and microwave RFID tags.

Unlicensed National Information Infrastructure

In 1997, the FCC developed regulation for additional bands in the 5 GHz range, known as the U-NII.[4] The band is significant in that it is commonly used for local wireless networks, under the IEEE 802.11 specifications. The upper band (5.725-5.825 GHz) overlaps with the ISM band and is used by wireless internet service providers. U-NII devices are unlicensed intentional radiators that use wideband digital modulation techniques to provide high-data-rate mobile and fixed communications used by individuals, businesses, and institutions, particularly for wireless local area networking—including Wi-Fi—and broadband access.

To promote use of U-NII, the FCC removed the indoor-only restriction and increase the permitted power for certain frequencies to accommodate the next generation of Wi-Fi technology. To ensure that all such devices comply with U-NII requirements intended to protect authorized users from harmful interference, the FCC set rules applicable to all digitally modulated devices operating across this 125 MHz of the spectrum. The FCC required that all U-NII device software be secured to prevent modification so that the devices will operate only as authorized, reducing the potential for harmful interference to authorized users. Finally, to protect Terminal Doppler Weather Radar (TDWR) systems and other radar systems operating in nearby frequencies from harmful interference, the FCC technical rules and compliance measurement procedures for U-NII devices were modified.

MILLIMETER WAVES

The mm-band lies in the 30-300 GHz range (with wavelengths from 10-1 mm, respectively).[5] There is significant diversity in the types of equipment and applications using this spectrum, but investments in commercial technology have been slower due to unknowns in operational conditions and unpredictable variations in propagation environments. However, giving the increasing demand for spectrum, swiftly increasing applications and research into the transmission of these high frequencies is imperative. Current applications include the following:

- Radio astronomy and remote sensing including temperature measurements in the upper atmosphere;
- Weapons systems, including short-range fire-control radar in tanks and aircraft, and automated guns on naval ships;
- Security screening commonly used by the Transportation Safety Administration for airport screening; and
- Telecommunication applications for unlicensed short-range data links.[6]

Governments and the ITU are just now generating standards for global spectrum bands are "frequencies that are at least an order of magnitude greater than today's fourth-generation (4G) Long Term Evolution (LTE) and WiMax mobile networks."[7] Similar to the WLAN unlicensed products moving from 1 to 5 GHs frequencies in early generation to 60 GHz today, the cellular industry is moving

[4] United States CFR Title 47, Part 15—Radio Frequency Devices, Subpart E—Unlicensed National Information Devices, Paragraph 15.407—General technical requirements.

[5] Millimeter Wave Transmission Website, European Telecommunications Standards Institute, Quarter 1, 2015, http://www.etsi.org/images/files/ETSITechnologyLeaflets/MillimetreWaveTransmission.pdf.

[6] The upcoming IEEE Wi-Fi standard is expected to run on the 60 GHz band with data transfer rates of up to 7 Gbit/s.

[7] T.S. Rappaport, R.C. Daniels, R.W. Heath, and J.N. Murdock, *Introduction to Millimeter Wave Wireless Communications,* October 6, 2014, http://www.informit.com/articles/article.aspx?p=2249780.

to mm-wave bands that support massive data rates. This immense increase in available spectrum bandwidth could lead to new capabilities. For example, the unlicensed band at 60 GHz contains more bandwidth capacity "than has been used by every satellite, cellular, Wi-Fi, AM radio, FM radio, and television station in the world."[8] Developing technologies to support the use of mm-wave frequencies to augment the currently densely allocated and assigned spectrum bands for wireless communications could provide a massive amount of bandwidth.

Research Challenges in the Use of High-Frequency Waves

Much research is needed to support the use of the mm-wave for telecommunication. Due to the higher carrier frequency, propagation characteristics of promising mm-wave frequencies show path loss is larger in non-line-of-sight conditions compared to UHF and microwave bands. The scattering effects also cause weak signals to become an important source of diversity, and non-line-of-sight paths are weaker, making blockage and coverage holes more pronounced.[9] Directional beamforming will be needed to allow high-quality links both at the base station and at the handset where propagation can be improved.

It is anticipated that the combination of cost-effective complementary metal-oxide semiconductor (CMOS) technology operating efficiently in the mm-wave frequency bands and high-gain steerable antennas at the mobile and base station strengthens the future practicability of mm-wave wireless communications. Rapid advancements and price reductions in integrated mm-wave (>30 GHz) analog circuits, baseband digital memory, and processors have enabled progress as well. Recent work in integrating mm-wave transmitters and receivers with advanced circuitry and new phased array and beamforming techniques also support telecommunication use.

It is expected that the semiconductor industry is poised to produce cost-effective, mass-market products for mm-wave communication. Operation at 60 GHz at reasonable costs will also be enabled through a continuation of advancements in CMOS and silicon-germanium technologies. Packaging the analog components along with the digital hardware necessary to process massive bandwidths has only been possible in the past decade.[10]

Additionally, the increased absorption and scattering loss at higher frequencies that shifts the technology away from long-range communications actually aids close-range communications. Thus, it permits aggressive frequency reuse while simultaneously operating networks that do not hinder each other.[11] Highly directional antennas needed for path loss mitigation actually work to promote security as long as network protocols and front-end hardware enabled antenna arrays are flexibly steered. Many communication networks are now residing at the 60 GHz range for distances less than 100 m. In addition, the 20 dB/km oxygen attenuation at 60 GHz disappears at other mm-wave bands, such as 28, 38, or 72 GHz. This development provides alternatives to today's cellular bands for longer-range outdoor mobile communications. Recent research in use of smart antennas, beamforming, and spatial processing has found that urban environments provide rich multipath, especially reflected and scattered energy at or above 28 GHz. It is anticipated that this rich multipath could be exploited to increase received signal power in non-line of sight propagation environments.[12]

> Mm-wave spectrum would allow service providers to offer higher channel bandwidths well beyond the 20 MHz typically available to 4G LTE users. By increasing the RF channel bandwidth for mobile radio channels, the data capacity is greatly increased, while the latency for digital

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[8] T.S. Rappaport, R.C. Daniels, R.W. Heath, and J.N. Murdock, *Introduction to Millimeter Wave Wireless Communications,* October 6, 2014, http://www.informit.com/articles/article.aspx?p=2249780.

[9] Ibid.

[10] Ibid.

[11] Ibid.

[12] Ibid.

> traffic is greatly decreased, thus supporting much better Internet-based access and applications that require minimal latency. Given this significant jump in bandwidth and new capabilities offered by mm-wave, the base station-to-device links, as well as backhaul links between base stations, will be able to handle much greater capacity than today's cellular networks in highly populated areas.[13]

It is worth mentioning that work is already under way to understand what might be done in the Terahertz bands. This is a wide open research area at this point, and the Boulder telecommunications laboratories could be engaged to think about this very unique spectrum and how it might be measured and used in the future.

[13] T.S. Rappaport, R.C. Daniels, R.W. Heath, and J.N. Murdock, *Introduction to Millimeter Wave Wireless Communications,* October 6, 2014, http://www.informit.com/articles/article.aspx?p=2249780.

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Acronyms

3GPP	3rd Generation Partnership Project
5G	fifth generation
ACT	ancillary terrestrial component
AWS	advanced wireless services
BAS	broadcast auxiliary service
CAC	Center for Advanced Communications
CRADA	cooperative research and development agreement
CRPL	Central Radio Propagation Laboratory
CTL	Communications Technology Laboratory
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DSRC	Dedicated Short Range Communication
ETRI	Electronics and Telecommunications Research Institute
FCC	Federal Communications Commission
FirstNet	First Responder Network Authority
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
INS2I	Institute for Information Sciences and Technologies
IoT	Internet of Things
ISO	International Standards Organization
ITS	Institute for Telecommunication Sciences
ITU	International Telecommunication Union
LAN	local area network
LTE	long-term evolution
MAN	metropolitan area network
MIMO	multiple input-multiple output
mm-wave	millimeter wave

NASCTN	National Advanced Spectrum and Communications Test Network
NICT	National Institute of Information and Communications Technology
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NSA	National Security Agency
NTIA	National Telecommunications and Information Administration
OSM	Office of Spectrum Management
PCAST	President's Council of Advisors on Science and Technology
PML	Physical Measurement Laboratory
PMW	propagation modeling website
PNT	positioning, navigation, and timing
PSCR	Public Safety Communications Research Program
QAM	quadrature amplitude modulation
R&D	research and development
RF	radio frequency
SDARS	Satellite Digital Audio Radio Service
SDO	Standards Development Organizations
U-NII	unlicensed national information infrastructure
USGS	U.S. Geological Survey
VCAT	Visiting Committee on Advanced Technology
Wi-Fi	Wireless Fidelity
WLAN	wireless local area network