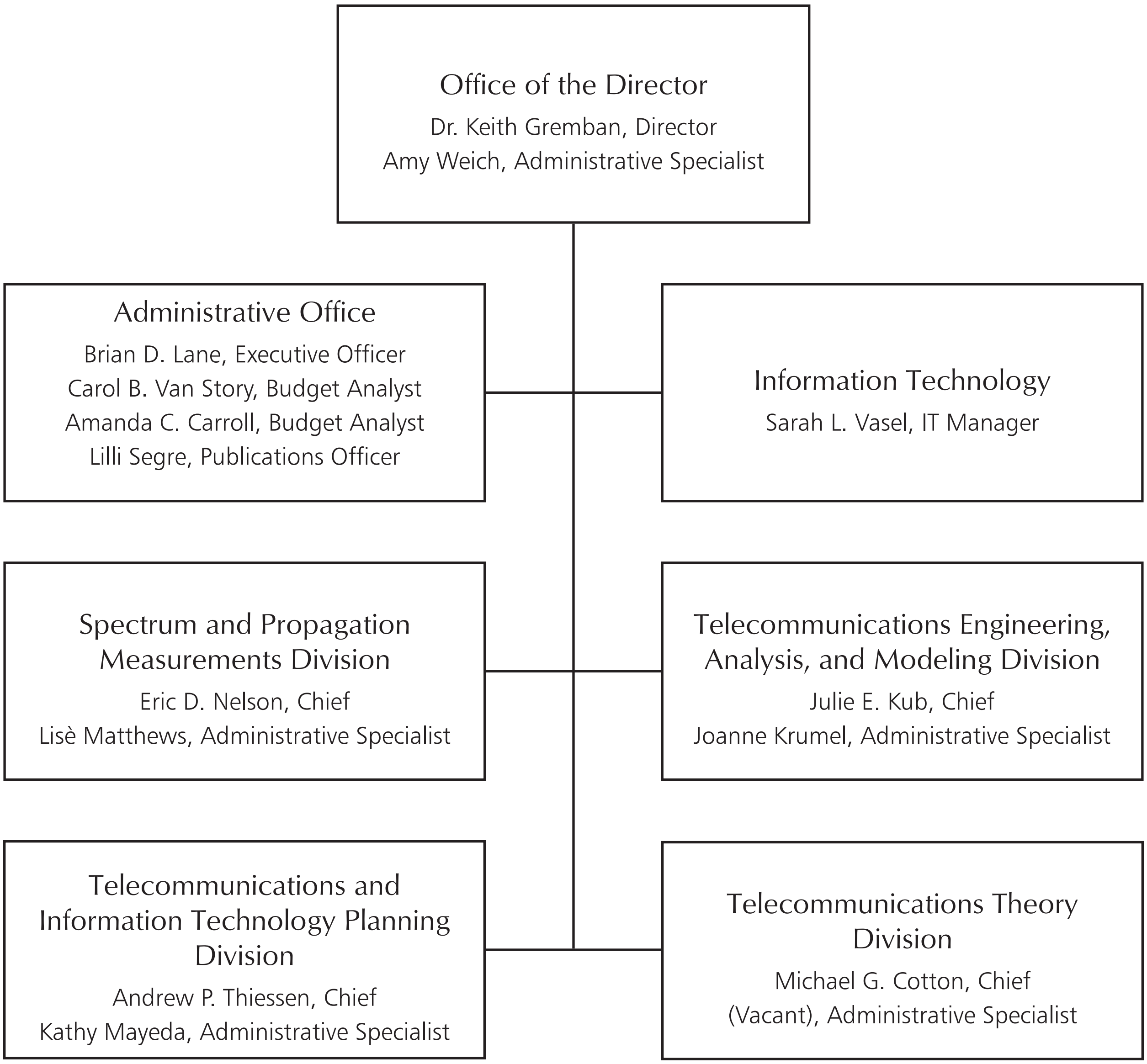
# Technical Progress Report
# Institute for Telecommunication Sciences
# Boulder, Colorado


U.S. DEPARTMENT OF COMMERCE
NTIA
NATIONAL TELECOMMUNICATIONS & INFORMATION ADMINISTRATION

# ITS Organization Chart

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# Institute for Telecommunication Sciences
# FY 2015 Technical Progress Report

Lawrence E. Strickling
Assistant Secretary for Communications and Information
National Telecommunications and Information Administration
United States Department of Commerce

May 2016

*“The Nation benefits from Federal government funding for basic and applied research in areas in which the private sector does not have the economic incentive to invest and a public benefit exists.”*[1]


The Institute for Telecommunication Sciences is an office of the National Telecommunications and Information Administration, an agency of the United States Department of Commerce.

The mission of the Department of Commerce is to create the conditions for economic growth and opportunity.

The National Telecommunications and Information Administration is principally responsible for advising the President on telecommunications and information policy issues.

The Institute for Telecommunication Sciences performs cutting-edge telecommunications research and engineering with both federal government and private sector partners.

* * *

*Certain commercial equipment, components, and software are identified in this report to adequately describe the design and conduct of the research and experiments at ITS. In no case does such identification imply recommendation or endorsement by the National Telecommunications and Information Administration, nor does it imply that the equipment, components, or software identified are necessarily the best available for the particular application or use.*



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Cover art by A.D. Romero.

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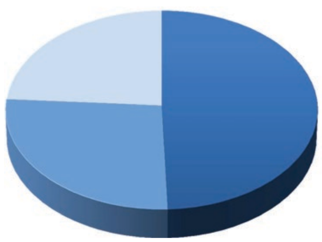
1. Executive Office of the President of the United States, Memorandum for the Heads of Executive Departments and Agencies, Science and Technology Priorities for the FY 2015 Budget, July 26, 2013. Accessed http://www.whitehouse.gov/sites/default/files/omb/memoranda/2013/m-13-16.pdf December 8, 2014.

# Contents

# At a Glance ...

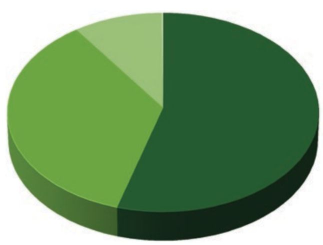
> *"ITS has extensive capabilities in public safety, radio-spectrum sensing, propagation modeling, and interference analysis. It is recognized by other government agencies (and, to some extent, private industry) for its objectivity, expertise, and physical resources; it is the historically trusted expert in certain areas of spectrum and communication engineering; and it is an essential provider of these services to government agencies."*[1]

## Research Areas Funded in FY 2015



- Enhancing Spectrum Utilization
- Public Safety Communications Interoperability
- Spectrum Sharing

## Research Funding Sources in FY 2015



- Interagency Agreements
- Direct Appropriation
- Fees
- CRADAs

## Tech Transfer in FY 2015

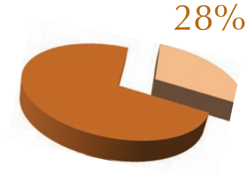
ITS participated in 56 CRADAs

ITS publications were downloaded 9,048 times

507 people downloaded the VQM software

Other software/data were downloaded 1,291 times

212 people downloaded 2,455 video clips from CDVL



28% of CRADAs were with small businesses

1. National Academies of Sciences, Engineering, and Medicine. 2015. *Telecommunications Research and Engineering at the Institute for Telecommunication Sciences: Meeting the Nation's Telecommunications Needs*. Washington, DC: The National Academies Press. Accessed http://www.nap.edu/21867 December 2, 2015.

# A Message from the ITS Director

*Dr. Keith Gremban, Director, Institute for Telecommunication Sciences.*

The Institute for Telecommunication Sciences (ITS) is a unique national resource that is well positioned to provide answers to the challenges posed by exploding demand for radio spectrum. The mission of ITS is to perform the research and engineering required to meet the telecommunications challenges of the future, and in so doing to inform the policies of National Telecommunications and Information Administration (NTIA) and the Department of Commerce (DoC).

2015 was filled with news stories about an impending spectrum shortage that would hinder the economic growth of the U.S.[1] But ITS and its predecessors have been responding to this alarm call for over 100 years, ushering in generation after generation of new technology aimed at more effectively exploiting available spectrum to fuel continued economic growth. Fiscal Year (FY) 2015 was no different—ITS was actively involved in addressing the spectrum shortage through research and analysis to enable spectrum sharing and improve the efficiency of spectrum utilization. ITS was recognized by the DoC for outstanding research, and also regrouped to prepare for the challenges of the next decade.

This 2015 Technical Progress Report documents our latest results, and describes how these results have influenced international standards, provided technology and tools to commercial and federal users, made fundamental contributions to spectrum management, supported the core missions of the NTIA and the DoC, and fueled economic growth in the telecommunications sector.

One way to meet the demand for spectrum is to enable many users to operate in the same spectral bands—that is, to enable spectrum sharing. For many years, ITS has been in the forefront of spectrum sharing research, in areas such as electromagnetic compatibility analysis (which defines the technical parameters that allow systems to share spectrum without interference) and propagation modeling (which is used to predict how far radio waves from a transmitter can travel and hence to predict interference among systems). ITS research is openly shared so that it can be leveraged to advance the state of the art. In FY 2015, ITS actively brought stakeholder communities together for the 14th International Symposium on Advanced Radio Technology (ISART 2015), where spectrum engineers and policy makers from industry, academia, and government could together consider next steps toward effective spectrum sharing. ITS research directly contributed to increased sharing between commercial and federal users, which will have substantial economic impact on the U.S. economy as commercial companies exploit the opportunity.

Spectrum scarcity also drives greater emphasis on more efficient spectrum utilization. The first step in improving efficiency is to develop baseline information on spectrum utilization. Under the umbrella of the Center for Advanced Communications, a collaborative partnership between NTIA and the National Institute of Standards and Technology, ITS researchers began developing the infrastructure and technology for spectrum monitoring. A spectrum monitoring pilot program began gathering spectrum occupancy information at several locations within the U.S. and defining data types and interfaces, modeling best practices that other organizations can follow to develop spectrum monitoring systems and freely share data.

Providing improved service despite bandwidth limitations is another way to increase efficiency of spectrum utilization. ITS researchers have a long history of evaluating the user experience of digital audio and video, and ITS results have directly influenced industry standards. For many years, user experience evaluation has relied on subjective tests with multiple subjects, which is time-consuming and expensive. ITS

1. For example, http://www.forbes.com/sites/realspin/2015/06/30/the-spectrum-shortage-is-coming/#4dc08d973450

researchers recently developed algorithms that automate the testing process, while achieving quality scores that closely align with those from subjective testing.

ITS also continues to support more effective public safety communications. In 2015, ITS researchers tested software and hardware proposed for public safety communications use, and evaluated system performance against conditions and scenarios representative of public safety operations. ITS researchers investigated approaches for extending public safety communications coverage to rural areas, developed technology for measuring in-building propagation loss, investigated different approaches for improving indoor coverage, and evaluated multiple audio digitization and compression algorithms for performance in scenarios uniquely important to the public safety community. ITS staff also participated in the development of international public safety communications standards.

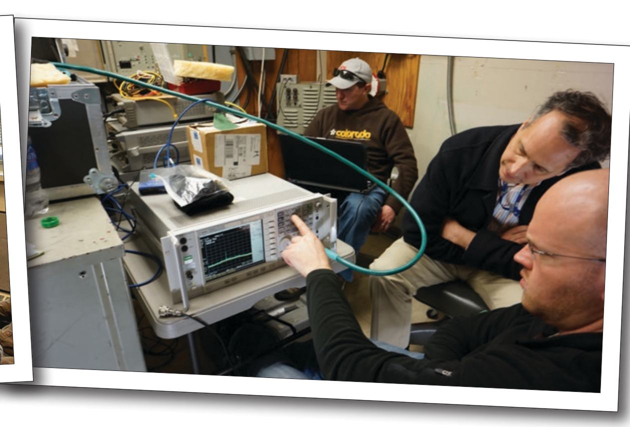
The world-class research ITS performed in FY 2015 was formally recognized by the DoC through Gold and Silver medals, the highest and second highest honors granted by the Secretary of Commerce for distinguished and exceptional performance. Six ITS researchers were presented with Gold Medals, and four were presented with Silver Medals.

In the spring of 2015, under the direction of the U.S. Congress, the National Academy of Sciences (NAS) undertook a study 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." The NAS found that ITS could provide an essential service to the nation, but has been limited by several factors, including lack of funding, staff, and strategic direction. The NAS recommended the development of a strategic plan, and identified three principal technical challenges important to the future of telecommunications: (1) spectrum use, management, and enforcement, (2) system-level optimization and related issues, and (3) public safety. All three of these areas are represented in the 2015 research portfolio reported in the following pages.

In May of 2015, I had the honor and privilege of becoming the 11th Director of the Institute for Telecommunication Sciences since its founding in 1913 as the Radio Section of the National Bureau of Standards. It is a pleasure to work with the ITS staff, and I continue to be impressed by their technical expertise and dedication to the mission.

One of my first tasks was to work with the senior staff to identify strategic thrusts for ITS and realign ITS to better meet the telecommunications challenges of the future. We redesigned our internal processes for defining research projects so that all members of the technical staff can participate to ensure that research projects directly address strategic challenges. We also put an increased emphasis on staff development and collaboration. Our FY 2016 research projects are off and running, and I look forward to introducing the FY 2016 Technical Progress Report next year to document more outstanding results.

Keith D. Gremban



# The Institute for Telecommunication Sciences

The Institute for Telecommunication Sciences (ITS) is the research and engineering laboratory of the National Telecommunications and Information Administration (NTIA), an agency of the Department of Commerce (DoC). ITS serves as a principal federal resource for the conduct of basic research on the nature of radio waves, supporting the Department's strategic objective to foster a more innovative U.S. economy—one that is better at inventing, improving, and commercializing products. ITS is recognized as one of the world's leading telecommunication research laboratories and our research results are widely disseminated to advance innovation that improves telecommunications technologies and network performance.

*ITS performs cutting-edge telecommunications research and engineering with both federal government and private sector partners.*

- Basic research and engineering efforts enhance scientific knowledge and provide new, expanded scientific understanding of cutting-edge telecommunications technologies and systems.
- Applied research, testing, and evaluation help drive innovation and development of advanced technologies and services, including improved public safety communications, and provide technical input to NTIA policy development and spectrum management, promoting a more agile and data-driven regulatory environment.
- ITS expertise is also applied to resolve specific telecommunications problems of other federal agencies and state and local governments, and to support optimization of federal agencies' use of spectrum for communications, radars, and satellites in an increasingly crowded and shared spectrum.
- Through cooperative research and development agreements (CRADA) with industry and academia, ITS federal research resources are leveraged to promote private sector innovation, entrepreneurship, and commercialization that leads to economic growth and opportunity.
- Leadership and technical contributions to national and international telecommunications fora help influence development of standards and policies to support U.S. communications and information technology competitiveness and position U.S. industry for international leadership in telecommunications technology.

ITS is located on the DoC Boulder Laboratories campus in Colorado, sharing advanced laboratory and test facilities with the National Oceanic and Atmospheric Administration (NOAA) and the National Institute of Standards and Technology (NIST), with whose Communications Technology Laboratory (CTL) ITS performs joint multi-disciplinary research through the Center for Advanced Communications (CAC). Chartered in 2013 to leverage the critical mass of DoC research and engineering capabilities concentrated in the Boulder campus, CAC provides a single focal point to engage and collaborate with industry, academic, and government partners to effectively and efficiently address current and future advanced communications challenges.

# Fiscal Year 2015 Research Areas

## Spectrum Sharing

All wireless devices make use of blocks of radio frequencies within the electromagnetic spectrum. For most of the industrial age, the number of wireless devices was small with respect to the amount of spectrum available. However, in recent years with the growth of mobile devices and consumer wireless devices, spectrum has become a scarce resource. Sufficient spectrum no longer exists to reserve blocks of spectrum for exclusive use by particular classes of devices. To accommodate the incredible growth rate of wireless systems, the alternative to exclusive use of spectrum is spectrum sharing, in which collections of device coexist in the same spectral bands. The President's Council of Advisors on Science and Technology (PCAST) makes an analogy between spectrum sharing and multi-lane highways—instead of dedicated lanes for particular users, all highway users share lanes.

*Wayde Allen, Linh Vu, Teresa Rusyn, and John Ewan take measurements of the dish antenna that will be used to collect GPS signal data for validating future propagation models. Photo by Tim Riley.*

The new reality is that all spectrum users will eventually be pressed to operate in shared bands. Effective spectrum sharing requires sophisticated and reliable technologies that can effectively thread the three parameters of time, frequency, and location to deliver acceptable service in shared bands without interfering with other users of the same or adjacent bands. Research to advance spectrum sharing includes radio frequency (RF) propagation modeling, needed to determine the ranges and conditions under which different signals can be transmitted and received; electromagnetic compatibility analyses to determine the conditions under which different wireless devices can co-exist; and interference analysis and mitigation studies, needed to quantitatively define interference criteria and approaches to mitigate interference. This research enables development of new spectrum sharing techniques, improved methods for dynamic frequency management, and advanced systems that can gracefully share spectrum.

- ITS has a hundred-year history of developing and validating, through scientific theory and measurements, reliable radio propagation models for various radio bands and environments and promulgating them to industry, other agencies, and national and international standard bodies.
- Electromagnetic compatibility studies help define technical parameters such as transmitter emission limits, frequency offsets, or separation distances for proposed rulemakings in support of new spectrum uses or sharing requirements. They are also used to develop receiver and sensor performance requirements for improved efficiency.
- Interference analysis and mitigation studies provide the data needed to continuously improve the technologies that allow users to gracefully share the same radio space or operate in adjacent bands.

## Public Safety Communications Interoperability

Wireless communications has revolutionized the private sector. In only a short span of years, cellular systems have advanced from analog voice through digital voice and data to broadband services capable of streaming video. Public safety organizations such as police, fire, Coast Guard and others could dramatically improve their efficiency and effectiveness with adoption of broadband wireless communications.

In February of 2012, Congress provided funding for a nationwide interoperable broadband network for public safety organizations. However, the public safety sector has unique requirements for communications that are not typical of commercial cellular systems. For example, first responder communications must still function in emergency situations when cellular systems are swamped and be usable in noisy conditions. Public safety communications also has unique requirements for security and privacy.

The Public Safety Communications Research (PSCR) program, a joint effort between ITS and NIST/CTL, addresses four key areas of public safety communications interoperability: (1) development of qualitative and quantitative public safety communication and information-sharing requirements that are accepted nationally by the public safety community and industry; (2) identification and development of interface standards that satisfy defined user requirements through leadership and direct technical contribution to national and international standards bodies focused on public safety communications; (3) research, development, testing, and evaluation of concepts, products, and services for long-term interoperability solutions as well as interim improvements; and (4) research and development to accommodate technical gaps that emerge during the entire process.

PSCR operates in close and constant coordination with public safety practitioners to develop standards, technologies, and test methods to ensure interoperability of land mobile radio and broadband systems used by public safety and justice communities, public service, and land transportation agencies and to develop information technology standards that public safety can adopt to ensure inter-connectivity and interoperability for information sharing.

PSCR hosts and manages the Public Safety Broadband Demonstration Network, a live test bed where public safety practitioners and vendors can exercise Long Term Evolution (LTE) systems under development for public safety use in a multi-vendor environment. This network allows research into systems engineering, planning, and testing of interoperable communications systems (e.g., voice, video, and data) to foster nationwide first-responder communications inter-connectivity and interoperability at federal, state, local, and tribal levels.

PSCR also performs research directed at maximizing the usability of public safety communications. PSCR researchers perform rigorous evaluation of voice and video technologies under simulated operational conditions to ensure that public safety personnel can effectively utilize advanced communications technology in anticipated real-world environments.

## Enhancing Spectrum Utilization

Spectrum is becoming ever more congested, and the situation is projected to get worse as the number of devices grows. Spectrum is a finite resource, while the demands on spectrum are growing. Some statistics from Cisco[1] illustrate the problem:

- Global mobile data traffic grew 69 percent in 2014
- Last year's mobile data traffic was nearly 20 times the size of the entire global Internet in 2000
- Almost half a billion (497 million) mobile devices and connections were added in 2014
- Global mobile data traffic will increase nearly tenfold between 2014 and 2019
- By the end of 2014, the number of mobile-connected devices will exceed the number of people on earth, and by 2019 there will be nearly 1.5 mobile devices per capita

One necessary approach to mitigating spectrum congestion is to make more efficient use of spectrum. For example, new techniques in video compression can transmit a movie while using ½ the bandwidth of standard compression techniques.[2] ITS performs research directed at improving spectral efficiency in wireless communications and laying the groundwork for next generation technology. Specific research includes continuously improving the accuracy and granularity of spectrum measurements; understanding how to optimize the user experience while minimizing bandwidth; and promoting standards to support competitive commercialization of advanced technologies.

- ITS designs, develops, and operates state-of-the-art systems to take accurate and trusted measurements of spectrum occupancy and transmitter emission characteristics. This data helps identify better ways to fully and effectively utilize the spectrum as well as inform spectrum management practices and policies.
- As spectrum becomes more crowded, industry continuously seeks to increase both signal compression and band utilization to provide more services within the available bandwidth. The key for industry is to minimize band utilization while providing users the same quality of experience. ITS research provides quantitative data to inform the trade between compression and user satisfaction.
- ITS research contributes to the development of new technologies and best practices for continuous spectrum monitoring and spectrum management, and for exploiting underutilized frequencies, such as the millimeter waveband, for cellular communication.

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1. Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2014–2019 (February 2015). Accessed http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white_paper_c11-520862.html December 4, 2015.

2. Andrew A. Catellier and Margaret H. Pinson, "Characterization of the HEVC Coding Efficiency Advance Using 20 Scenes, ITU-T Rec. P.913 Compliant Subjective Methods, VQM, and PSNR ," *Proceedings of the IEEE International Symposium on Multimedia*, Miami, FL, December 14-16, 2015. Available http://www.its.bldrdoc.gov/publications/2818.aspx.

# Awards

Ten ITS researchers received Department of Commerce Gold or Silver Honor Awards in September 2015. The Gold and Silver Medals are the highest and second highest honor granted by the Secretary of Commerce for distinguished and exceptional performance.

*Bruce H. Andrews, Deputy Secretary of Commerce (far left), and Larry Strickling, Assistant Secretary for Communications and Information (far right), present the Gold Medal Award to, from left, Geoff Sanders, Robert Sole, Frank Sanders, John Carroll, and Bob Achatz.*

## Gold Medal

Frank Sanders, Robert Achatz, John Carroll, Michael Cotton, Roger Dalke, and Geoffrey Sanders of ITS, along with Robert Sole of NTIA's Office of Spectrum Management (OSM), received a Gold Medal Award for rapidly developing a creative, innovative new method to perform electromagnetic compatibility (EMC) studies to support, through critical technical analysis, DoC efforts to increase federal/commercial sharing to make additional spectrum available for wireless commercial broadband services to promote innovation and economic development. A study perfumed using this new method, reported on page 18, informed new Federal Communications Commission (FCC) rules for spectrum sharing in the 3.5 GHz band. Rapid publication of the method and results enables reuse for timely EMC studies in other bands being considered for sharing. The results and the new methodology were published in a highly impactful series of publicly available NTIA Reports.[1] The group's work has also been used by other federal agencies that will have to share the band and by Industry that will build new systems (e.g. LTE) to operate in the band. The availability of this new method will significantly advance the development of new spectrum sharing approaches to facilitate continued economic growth and innovation by making more spectrum available for new commercial uses while allowing existing, incumbent federal spectrum operations to continue.

## Silver Medal

Bob Johnk, Jaydee Griffith and Mitchell Powell received a Silver Medal Award for developing and using an innovative approach to measure building-penetration characteristics of radio signals, for inventing

1. Frank H. Sanders, John E. Carroll, Geoffrey Sanders, Robert L. Sole, "Effects of Radar Interference on LTE Base Station Receiver Performance," NTIA Technical Report TR-14-499, December 2013

   Michael G. Cotton, Roger A. Dalke, "Spectrum Occupancy Measurements of the 3550–3650 Megahertz Maritime Radar Band Near San Diego, California," NTIA Technical Report TR-14-500, January 2014

   Geoffrey Sanders, John E. Carroll, Frank H. Sanders, Robert L. Sole, "Effects of Radar Interference on LTE (FDD) eNodeB and UE Receiver Performance in the 3.5 GHz Band," NTIA Technical Report TR-14-506, July 2014

   Frank H. Sanders, John E. Carroll, Geoffrey Sanders, Robert L. Sole, Robert J. Achatz, Lawrence S. Cohen, "EMC Measurements for Spectrum Sharing Between LTE Signals and Radar Receivers," NTIA Technical Report TR-14-507, July 2014

   Frank H. Sanders, John E. Carroll, Geoffrey A. Sanders, Lawrence S. Cohen, "Measurements of Selected Naval Radar Emissions for Electromagnetic Compatibility Analyses," NTIA Technical Report TR-15-510, October 2014

   Geoffrey A. Sanders, John E. Carroll, Frank H. Sanders, Robert L. Sole, Robert J. Achatz, "Emission Spectrum Measurements of a 3.5 GHz LTE Hotspot," NTIA Technical Report TR-15-512, February 2015 and implementing a compact, radio signal measurement system, and for developing an efficient and effective methodology for determining optimal configurations and designs for in-building communication systems for use by first responders. Building walls reduce radio signal power in complex ways, creating difficult and sometimes life-threatening communication challenges for first responders. The team investigated different building types and different ways to enhance coverage by LTE systems. Dr. Johnk independently designed and, with the help of the team, performed a comprehensive series of measurements using an innovative system of his own invention to measure signal strengths and equipment performance. Because the system was mounted in a backpack, measurements could be conducted in places and circumstances that closely resembled those of first responders moving through various building types during incident responses. The work is described on page 38. Measurement results led to concrete recommendations for improving in-building performance of LTE communications equipment. Many of these recommendations are already being implemented, using currently available equipment, to enhance the safety and effectiveness of America's first responders. The results also identified the most critical needs for additional research. A summary of results and recommendations from this work was presented to wide acclaim from public safety communications professionals at the 2014 International Wireless Communications Expo (ICWE) and at the 2014 Public Safety Broadband Stakeholder Conference. A full description was published in NTIA Technical Report TR-15-518.[2]

*Silver Medal Award recipients Jaydee Griffith (left) and Bob Johnk.*

## Silver Medal

Edward Drocella, James Richards, and Frederick Najmy of OSM and Paul McKenna of ITS received a Silver Medal Award for outstanding leadership in developing and implementing innovative techniques to enable new spectrum sharing opportunities between federal and commercial users. To fuel continued economic growth and innovation by making additional spectrum available for commercial broadband, NTIA recommended the reallocation of the 3550–3650 MHz band using geographic exclusion zones to protect federal systems. As originally calculated, these exclusion zones were so large as to limit the deployment of broadband systems in many top markets. The group led a joint NTIA, Department of Defense (DoD), and FCC working group that spearheaded innovative collaboration methods to develop a specialized analysis model. The unique analysis model developed by this team and reported on page 20 applied cutting-edge analysis techniques and geographic information system (GIS) data to more realistically assess potential interference to federal systems in an effort to reduce the exclusion zones. The improved technical analysis reduced the exclusion zones previously deemed necessary to protect federal operations by an average of 77%, increasing the overall market access for commercial broadband systems by an average of 34% and thereby maximizing auction revenue resulting from the sale of license for the use of this band. The results of this effort formed a basis for the FCC rulemaking establishing a flexible regulatory framework necessary to auction the spectrum for commercial broadband systems. This effort directly supported the President's goal of identifying 500 megahertz to be made available for commercial wireless broadband services. The assumptions, methods, analyses, and system characteristics used to generate the revised exclusion zones were published in NTIA Technical Report TR-15-517.[3]

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2 Robert T. Johnk, Mitchell Powell, Jaydee L. Griffith, Mark A. McFarland, Kenneth R. Baker, Prachee Daithanker, Saman Samdian, Lavanya Gopal, Sai Gavva, "In-Building LTE Testing at the University of Colorado," NTIA Technical Report TR-15-518, July 2015

3. Edward F. Drocella Jr., James C. Richards, Robert L. Sole, Fred Najmy, April Lundy, and Paul M. McKenna, "3.5 GHz Exclusion Zone Analyses and Methodology," NTIA Technical Report TR-15-517, June 2015.

*"Federal government funding for research and development (R&D) is essential to address societal needs in areas in which the private sector does not have sufficient economic incentive to make the required investments. Key among these is basic research—the fundamental, curiosity-driven inquiry that is a hallmark of the American research enterprise and a powerful driver of new technology. Simply supporting research is not sufficient, however, Federal agencies should ensure that the results of that research are made available to other scientists, to the public, and to innovators who can translate them into the businesses and products that will improve all of our lives."*[1]

# Technology Transfer

Technology transfer to the private sector aims to rapidly integrate federal research outcomes into the mainstream of the U.S. economy to fuel new economic growth and enhance U.S. competitiveness in the global marketplace. From the Stevenson-Wydler Technology Innovation Act of 1980 to the July 2015 Office of Science and Technology Policy Memorandum on Science and Technology Priorities for the 2017 Budget, there has been an increasing emphasis on "stimulating improved utilization of federally funded technology developments, including inventions, software, and training technologies, by State and local governments and the private sector.[2]" Innovation fostered through technology transfer multiplies the economic and societal impact of federal research and development investments.

Interagency cost-reimbursement agreements, authorized under the Economy Act of 1932, provide a parallel path to leverage research investments within the Government by allowing federal agencies to benefit from the unique resources of other federal agencies. Technology transfer between federal agencies provides an economical and effective means of leveraging federal research investments, allowing other agencies to reap the benefits of the expertise, equipment, and facilities of which ITS is the steward. Federal partners reimburse ITS for the cost of research conducted under an interagency agreement, but—unless restricted or classified—the results are released into the public domain for the benefit of other researchers, both public and private. Interagency agreements thus extend the impact of federal funding by eliminating duplicate research efforts in federal laboratories and at the same time making more research available for technology transfer. ITS world-class facilities and capabilities shared through CRADAs and interagency agreements are described in the section on ITS Resources on page 65.

ITS is a member of the Federal Laboratory Consortium for Technology Transfer (FLC), a nationwide network of about 300 federal laboratories organized in 1974 and formally chartered by the Federal Technology Transfer Act of 1986 (FTTA). The FLC provides an interagency forum to develop strategies and opportunities for linking laboratory mission technologies and expertise with the marketplace.

The principal means by which ITS transfers the fruits of federally funded research efforts to the private sector and other government agencies are:

- Cooperative research and development agreements
- Interagency research and development agreements
- Technical papers, royalty-free data and software releases, and collaborative standards contributions
- Conferences, workshops, and symposia
- Senior Technical Fellows and technical lectures

1. Executive Office of the President, Office of Science and Technology Policy, Memorandum on Science and Technology Priorities for the 2017 Budget, July 9, 2015. Accessed https://www.whitehouse.gov/sites/default/files/omb/memoranda/2015/m-15-16.pdf November 24, 2015.
2. 15 U.S.C. § 3702 (3).

*For more information contact: Brian D. Lane, (303) 497-3484, blane@its.bldrdoc.gov*

# Cooperative Research and Development Agreements (CRADA)

CRADAs provide an extremely flexible vehicle to facilitate the transfer of commercially useful technologies from federal laboratories to the non-federal sector. They protect proprietary information, grant patent rights, and provide for user licenses to private entities. They also provide the legal basis for shared use of Government facilities and resources with the private sector.

In FY 2015, ITS participated—as it has for a number of years—in CRADAs with private-sector organizations to design, develop, test, and evaluate advanced telecommunication concepts. CRADAs provide insights into industry's needs for productivity growth and competitiveness that enable ITS to adjust the focus and direction of its programs for effectiveness and value. The private industry partner benefits by gaining access to the results of research in commercially important areas that it would not otherwise be able to undertake.

Major contributions to rapid introduction of new socially constructive communications technologies have been achieved through CRADAs in which ITS was a partner. Recent CRADAs have allowed ITS to contribute to the development of new products and services in the areas of high resolution laser radar (LADAR), autonomous networks for unmanned aerial vehicles (UAVs), and broadband air-interface and core network capabilities for LTE mobile communications.

## Public Safety 700 MHz Broadband Demonstration Agreements

Under the joint ITS/CTL PSCR program, ITS maintains a laboratory for research and testing of public safety communications systems. CRADAs offer private sector organizations the opportunity to use this state-of-the-art government laboratory to complement their own research and development efforts. In fact, the vast majority of CRADAs ITS has entered into in the past four years are the Public Safety 700 MHz Broadband Demonstration Agreements. These agreements allow vendors, including equipment manufacturers and wireless carriers, who intend to supply 700 MHz LTE equipment and service to public safety organizations to operate various elements of an LTE network in the PSCR test bed and over-the-air (OTA) network (both hosted and managed by ITS) to test interoperability of public safety communications equipment under simulated field conditions, with the participation of public safety practitioners.

At the close of FY 2015, 49 CRADAs were in place under this program. The CRADAs protect the intellectual property of vendors and manufacturers, encouraging participation in testing that simulates real multi-vendor environments in the field. This is the first government or independent facility in the U.S. capable of testing or demonstrating public-safety-specific LTE implementation requirements.

## CRADAs for the Use of Table Mountain

Established in 1954, the Table Mountain Field Site (TMFS) and Radio Quiet Zone is a unique research facility that ITS manages (see page 73 for a full description). Table Mountain, located north of Boulder, Colorado, is designated as an area where the magnitude of strong, external RF signals is restricted by both state law and federal regulation. All RF emissions on or near Table Mountain are coordinated through the Regional Frequency Coordination Office in order to minimize interference to sensitive research projects. The site provides a unique opportunity for radio research and experimentation in a controlled outdoor environment that is relatively free from interference. Partnerships and cooperative research activities with other entities are encouraged at the site. In addition to ongoing ITS basic research, other Department of Commerce laboratories collocated on the Boulder Labs campus maintain ongoing research efforts on the site. Other research is performed at Table Mountain by federal and non-federal entities under specific project agreements.

CRADAs allow private industry to use this facility to test and optimize new and improved products prior to bringing them to market. Universities can also enter into CRADAs to conduct experiments there. Access to Table Mountain particularly benefits small businesses, who would otherwise be unable to perform research that may be crucial to bringing a product to market. Interagency agreements allow agencies other than Commerce to also take advantage of this unique federal resource for testing and research that requires the unique features of the site, which are fully described in the *ITS Resources* section on page 73. In FY 2015, ITS participated in five CRADAs for research conducted at the Table Mountain Field site, three of which were with small businesses.

## Ad Hoc Communication Networks

*The Tempest UAV was developed to fly into severe storms to study tornadogenesis. Photo courtesy RECUV.*

The University of Colorado Research and Engineering Center for Unmanned Vehicles (RECUV) program develops unmanned aircraft systems for atmospheric science applications, and conducts flight experiments at Table Mountain to validate airframes and avionics systems. The University has taken advantage of the TMFS for many years, and is currently experimenting with communication networks between low-cost small UAVs similar to model airplanes and ground-based radios. The experiments center on IEEE 802.11 based ad hoc (mesh) wireless networks developed at the University of Colorado. The networking is used to coordinate UAV activities with the objective of developing autonomous "flocking" behaviors to enable the "swarm" of UAVs to collectively and autonomously complete sensing and communication tasks. Table Mountain provides a unique combination of a large flat area to set up wireless network experiments, simplified flight operations, a controlled radio environment, and proximity to the University of Colorado.

## Adaptive Tactical Laser System Testing

Nutronics, Inc. develops adaptive optical (AO) system solutions for laser propagation through turbulence. The TMFS is an ideal test location for laser applications because of its very flat surface and the ability to safely test and evaluate performance over an extended area that encompasses a broad range of turbulence conditions. Under a CRADA in FY 2015, Nutronics performed turbulence strength measurements on two different advanced adaptive optical system technologies (ATLAS – Advanced Tactical Laser System, and a phased array system) over a horizontal, near ground, turbulent path. The testing allowed the company to verify and validate the modeling and simulation tools used to optimize future designs to continue advancing this technology for a broad range of applications, including free space optical communication and directed energy applications.

## Installed Performance of Antennas Under Test

FIRST RF Corporation is a small business that designs and manufactures radio antennas and systems. This CRADA allowed FIRST RF to use the TMFS as a field location to fully test the functionality of new antenna designs during product development. Antennas under test may be used in communications, electronic warfare, direction finding/geolocation, or radar systems for body-borne, ground vehicular, fixed-site, airborne, and space platforms. Using the large turntable at the facility, in FY 2015 First RF was able to test several antennas on a full sized mockup of the final mounting platform for each. Antenna patterns were taken for over a dozen antennas operating at frequencies ranging from 3 MHz to 8 GHz to assess coverage around the mounting platform, test installed system performance, or verify direction-finding accuracy.

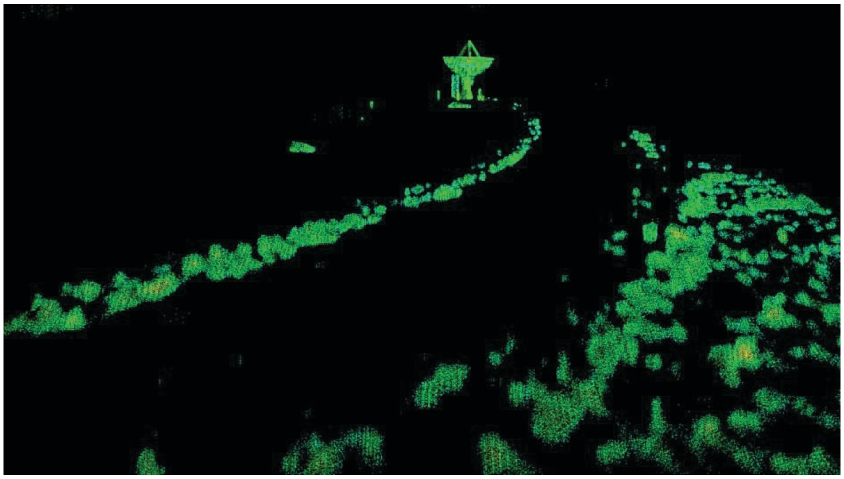
## Laser Radar (LIDAR) Testing

Lockheed Martin Coherent Technologies (LMCT) has had CRADAs with ITS for many years to field-test and characterize components, subsystems, and systems for eyesafe coherent laser radar at Table Mountain. The instruments being tested use light detection and ranging systems (LIDAR), an advanced remote sensing technique that uses pulsed laser light instead of radio waves (radar) to detect particles and varying conditions in the atmosphere. The technology is used, among other things, to improve flight safety by detecting hazardous winds and aircraft wakes. Table Mountain's unique topography provides an excellent setting for collecting test data on systems designed for use in ground or air applications under different atmospheric conditions, while easily varying targets, ranges, and sensor configurations. In FY 2015, LMCT completed a long-term, long-range staring-beam lidar experiment. A WindTracer® Scanning Doppler LIDAR was installed at the site to generate radial wind measurements at very long ranges (23 km) for comparison with ground truth obtained by both in-situ and remote sensors located at NOAA's Boulder Atmospheric Observatory in Erie, Colorado. A single WindTracer showed strong correlations with both ground truth sensors over 100 days, a significant finding. A second WindTracer was installed for about one month at a different location; by combining radial wind measurements from the two, a full wind vector measurement could be derived over the point of interest. The derived measurements showed strong correlation to the ground truth sensor data, a finding that offers promise for a new method to obtain precise remote wind measurements for the offshore wind energy industry.

*WindTracer at the Table Mountain Field Site. Photo courtesy Lockheed Martin Coherent Technologies.*

## Laser Radar (LIDAR) Testing for Degraded Visual Environments

Areté Associates is a small business that develops and produces responsive, innovative, and cost-effective remote sensing solutions. A CRADA with ITS allows the company to safely conduct field experiments at the TMFS in support of their advanced LIDAR system development in atmospheric conditions and at distances relevant to potential applications. Areté is developing a variety of new technologies that combine 2-D and 3-D imaging to provide high resolution three-dimensional imagery that can be transmitted over limited bandwidths for the U.S. Department of Defense. In FY 2015, Areté used the site to test and demonstrate a unique enhancement to expand the flexibility and utility of their LIDAR technologies by enabling the system to focus down on a high-resolution subframe within a wide field of view image while maintaining a reasonable frame update rate. Successful implementation would represent a significant advance in the state-of-the-art in long-range LIDAR systems.



*Wide field of view LIDAR image of one of the Table Mountain dish antennas. Image courtesy Areté Associates.*

Technology Transfer

# Interagency Research and Development Agreements

Interagency agreements, authorized by the Economy Act (31 U.S.C. §1535), allow federal agencies to obtain supplies or services from another federal agency, leveraging one agency's unique expertise or specialized resources to benefit others. ITS staff expertise in propagation modeling, ITS-developed propagation modeling software, staff expertise in accurate spectrum measurement, the specialized radio emission measurement equipment of the ITS Radio Spectrum Measurement System, and the Table Mountain Field Site and Radio Quiet Zone are some of the unique resources that ITS makes available to other agencies.

Research funded under interagency agreements with a dozen different agencies in FY 2015 includes propagation modeling, electromagnetic compatibility analyses, interference analyses of new or proposed systems, development of interference mitigation strategies, and engineering analysis and support for standards development for evolving technologies. Increasingly, such studies support planning for spectrum reallocation or sharing as well as providing data and approaches to improve spectrum utilization.

Several projects funded by the First Responder Network Authority (FirstNet), NIST/CTL, and different offices of the Department of Homeland Security are reported in the section on *Public Safety Communications Interoperability*. ITS tasks under these agreements include engineering analyses, technical feasibility studies of emerging technologies, development and validation of interoperability standards, and laboratory and field measurements.

ITS provided similar services to two Operating Administrations of the Department of Transportation: to the Federal Railroad Administration Office of Research and Development to improve railroad telecommunications efficacy, and to the Federal Highway Administration to determine the potential impact of sharing in bands currently reserved for the Intelligent Transportation System (see story on page 24).

The DoD and NOAA's National Weather Service (NWS) entered into agreements to use the ITS's unique expertise in propagation modeling to provide specialized RF propagation prediction tools for coverage and interference prediction, as reported in the section on *Web-based Propagation Analysis Services*.

## Interagency Agreements for the Use of Table Mountain

Other federal agencies, particularly NOAA and NIST laboratories collocated with ITS on the DoC Boulder Laboratories campus, enter into interagency agreements with NTIA to use the TMFS for research activities to be conducted either by their own or ITS researchers.

NOAA's National Geodetic Survey (NGS) Operations and Analysis Division operates the Table Mountain Gravity Observatory (TMGO) on the site. In addition to having only a low uniform slope and relatively homogeneous underlying ground, Table Mountain is seismically quiet, making it a very good location for NGS to base the absolute gravity observing program. Measurement of absolute gravity is conceptually simple, but accurate free-fall measurement of the acceleration of gravity is technologically challenging. The observatory has become a major center for performance intercomparisons of absolute gravity meters, with space for up to ten instruments operating simultaneously on separate and isolated piers. NGS also has a Continuously Operating Reference Station (CORS) on Table Mountain, one of over 2000 stations that provide Global Navigation Satellite System (GNSS, also called GPS) data to support three-dimensional positioning, meteorology, metrology, space weather, and geophysical applications throughout the U.S.

*NOAA Central UV Calibration Facility at Table Mountain. Photo courtesy Earth System Research Laboratory.*

The Central UV Calibration Facility (CUCF), a joint project of NOAA and NIST, provides highly accurate and long-term repeatable calibrations and characterizations of ultraviolet radiation monitoring instruments.

The facility has several UV instruments and is a useful test bed for intercomparisons, including annual spectroradiometer comparisons.

NOAA's Earth System Research Laboratory Global Monitoring Division maintains a SURFRAD (Surface Radiation) Network monitoring station on Table Mountain. SURFRAD stations perform ground-based measurements of upwelling and downwelling solar and infrared radiation; ancillary observations include direct and diffuse solar radiation, photosynthetically active radiation, UVB, spectral solar, and meteorological parameters. Data are available near real time by anonymous FTP and over the Internet. Observations from SURFRAD have been used for evaluating satellite-based estimates of surface radiation and for validating hydrologic, weather prediction, and climate models.

The National Geomagnetism Program of the U.S. Geological Survey (USGS) of the U.S. Department of the Interior operates a Magnetic Observatory on Table Mountain. In addition to serving as a site for routine collection of magnetometer data, the Table Mountain observatory also functions as the program's test bed for on-going operational developments. USGS data are used to model and map the global magnetic field in cooperation with the international geomagnetic community and various satellite programs. Regionally, USGS data are used to support aeromagnetic surveys and directional drilling programs for the oil and gas extraction industry. USGS data are also used by the pipeline and electrical power grid industries and for academic studies across a broad range of geophysical sciences.

*SURFRAD instruments mounted on a solar tracker on an instrument deck at Table Mountain. Photo courtesy NOAA.*

*Azimuth mark at the USGS Table Mountain magnetic observatory. Photo courtesy USGS.*



## Technical Publications, Royalty-free Data and Software Releases, and Collaborative Standards Contributions

Historically, ITS has transferred research results to other researchers, the commercial sector, and government agencies through publication of results either directly as NTIA publications or by submission of articles to peer-reviewed external scientific journals or conferences. Many of these publications—both NTIA reports and monographs and peer-reviewed articles in external venues—have become standard references in several telecommunications areas. Technical publication remains a principal means of ITS technology transfer. All NTIA technical publications released since 1978 have been made available through the ITS public web site as downloadable PDF files. Publication files are tagged with standardized metadata to assist Internet searches, and the ITS web site offers advanced search capabilities to locate relevant publications by keyword. ITS publications were downloaded over 9,000 times in FY 2015.

An internal peer review process managed by the ITS Editorial Review Board (ERB) ensures the quality of new publications. In FY 2015, ITS authors published 11 NTIA Technical Reports and Memoranda that were peer-reviewed through the ERB process and 11 journal articles or conference papers that underwent both ERB review and additional peer review outside ITS. ITS experts are also frequently invited to participate as speakers or presenters at technical conferences, workshops, and symposia. A list of FY 2015 presentations and publications with citations and abstracts begins on page 75.

ITS makes several software and data tools available via open-source download:

- Software developed to predict propagation for planned communications systems through input of specific parameters to propagation prediction algorithms has been developed and shared over the years; sample data sets that can be used to test and validate propagation prediction models are also available.

- An ITS-developed objective estimator of speech intelligibility that follows the paradigm of the Modified Rhyme Test (MRT), the Articulation Band Correlation MRT (ABC-MRT) consumes a tiny fraction of the resources required by MRT testing and provides excellent estimates of MRT intelligibility results. ABC-MRT tools, MRT databases, and sample clips are available for download on the ITS web site.
- ITS video quality measurement software tools use an objective video quality measurement method, which has been made a national standard by ANSI, to estimate the quality of video impairments, providing users an inexpensive alternative to viewer panels for testing new transmission technologies.
- The Web-Enabled Subjective Test (WEST) software package facilitates gathering subjective testing data from multiple locations and multiple portable or computing devices and is also freely available for download.

ITS works with industry to apply research results to developing telecommunication performance standards and guidelines by providing leadership and technical contributions to national and international organizations responsible for developing telecommunication standards. ITS's technical inputs are relied upon as technically advanced and sound, and as unbiased by commercial interests. Information about standards activities in FY 2015 begins on page 61; a full list of positions held by ITS staff is on page 82.

# Conferences, Workshops and Symposia

## International Symposium on Advanced Radio Technologies (ISART)

Over 130 spectrum engineers and policy makers from industry, academia, and government convened at the DoC Boulder Labs on May 12-14, 2015, to consider next steps toward successful deployments of commercial systems in spectrum bands recently opened to sharing between federal and commercial systems. The 14th International Symposium on Advanced Radio Technologies (ISART 2015) focused on *Measurements, Models, Simulations, and Technologies for Improved Spectrum Sharing*. Prevailing themes included the need for collaboration and cooperation among industry, government and academia in research to advance spectrum sharing technologies and methodologies and the importance of open and transparent engineering approaches supported by validation tests and measurements to build trust among stakeholders. Panelists also highlighted the need for spectrum monitoring to support system deployments and anticipated enforcement requirements.

Tutorials on the first day provided a common base of understanding of the engineering studies that led up to the record-breaking AWS-3 auction and the recent FCC rulemaking establishing a new Citizens Broadband Radio Service (CBRS) in the 3.5 GHz band. These multi-stakeholder studies involved an unprecedented commitment of engineering resources from federal agencies, industry partners, and regulators and established a sound framework for future endeavors.

ISART brought together a diverse set of spectrum sharing stakeholders representing commercial, government, and policy organizations. Attendees included: Fred Moorefield, Director of Spectrum Policy and Programs in the Office of the DoD Chief Information Officer (CIO), who represented the interests of DoD organizations that are being required to share previously reserved spectrum; Meredith Atwell Baker, President and CEO of CTIA – The Wireless Association, which represents the wireless industry in calling for more federal spectrum to be made available for commercial use; and DoC Assistant Secretary and NTIA Administrator Larry Stickling, whose agency is responsible for identifying federal spectrum to be made available. At the end of the third day, Fred Moorefield cited ISART and the work presented as examples of fruitful industry-government collaboration that "broke down a lot of barriers of mistrust."

Larry Strickling's keynote address on day two highlighted the DoC's recent commitment of resources through its newly formed CAC to facilitate research and engineering to address ongoing spectrum sharing challenges—especially with regard to spectrum monitoring. The conference was organized around five discussion panels that explored the key components of a spectrum sharing deployment, from a review of system compatibility models and simulations to propagation models, new radio technologies, test and measurement approaches, and, finally, regulatory processes and enforcement challenges. Technical presentations by NTIA/ITS and NIST/CTL staff underscored recent work in measuring interference protection criteria between radars and LTE devices, propagation clutter measurements, spectrum monitoring, and millimeter wave research. In her keynote on the final day Meredith Atwell Baker applauded recent government success in identifying additional spectrum for commercial applications and encouraged conference participants to continue efforts to funnel additional bands into the spectrum sharing pipeline.

## Public Safety Workshops

ITS hosted or co-hosted several public safety communications workshops and conferences in 2015 to encourage technology transfer among multiple research organizations and enhance stakeholder interactions.

### Priority and Quality of Service Working Group

PSCR hosted a National Public Safety Telecommunications Council (NPSTC) Priority and Quality of Service (PQOS) Working Group meeting in Boulder February 24-25, 2015, to finalize key recommendations for the FirstNet Public Safety Advisory Committee (PSAC) regarding priority and preemption requirements.

### Video Quality in Public Safety

ITS provided invitational travel support for some 30 public safety practitioners to attend the Sixth Video Quality in Public Safety (VQiPS) conference, sponsored by the Department of Homeland Security's Office for Interoperability and Compatibility (DHS/OIC), in Elizabeth, NJ, June 17–18, 2015. First responders rely heavily on video technology to increase situational awareness, and the VQiPS Initiative began in 2008 as a partnership between DHS and PSCR to provide a forum for end users, academia, and industry to learn from each other. The 2015 agenda included briefings on VQiPS knowledge products/tools in development, emerging technologies, and video standards developments. Over 65 attendees also gained insights through sharing of experiences, including key lessons learned from the 2015 Baltimore riots and case study presentations from representatives of the Philadelphia Police Department, the South Dakota Division of Criminal Investigation, General Mitchell International Airport, and the Port Authority of New York and New Jersey.

### Public Safety Broadband Stakeholder Conference

ITS co-hosted PSCR's latest Public Safety Broadband (PSBB) Stakeholder Conference in San Diego, CA, June 3–5, 2015. This was the sixth face-to-face stakeholders meeting for the PSBB 700 MHz band class 14 Demonstration Network, with over 500 attendees from public safety, federal agencies, industry, and academia. Conference attendees benefited from the collocation of the FirstNet June Board Meeting at the conference hotel the morning of June 3. The FirstNet Board Meeting was webcast live into the PSCR Conference Room. Following the Board Meeting, FirstNet Chairwoman Sue Swenson delivered the first day's keynote address. Swenson reported on performance to date and future plans in four key FirstNet focus areas: (1) Execute, (2) Engage, (3) Communicate, and (4) Collaborate. Other keynote speakers were Admiral Ronald Hewitt, Director of the Department of Homeland Security Office of Emergency Communications, and NIST/CTL Director Kent Rochford. Participants were briefed on FirstNet efforts to build out the National Public Safety Broadband Network (NPSBN) and on test results from the Public Safety Broadband Demonstration Network.

*ISART 2015 was attended by spectrum engineers and policy makers. May 13, 2015 photo by Lilli Segre.*


*A broad range of representatives from government, industry, academia, and the public safety community attended the 2015 Public Safety Broadband Stakeholder Meeting.*

ITS briefings covered international standards development, extended-range cell testing, and audio quality research to assess intelligibility of broadband codecs in loud noise environments. More information and materials are available at http://www.pscr.gov/about/highlights/psbb_062015/index.htm.

# Senior Technical Fellows and Technical Lectures

## ITS Senior Technical Fellow Program

Newly appointed ITS Director Dr. Keith Gremban initiated the Senior Technical Fellow program at ITS in FY 2015 to enhance the Institute's focus on scientific excellence and engineering innovation. The program provides a formalized way to sustain and share ITS technical expertise, both internally and externally. IT recognizes the outstanding technical achievements of senior ITS researchers and allows them to devote more time to training and mentoring junior and mid-level scientists and engineers, and disseminating best practices to industry and other government agencies. Frank Sanders, who has served as Chief of the Telecommunications Theory Division, was the first Senior Technical Fellow named under the new ITS program. Mr. Sanders has been at ITS for over 30 years and is a renowned subject matter expert on radar system design, radar spectrum emissions, and radar receiver sensitivity to interference, and on the analysis and resolution of electromagnetic compatibility problems. He literally wrote the book on best practices in radar spectrum emissions measurement, NTIA Technical Report TR-05-420, "Measurement procedures for the radar spectrum engineering criteria (RSEC)," March 2005.

## FY 2015 Radar Engineering Lecture Series and Classes

The first set of four talks in an ongoing, and still-developing, series on radars was developed and delivered in FY 2015, as were class lectures for the NTIA Federal Frequency Management Course and the multinational U.S. Telecommunications Training Institute (USTTI). The lecture series disseminates knowledge of radar design principles, practical aspects of radar design, and principles of performing accurate radar spectrum emission measurements. The underlying theory is discussed, as are the best practices gained through decades of experience in characterizing radar emissions and their behavior. In FY 2015, the talks were given in-house for ITS and NIST personnel collaborating in CAC. The lectures are being further developed in FY 2016. Similar series of lectures were developed for NTIA's Federal Frequency Management Course, given at the Hoover Building in Washington for federal spectrum managers and private-sector engineers who design and develop systems for the federal government, and for the USTTI class, also given in Washington and hosted by an NTIA moderator.

*The radar lectures at the Boulder Labs provided an opportunity for knowledge transfer and cross training to about 40 ITS and NIST staff. Photo by Lilli Segre.*

All classes discussed spectrum management in general, but focused on radar systems as they relate to spectrum management. Given that even small radars may routinely operate at peak effective radiated power (ERP) levels of more than a billion watts (1 gigawatt), the information disseminated through these classes plays an important role in enabling the integration of radar operations into the overall spectrum management scheme of both the U.S. and foreign administrations.

# Spectrum Sharing

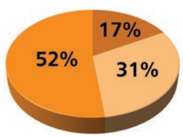
> "As NTIA continues to review spectrum bands for reallocation, spectrum sharing is becoming the new reality."[7]

In 2014, CTIA estimated that Americans used 4.1 terabytes of data over 355.4 million cellular devices.[1] Other surveys found that 69% of adults access the Internet on a smartphone[2] and nearly half of U.S. homes have only cellular phones.[3] In addition to smartphones, which on average generate 22 times more network traffic than "dumb" phones, a plethora of new devices are driving seemingly insatiable demand for spectrum. Predictions are that by 2019, 11.5 billion "smart" devices will connect to mobile networks, including machine-to-machine (M2M) modules in automated buildings, security, smart meters, utility grids, transportation safety, healthcare monitors, and wearables. To handle the volume, cellular networks increasingly offload traffic to the fixed network—by 2016 over half of mobile traffic may be offloaded through Wi-Fi and femtocells.[4] This relieves the load on cellular networks, but creates demand for other spectrum for connecting wireless services—in the same or different bands.

Spectrum is a physically limited asset: to make more spectrum available for use, users need to share spectrum, use wavelengths previously considered unsuitable for radio communication, or do both. Improving technologies to increase the number of users who can operate in each band or inventing new equipment that can operate in previously unused bands are goals for the long term; even while research and development efforts move forward to accomplish them, the immediate focus is on expanded sharing.

"America's future competitiveness and global technology leadership depend, in part, upon the availability of additional spectrum" said a 2010 Presidential Memorandum[5] that directed NTIA to work with the FCC to identify 500 MHz of spectrum that could be repurposed for commercial broadband use. Though both federal and non-federal spectrum will be used to achieve this goal, much of the 500 MHz will come from repurposing bands now used by federal agencies. The complexity of reallocating incumbents from the most desirable spectrum bands while ensuring continuity of critical federal government functions is daunting and in some cases cost-prohibitive—radars or satellites, for example, may have a 50 year lifespan and cost billions of dollars to replace. Thus, in 2012, the President's Council of Advisors on Science and Technology (PCAST) concluded that "the norm for spectrum use should be sharing, not exclusivity,"[6] and highlighted the importance of sound technical assessments in evaluating potential risks and benefits and ensuring that spectrum-dependent services in shared bands can coexist without receiving or creating interference.

*"Beachfront Spectrum" Allocations*




*Over half of the most desirable "beachfront spectrum" (225–3700 MHz) is already allocated for shared use. ("Understanding Federal Spectrum Use," July 30, 2015 NTIA blog by Paige R. Atkins, Associate Administrator, NTIA OSM)*

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1. CTIA-The Wireless Association, *Wireless Industry Summary Report, Year-End 2014 Results*, 2015, Accessed http://www.ctia.org/your-wireless-life/how-wireless-works/annual-wireless-industry-survey December 3, 2015.
2. Leichtman Research Group, Inc., Press Release: *Over 80% of U.S. Households get Broadband at Home*, December 3, 2015, Accessed http://www.leichtmanresearch.com/press/120315release.html December 4, 2015.
3. Centers for Disease Control and Prevention. *Wireless Substitution: Estimates From the National Health Interview Survey*, January-June 2015, p. 1. (12/1/2015). Accessed http://www.cdc.gov/nchs/data/nhis/earlyrelease/wireless201512.pdf December 2, 2015.
4. Cisco Visual Networking Index: *Global Mobile Data Traffic Forecast Update, 2014–2019* (February 2015). Accessed http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white_paper_c11-520862.html December 4, 2015.

5 The White House, *Presidential Memorandum: Unleashing the Wireless Broadband Revolution*, June 28, 2010. Accessed http://www.whitehouse.gov/the-press-office/presidential-memorandum-unleashing-wireless-broadband-revolution January 9, 2014.

6 Executive Office of the President, President's Council of Advisors on Science and Technology, *Realizing the Full Potential of Government-held Spectrum to Spur Economic Growth*, July 2012. Accessed https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf February 17, 2015.

7. Lawrence E. Strickling and Alexander Macgillivray, "AWS-3 Auction Highlights New Approach to Spectrum Policy," January 29, 2015, The White House, Office of Science and Technology Policy. Accessed http://www.whitehouse.gov/blog/2015/01/29/aws-3-auction-highlights-new-approach-spectrum-policy February 13, 2015.

Technical assessments to evaluate spectrum sharing scenarios are complex and multi-faceted. Proposals for spectrum sharing look to emerging technologies to enable interference-free sharing between entrants and incumbents. In some bands, the onus will be on entrants to devise and adopt new technologies for this purpose, since incumbents may be either difficult or impossible to update due to their cost, complexity, or location. Safety-of-life systems such as radars or satellites used by the Federal Aviation Authority (FAA), the U.S. Coast Guard, and the National Weather Service are good examples. While it is critical that these safety-of-life systems be fully protected, entrants into bands where such devices operate must also be able to reliably operate in the presence of these systems to fully exploit the bandwidth being opened to them.

Two principal analytical tools needed to point the way forward for radio systems to successfully coexist in shared or adjacent spectrum bands while continuing to operate efficiently are electromagnetic compatibility analyses and propagation analyses, and ITS is a recognized leader in both. ITS works closely with NTIA's Office of Spectrum Management (OSM) to perform EMC and propagation studies to inform spectrum management policy and procedures.

## Electromagnetic Compatibility Analyses

Electromagnetic compatibility (EMC) analyses examine the totality of spectrum usage by radio transmitters and receivers and the interactions between different radio systems. EMC studies use models, simulations, tests, and measurements to characterize the emissions of different radio devices for many purposes. They help define technical parameters such as transmitter emission limits, frequency offsets, or separation distances for proposed rulemakings in support of new spectrum uses/sharing requirements.

Effective spectrum sharing and spectrum reallocation can only be accomplished if both legacy and new services operating in the same or adjacent bands can be protected from interference. Interference analysis and mitigation studies are focused EMC analyses that provide data needed to continuously improve the technologies that allow users to gracefully operate in the same or adjacent bands. Ideally, these studies are carried out proactively, while new equipment or new sharing regulations are still under development. Sometimes, however, they are needed to trace to its root cause interference experienced in situations that were previously thought to be safe for sharing and to devise mitigation strategies. EMC studies are undertaken to develop interference protection criteria (IPC), which define interfering signal levels that allow a communication system to continue to operate without being significantly compromised. They can also be used to develop algorithms for detection and avoidance so that equipment in shared bands can be programmed to limit interference. First, the interference potential in both directions must be understood and quantified. Then mitigation methods can be devised, tested, and standardized.

## Propagation Modeling

RF propagation models are mathematical algorithms that predict the behavior of radio waves. The National Bureau of Standards (NBS) Radio Section (ITS's ancestor) began research to predict how far radio waves can travel under specific conditions in about 1909, and the search for better methods of prediction has continued uninterrupted since. The behavior of radio waves depends on their frequency, amplitude, and polarization, as well as on their interaction with the environment through which they travel through phenomena such as reflection, refraction, diffraction, absorption, and scattering. Radio receiver sensitivity, radio noise, and interference from natural and man-made sources must also be taken into account.

Many radio propagation models are empirical/statistical, predicting the most likely behavior of a radio link under specified conditions based on large amounts of measured data. As computing equipment has become more powerful, more data and more parameters can be included in the calculation, and prediction becomes correspondingly more accurate. Methods to predict the propagation of radio waves in ionized and non-ionized media are standardized internationally by the ITU. (See page 62 for a description of ITS activities to advance international propagation modeling standards in FY 2015.) At the core of some of those are propagation prediction models first developed by ITS's immediate predecessor, the Central Radio

Propagation Laboratory (CRPL), in the mid 20th century and first computerized in the 1960s. Two of the most well-known and widely-used propagation models published by CRPL and eventually computerized by ITS are the Longley-Rice or Irregular Terrain Model (ITM) and the IF-77 or Gierhart-Johnson model.

Propagation models are an essential enabler for spectrum sharing. Analysts use them to predict the areas that different transmitters can cover, and identify regions where interference is likely. For example, if different systems are completely incompatible, propagation modeling is essential to help define "protection zones" in which certain transmitters are not allowed to operate because harmful interference would result.

## FY 2015 Research to Advance Spectrum Sharing

Of continued interest in FY 2015 were studies to inform sharing decisions in the 3.5 GHz band. NTIA identified the 3.5 GHz band as a "fast track" band for potential sharing because unlicensed WiMAX equipment has already been developed and deployed in this band, federal operations in the band are geographically limited, and the band has already been allocated for fixed services in other parts of the world. The FCC proposed a new Citizens Broadband Service that would share 100 MHz of spectrum (3550–3650 MHz) in this band with incumbent federal radars. It called for an innovative framework of small cell and database technologies to facilitate rapid broadband deployment while protecting existing incumbent users. ITS performed two important analyses (described on pages 18 and 20) to support final rulemaking in this band: an EMC analysis to examine the compatibility of radar and non-radar services that might operate in the band, and a propagation analysis to designate geographic protection zones around incumbent radars.

Other Government agencies also sought out ITS expertise for interference prevention, diagnosis and mitigation in FY 2015. The FCC issued rules opening the 1695–1710 MHz, 1755–1780 MHz, and 2155–2180 MHz bands to sharing in 2014. In the first of those bands, several agencies operate meteorological satellites. Protection zones were designated around the sensitive Earth receiving stations to which the satellites transmit, and ITS was asked to develop a web-based frequency coordination portal (described on page 22) to enable entrants and incumbents to negotiate frequency use in these protection zones.

When a spectrum band is opened to new users, entrants must ensure that their use does not cause interference to incumbents in that or adjacent bands. In 2015, a NOAA receiving station that collects and redistributes meteorological satellite data to government and commercial users experienced intermittent interference that caused data loss. ITS was asked to perform a forensic interference study. As described on page 23, ITS engineers installed a temporary spectrum monitoring site and were able to identify and locate the interference source. Prospectively, the Department of Transportation Federal Highway Administration (FHWA) asked ITS to perform an EMC analysis to evaluate the impact of a proposal to open up sharing by unlicensed devices in the 5 GHz band. That band is currently used by a critical FHWA communications system, part of the Intelligent Transportation System. The FCC has opened adjacent bands to sharing, but is proceeding cautiously in the band allocated to intelligent transportation systems because incumbent systems are still under development and entrant systems are still on the drawing boards. The results of ITS's EMC analysis, described on page 24, will be critical for this rulemaking.

The 5 GHz case also illustrates the importance of reliable simulation for EMC analysis of sharing scenarios proposed for technology that does not exist or is being reconfigured to operate in new areas of the spectrum. To determine if sharing is even feasible in specific bands and circumstances, policy makers planning to enhance spectrum utilization through sharing have traditionally depended on laboratory and field measurement data from the equipment and systems involved. When the equipment does not yet exist or the system has not yet been deployed, researchers and policy makers must rely on software simulation to predict potential interference scenarios and analyze approaches to avoid or mitigate interference. In FY 2015, as described on page 26, ITS significantly expanded the capacity and accuracy of computer simulations used to predict the compatibility of LTE technology being proposed for use in bands where it has never previously operated and the incumbent radar systems. ITS also continues to refine and expand computerized propagation prediction methods as the technology advances. Accurate, rapid, and easily accessible RF propagation prediction is a critical planning tool for deployment of new, relocated, or expanding wireless services. Web-based propagation analysis services, described on page 29, allow other agencies to benefit from ITS's expertise in this area in support of their own missions.

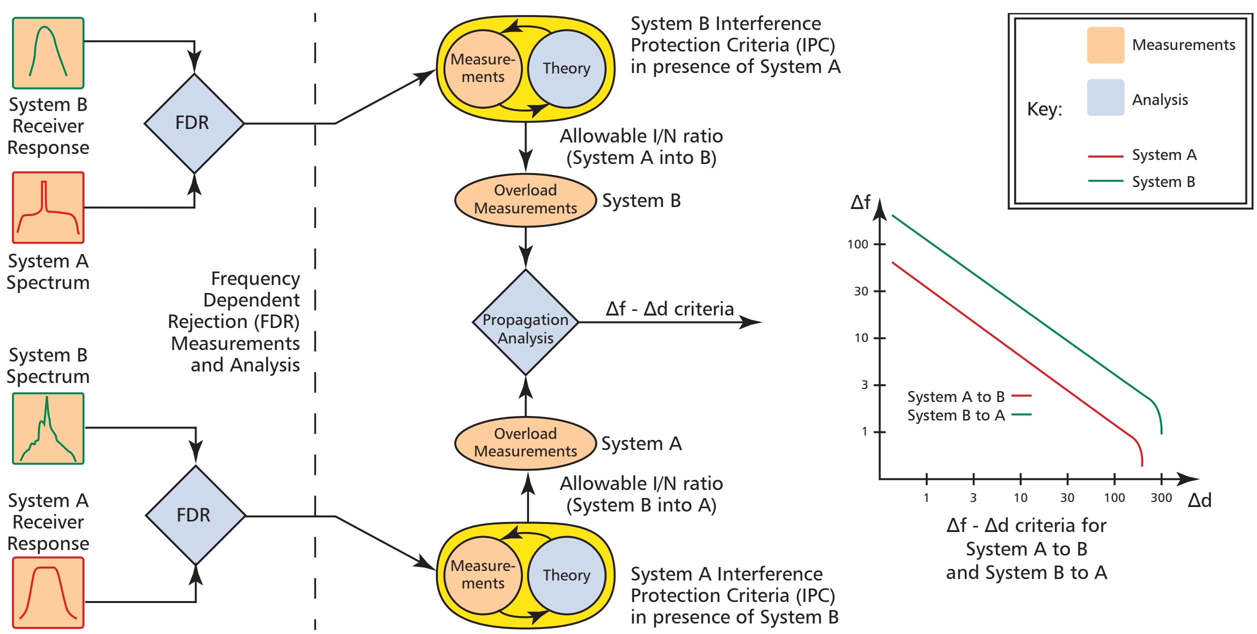
# Pioneering EMC Study: 3.5 GHz Sharing Scenario

## Objectives

- *Develop a sound and repeatable methodology for EMC studies to inform rulemaking for new band-sharing scenarios*
- *Demonstrate the efficacy of the method by performing studies for a rulemaking in process and widely disseminate the results and the methodology for use by other researchers*

## Scenario

The 3550–3650 MHz ("3.5 GHz") spectrum is primarily occupied at present by government radar systems, particularly radars deployed on Navy ships. The FCC adopted rules[1] for a new 3.5 GHz terrestrial broadband communication service in April of 2015, over two years after first proposing to open the band for sharing. Recognizing that the incumbent radars cannot be relocated and will have to continue to share this band with the new systems, the FCC called for tests and measurements to investigate the compatibility of broadband communications systems and incumbent federal radars. NTIA's 2010 "Fast Track" Report[2] presented a summary of existing system characteristics and some theoretical analysis of sharing criteria. Following up, ITS and NTIA's Office of Spectrum Management (OSM) developed a new, comprehensive approach for band sharing EMC measurements and analysis and applied it to the 3.5 GHz band.




*The spectrum sharing methodology developed and applied by ITS-OSM for the 3.5 GHz band-sharing EMC study results in quantitative criteria for frequency and distance separations between new and incumbent systems.*

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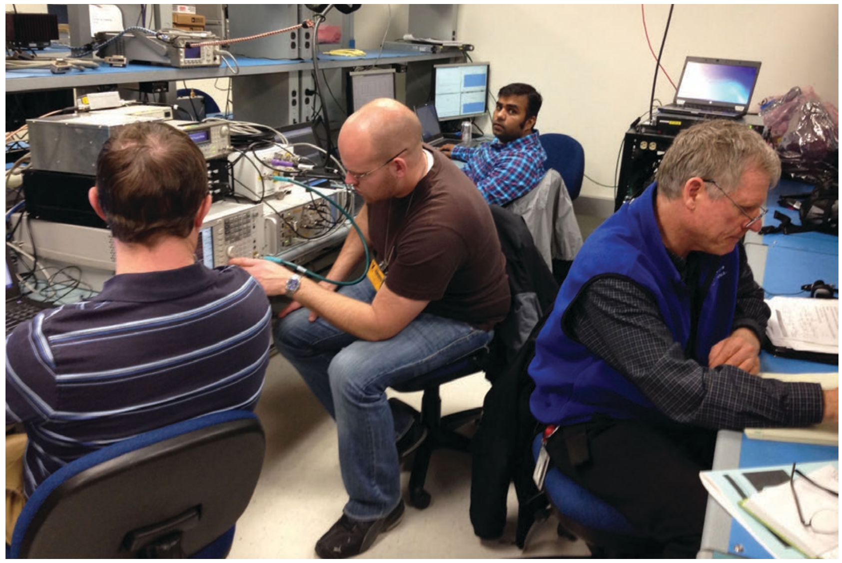
1. Federal Communications Commission, "Amendment to the Commission's Rules with Regard to Commercial Operations in the Band 3550-3650 MHz," FCC Docket No. 12-354, Report and Order and Second Further Notice of Proposed Rulemaking, April 17, 2015. Accessed https://apps.fcc.gov/edocs_public/attachmatch/FCC-15-47A1.pdf December 14, 2015

2. U.S. Department of Commerce, National Telecommunications and Information Administration, *An Assessment of the Near-Term Viability of Accommodating Wireless Broadband Systems in the 1675-1710 MHz, 1755-1780 MHz, 3500-3650 MHz, 4200-4220 MHz and 4380-4400 MHz Bands ("NTIA Fast Track Report")*, October 2010. Available http://www.ntia.doc.gov/files/ntia/publications/fasttrackevaluation_11152010.pdf

## Approach

The approach calls for methodically measuring the emission spectra and receiver characteristics of systems that will share a band, as well as performing interference-protection criteria (IPC) measurements and analysis. Propagation and antenna coupling factors are then applied to develop final criteria for frequency and distance separations required for compatible operations between the new and incumbent systems.

Implementing this approach for the 3.5 GHz band, ITS and OSM engineers performed measurements at locations across the U.S. These included measurements of emission spectra of LTE and radar transmitters and of those same systems' receiver characteristics. The same engineers performed interference-effects measurements of radar signals in LTE receivers and LTE signals in radar receivers. ITS and OSM engineers used those measurement results to inform the *Propagation Analysis for Spectrum Sharing at 3.5 GHz* reported on page 20.



*ITS engineers Geoff Sanders, John Carroll, and Bob Achatz (foreground) working with private-sector engineers to perform interference-effects measurements of radar signals on 3.5 GHz LTE receivers at a private-sector lab. Photo by F. Sanders.*

### Related Publications:


- *F.H. Sanders, J.E. Carroll, G.A. Sanders and L.S. Cohen, "Measurements of Selected Naval Radar Emissions for Electromagnetic Compatibility Analyses," NTIA Technical Report TR-15-510, Oct. 2014. Available http://www.its.bldrdoc.gov/publications/2781.aspx.*
- *F.H. Sanders, J.E. Carroll, G.A. Sanders, R L. Sole, R.J. Achatz and L.S. Cohen, "EMC Measurements for Spectrum Sharing Between LTE Signals and Radar Receivers," NTIA Technical Report TR-14-507, Jul. 2014. Available http://www.its.bldrdoc.gov/publications/2760.aspx.*
- *G.A. Sanders, J.E. Carroll, F.H. Sanders and R.L. Sole, "Effects of Radar Interference on LTE (FDD) eNodeB and UE Receiver Performance in the 3.5 GHz Band," NTIA Technical Report TR-14-506, Jul. 2014. Available http://www.its.bldrdoc.gov/publications/2759.aspx.*


## Results

The entire measurement-and-analysis campaign contributed to being able to define substantially smaller coastal exclusion zones for initial deployment of new 3.5 GHz terrestrial communication systems than had been originally estimated. Looking further down the road, to the day when the exclusion zones are converted into protection zones for true spectrum sharing between naval radars and communication systems, these same measurement and analysis results will be instrumental in determining the exact conditions under which a future 3.5 GHz spectrum access system (SAS) will switch frequencies and bands on the communication systems to maintain compatible operation with the radars.

This band-sharing EMC approach will be further applied to other spectrum bands in the near future, including 1300–1390 MHz and 1695–1710 MHz. The usefulness of this approach was recognized this year when the Department of Commerce awarded Gold and Silver Medals for Scientific and Engineering Achievement to the ITS-OSM engineering teams that developed and applied it (see page 4).

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# Propagation Analysis for Spectrum Sharing at 3.5 GHz

## Objective

- *Develop and disseminate a new propagation model appropriate for designating minimum effective geographic protection zones for federal systems required to share spectrum with new Citizens Broadband Service in the 3.5 GHz band*

## Understanding Propagation at 3.5 GHz

As the FCC Notice of Proposed Rulemaking pointed out, the 3.5 GHz band has some unique characteristics that can be seen as both advantages and disadvantages from a radio propagation perspective. Signals propagating at 3.5 GHz decay faster and penetrate buildings less well than those transmitted in lower frequency bands. These same characteristics, however, make the band an excellent candidate for use in small cell communications. The FCC concluded that "the band's characteristics make it well-suited to spectrum sharing, particularly geographic sharing. The limited propagation—especially in combination with low-power operation—should allow disparate radio systems to operate in closer proximity than lower frequency bands. This feature of the band should enable greater sharing opportunities with incumbent systems (such as radars and satellite communications networks) with appropriate geographic separation and other mitigation techniques such as resilient and flexible technologies. It also raises the possibility of greater sharing between disparate commercial systems in the band."[1] A multi-agency Joint Working Group of experts from NTIA, the FCC, and agencies with incumbent systems in the 3.5 GHz band began to explore how to apply known RF propagation prediction models to planning under the proposed sharing scenario. To accurately predict interference in a communications network deployment relying on small cell infrastructure in heavy cellular traffic areas, RF propagation models need to account for radio propagation in man-made and naturally cluttered environments, as well as other impediments to propagation such as terrain obstructions.

## Modeling Propagation at 3.5 GHz

Several possible alternative models were considered and a plan of work was drawn up that proposed a new extended Hata model.[2] The frequency range of the Hata (1980) model was extended in frequency and distance; frequencies from 1,500 to 3,000 MHz were included based on Hata's original path loss exponent method for path distances less than approximately 20 km and on a different method for longer distances. Other site-specific corrections that depend on the details of the terrain profile between the transmitters and receivers were also implemented, as well as corrections to account for urban or suburban environments.

When modeling the propagation effects of small cell communications networks, a concern is how the radar's radio receiver might be affected by the aggregate impact of transmission from multiple cells. To predict the propagation of multiple transmissions from a grid of small cells using this newly extended model, the results were compared to the predictions using the Longley-Rice Irregular Terrain Model (ITM)[3] and the larger median loss value was used as the basis for Monte Carlo studies of the aggregate interfering power. The effect of the aggregate interference from a small cell communications network on the radars is expressed as the radar's interference protection criterion (IPC). The IPC had been previously measured by engineers from ITS, OSM, and the U.S. Naval Research Laboratory (NRL) and reported in NTIA TR-14-507.[4]

1. Federal Communications Commission, "Enabling Innovative Small Cell Use In 3.5 GHZ Band NPRM & Order," Notice of Proposed Rulemaking, GN Docket No. 12-354, FCC 12-148, (Adopted December 12, 2012, Released December 12, 2012). Accessed http://www.fcc.gov/document/enabling-innovative-small-cell-use-35-ghz-band-nprm-order December 14, 2015.
2. M. Hatay, "Empirical formula for propagation loss in land mobile radio services," in *IEEE Transactions on Vehicular Technology*, vol. 29, no. 3, pp.317-325, Aug. 1980. doi: 10.1109/T-VT.1980.23859
3. G.A. Hufford, A.G. Longley, W.A. Kissick, A Guide to the Use of the ITS Irregular Terrain Model in the Area Prediction Mode, NTIA Technical Report TR-82-100, April 1982. Available http://www.its.bldrdoc.gov/publications/2091.aspx.
4. F.H. Sanders, J.E. Carroll, G.Sanders, R.L. Sole, R.J. Achatz, and L.S. Cohen, "EMC Measurements for Spectrum Sharing Between LTE Signals and Radar Receivers," NTIA Technical Report TR-14-507, July 2014. Available http://www.its.bldrdoc.gov/publications/2760.aspx.

The simulated aggregate interfering power studies used specific, notional ship/radar locations, generally situated at multiple sites 10 km seaward of the continental United States Atlantic, Pacific, and Gulf of Mexico Coastal areas, including bays, sounds and estuaries (Alaska and Hawaii and inland radar deployment sites were treated as special cases), and exclusion zone distances (i.e., all devices within that distance to the ship/radar location were turned off and the resulting simulated aggregate interference was less than or equal to the radar's IPC) were computed along each inland radar bearing (typically at 1° increments) and on each Monte Carlo iteration. In this Monte Carlo analysis, devices' numbers, locations, heights, indoor/outdoor deployments, and basic transmission losses were randomly distributed on each iteration according to USGS NLCD 2006 land use categories, over a large inland region adjacent to the coast relative to the ship/radar site. All simulations initially assumed that the radar's main beam elevation angle was 0°.

For each notional ship/radar site and on each inland radar bearing, the exclusion zone distances were then rank ordered from largest to smallest, yielding a cumulative distribution function of exclusion zone distances for each bearing at that site. Then taking the 5% exceedance value (only 5% of the exclusion zone distances exceeded the chosen value) for each bearing and rank ordering these from largest to smallest over all inland bearings, the ship/radar's exclusion zone distance was the maximum of the 5% exceedance distances over all inland bearings.

## Results

As a result of this analysis, NTIA reevaluated the exclusion zone distances needed to protect federal shipborne and ground-based radar systems in these bands. The total geographic area impacted by the coastal exclusion zones recommended to the FCC and included in the final rulemaking was reduced by 77% compared to the original recommendations when the band was first proposed as a candidate for sharing. The methods used and results of the interference analysis are reported in NTIA TR-15-517.[5]


*This screenshot from Google Earth™ shows the exclusion zones for the protection of radar operations in the lower 48 states before (yellow line) and after application of the new extended Hata model (blue line).*

The technically complex discussions within the multi-agency Joint Working Group were instrumental in developing a more in-depth understanding among federal stakeholders of the options available for implementing commercial broadband services while protecting federal operations. The ITS/OSM team received a Department of Commerce Silver Medal Award (see page 4) for its outstanding leadership of the stakeholder group in addressing this complex technical analysis to enable new spectrum sharing opportunities between federal and commercial users. The successful outcome of this effort established a proven method for federal and commercial entities to share detailed technical and operational information, a key element to successful long-term spectrum sharing.

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5. E.F. Drocella Jr., J.C. Richards, R.L. Sole, F. Najmy, A. Lundy, P.M. McKenna, "3.5 GHz Exclusion Zone Analyses and Methodology," NTIA Technical Report TR-15-517, June 2015. Available http://www.its.bldrdoc.gov/publications/2805.aspx.

# Radio Frequency Coordination Portal

## Objective

- *Facilitate spectrum sharing in the 1695–1710 MHz band.*

## Solution

In March 2014, the FCC adopted new rules[1] to make significantly more commercial spectrum available for a broad variety of different commercial fixed and mobile terrestrial wireless services for voice, data, video and/or messaging—collectively called Advanced Wireless Services (AWS)—through sharing with incumbent federal users in the 1695–1710 MHz, 1755–1780 MHz, and 2155–2180 MHz bands. In making these bands available for sharing, the FCC adopted rules that give licensees flexibility to provide any fixed or mobile service that is consistent with the allocations for this spectrum—as long as they comply with technical and operational requirements to protect against harmful interference.

Although many federal incumbents will eventually relocate out of these bands, relocation is not feasible for agencies that operate meteorological satellite Earth stations. Thus, the FCC rules require that non-federal entrants successfully coordinate with federal incumbents prior to operating in certain geographic areas (coordination zones) around these stations, which will continue to operate indefinitely in this band. Affected agencies include the U.S. Air Force, Army, and Navy; the Department of the Interior; and NOAA. ITS developed the Radio Frequency Coordination Portal (RFCP) to manage this coordination process. The RFCP provides a formal structure through which entrant licensees and incumbents can exchange information and communicate about radio system engineering issues to enable successful sharing.

*RFCP project team members, clockwise from bottom left: George Engelbrecht, Elizabeth Lor, Julie Kub, Teresa Rusyn, Kristen Davis, Ken Tilley, and Billy Kozma. Photo by L. Segre.*

A team of 10 ITS developers, documentation experts, and quality assurance personnel worked over a period of just five months to develop the RFCP. The solution was designed to be cost efficient, modular and scalable, combining commercial off-the-shelf hardware and software into an advanced web-based architecture that ensures scalability for future growth and will aid in modernizing existing ITS software products.

Licensees upload an electronic form with the applicable system parameters and any relevant attachments to initiate a coordination request. The database performs verification checks on the form data and manages the request, sending notifications to the appropriate parties and tracking response due dates and completion. After certification, the RFCP portal will be available seven days a week, 24 hours a day at https://rfcp.ntia.doc.gov.

The launch of this streamlined method for coordinating spectrum sharing between federal and non-federal users in this highly desirable band represents a significant advance towards facilitating expanded commercial use of the spectrum while ensuring federal agencies continue to have access to the airwaves they need to perform critical functions.

*For more information contact Kristen Davis, (303) 497-4619, kdavis@its.bldrdoc.gov*

1. Amendment of the Commission's Rules with Regard to Commercial Operations in the 1695-1710 MHz, 1755- 1780 MHz, and 2155-2180 MHz Bands, GN Docket No. 13-185, Report and Order, 29 FCC Rcd 4610 (2014). Accessed https://transition.fcc.gov/Daily_Releases/Daily_Business/2014/db0401/FCC-14-31A1.pdf December 8, 2015.

# Investigating Interference Into Satellite Transmissions

## Objectives

- *Identify and resolve intermittent interference into environmental satellite transmissions*
- *Design and deploy a standalone interference monitoring system*

## Problem

NOAA's National Environmental Satellite, Data, and Information Service (NOAA/NESDIS) is dedicated to providing timely access to global environmental data from satellites and other sources to promote, protect and enhance the Nation's economy, security, environment, and quality of life. The NOAA/NESDIS Command and Data Acquisition Station (CDAS) located at Wallops Island, Virginia, is responsible for ensuring scheduled data flow from NOAA satellites to designated user subsystems. CDAS executes spacecraft commands and schedules and acquires, maintains, and distributes a continuous flow of meteorological satellite data. In the summer of 2015, ITS was contacted by NOAA/NESDIS about an intermittent interference problem affecting the Wallops CDAS that led to disruptions in the scheduled data flow from NOAA satellites to users.

## Interference Analysis

ITS researchers travelled to Wallops Island and used a suitcase-sized portable system to perform a detailed set of measurements to characterize the interfering signals. They found that the interference was caused by broadband digital video transmissions from one or more towers within the geographic region. The broadband video emission was located in a band adjacent to the 1675 to 1710 MHz meteorological bands, but unwanted out-of-band emissions were falling into the meteorological bands, causing disruptions to the data flow. Interestingly, the closest of these towers is nearly 100 miles from the CDAS facility. Under normal circumstances, these towers would not interfere with CDAS operations. However, atmospheric ducting in the area is a known phenomenon, especially during the spring and fall seasons. Ducting occurs when there are rapid changes in atmospheric temperature or humidity. Radio waves are bent by atmospheric refraction and their mode of propagation changes. Radio signals that enter the duct are guided or ducted, tend to follow the curvature of the Earth, and experience less attenuation in the ducts than they would if the ducts were not present. That is, they travel farther.

## Moving Towards Mitigation

ITS engineers quickly designed and deployed a monitoring system, continuously sweeping across 1650 to 1750 MHz for six weeks. The system was completely standalone and used an omnidirectional monitoring antenna. The ITS monitoring system was designed to have greater sensitivity to the interference than did the CDAS systems. Consequently, the ITS system was able to "see" the interference starting to increase via the duct before the CDAS systems were affected. CDAS engineers used

*ITS engineer Frank Sanders installs a monitoring antenna at the NOAA/NESDIS CDAS. Photo by David Franc.*

the system to receive independent confirmation of an ongoing ducting event causing interference. Over the six week measurement period, two ducting events were captured. ITS engineers plan to redeploy the same monitoring system for a similar duration in spring 2016. In parallel to the ITS effort, NOAA/NESDIS is also working with the operator of the broadband digital video towers to develop and implement protection strategies for the Wallops Island CDAS facility in the future.

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# EMC Analysis for Sharing in Transportation Safety Bands

## Objective

- *Determine if Unlicensed National Information Infrastructure (U-NII) devices can share spectrum with the Intelligent Transportation System communication services in the 5850–5925 MHz band*

## The Incumbent

The dedicated short range communication (DSRC) system is a short to medium range intelligent transportation system communication service that supports both public safety and private operations in vehicle-to-vehicle and vehicle-to-infrastructure communication modes on the Nation's roads and highways. In 1999, the FCC allocated spectrum at 5850–5925 MHz (also known as the U-NII-4 band) for DSRC systems intended to improve roadway safety.

## Potential Entrants

The Middle Class Tax Relief and Job Creation Act of 2012 called for the FCC to modify its rules to allow more unlicensed use by U-NII devices in specific segments of the 5 GHz band, as codified in 47 U.S.C. §1453 (b) (1). The act also directed NTIA to conduct a study to evaluate the risks of allowing these devices to operate in the 5850–5925 MHz band. NTIA's January 2013 evaluation of spectrum sharing challenges in this band cautioned that U-NII regulations in effect at that time had no technical requirements for protection of the type of transmitters and receivers used by DSRC systems.[1] In March 2014, eleven months after publishing its first Notice of Proposed Rulemaking on this topic,[2] the FCC issued new rules for use of the U-NII-1 (5150–5250 MHz), U-NII-2 (5250–5725 MHz), and U-NII-3 (5725–5850 MHz) bands.[3] In issuing the new rules, the FCC cited the NTIA study and pointed out that it was specifically not proposing any changes in the use of the 5850-5925 MHz band pending additional technical analysis.

## EMC Analysis

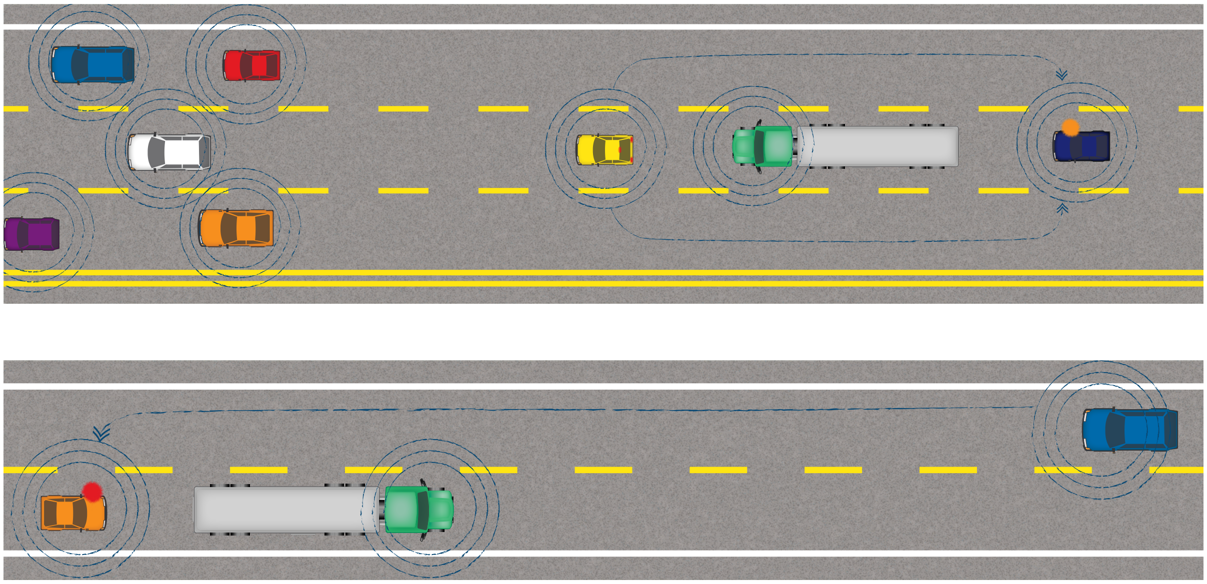
The Federal Highway Administration (FHWA) asked ITS to perform an EMC analysis to determine if U-NII devices can share the 5850–5925 MHz spectrum without causing harmful interference to the DSRC devices that are the primary users of the band. The goal of the effort was to ensure that systems developed for use in this band are compatible with each other and the environment in which they are used, and that sufficient spectrum is available for new DSRC systems. Determination of the required parameters for an EMC analysis of both the DSRC and the other systems in the environment was necessary in order to evaluate

1. Department of Commerce, "Evaluation of the 5350-5470 MHz and 5850-5925 MHz Bands Pursuant to Section 6406(b) of the Middle Class Tax Relief and Job Creation Act of 2012," available at http://www.ntia.doc.gov/files/ntia/publications/ntia_5_ghz_report_01-25-2013.pdf

2. Federal Communications Commission, "Revision of Part 15 of the Commission's Rules to Permit Unlicensed National Information Infrastructure (U-NII) Devices in the 5 GHz Band," Notice of Proposed Rulemaking, ET Docket No. 13-49, FCC 13-22, 78 Fed. Reg. 21320 (2013) (to be codified at 47 C.F.R. 15) (proposed Apr. 10, 2013).

3. Revision of Part 15 of the Commission's Rules to Permit Unlicensed National Information Infrastructure (U-NII) Devices in the 5 GHz Band, ET Docket No. 13-49, First Report and Order (R&O), 29 FCC Rcd 4127, 79 Fed. Reg. 24569 (2014). Accessed https://www.fcc.gov/document/5-ghz-u-nii-ro July 17, 2015.

Intelligent Transportation System Dedicated Short Range Communication Safety Use Cases



*Two vehicle-to-vehicle DSRC safety use case scenarios considered in this analysis. The top schematic illustrates the Emergency Electronic Brake Lights application of DSRC. The car ahead of the trailer truck brakes at a high deceleration rate to avoid hitting the traffic jam ahead. Its DSRC unit senses the brake lights and sends a signal to the car behind the trailer truck to inform this car within 100 milliseconds of the rapid deceleration and before the trailer truck brakes. This gives the trailing car more time to react before the trailer truck brakes. The lower schematic illustrates the Do No Pass Warning application of DSRC. If there is insufficient distance to pass safely, when the driver in the car behind the trailer truck switches the turn signal on to enter the oncoming lane a warning is triggered that there is a car in the oncoming lane and it is not safe to pass.*

sharing strategies. ITS performed an analysis, collected live test data for comparison to analysis predictions, then updated and validated the analysis with live data.

As a first step in technical analysis, ITS conducted a survey of potential interference sources operating in and adjacent to the 5850–5925 MHz band. Wi-Fi devices that use the 802.11ac wireless network standard were selected to represent typical parameters and characteristics of the type of U-NII devices that would be operating in that band if it were opened for unlicensed use. The 802.11ac standard was approved in January 2014 to support high-throughput wireless local area networks (WLANs) in the 5 GHz band.

For the transmitter or interference source, key parameters include: operating frequency, transmitter power, transmitter emission bandwidth with roll-off of the emission spectra at the band edges, antenna gain and patterns, feed losses, and modulation. For the receiver or victim, these parameters include: operating frequency, sensitivity, modulation, bandwidth with sufficient information to characterize rejection outside of the receiver bandwidth, antenna gain and patterns, and interference to desired signal ratio for desired victim receiver performance. The particular parameters to monitor to determine DSRC interference include the received signal strength indicator (RSSI) and the packet error rate (PER) outputs of the DSRC. As required, devices were bench tested to determine the parameters necessary for an EMC analysis, which would include in-band and out-of-band responses to frequency scanned signals. A representative model was selected for each device.

Performing a complete EMC analysis involves identifying existing and future scenarios of the communication systems in the target environment. ITS incorporated input from the FHWA, the auto industry, and the organizations involved in the development of the 802.11ac standard in order to apply the analysis models appropriately. The test scenarios contained geometries representative of worst case situations that would occur in a real environment that included interference from U-NII 802.11ac devices to the DSRC devices. Also included for the second phase of this effort was the reverse situation, where interference to U-NII devices from DSRC devices was considered.

RF propagation modeling for both DSRC and U-NII devices in the roadway environment required specialized models due to the ultra-short distances and very low antenna heights of both the DSRC and the U-NII devices. Other parameters it was necessary to identify included antennas, indoor versus outdoor use, antenna heights, separation distances, and propagation through various building materials and foliage. Separation distances include those between the transmitters and desired receivers and between the interference sources and the desired receivers.

Three models were determined to be suitable to address this range of antenna heights and separation distances required: the NTIA/ITS developed Undisturbed-Field Model, the NTIA/ITS developed Undisturbed-Field Empirically-Derived ITS-UFED Model, and the ITU-R model described in Recommendation ITU-R P.1411. All of these were verified and validated with measured data. ITS identified the appropriate interference, analysis, and antenna models based on the scenarios used in conjunction with those three propagation models to determine frequency dependent rejection, assess interference potential, and determine protection distances.

The results from the analysis models were compared to data from tests using scenarios determined by FHWA and ITS. This thorough communications and EMC analysis of the test data identified whether it was necessary to modify the input parameters of the systems or re-evaluate the initial assumptions; the analysis was rerun as necessary until the model output matched the live test data. This iterative process verified the analysis procedure and provided confidence that the approach yields realistic and reliable results. With this confidence, the analysis results can be applied to other scenarios that may not be verified with actual testing due to time constraints. This approach allows researchers to extrapolate and assess many more potential interference interactions than would otherwise be possible.

Work in FY 2014 and FY 2015 focused on developing the methodology, performing the EMC analysis, and validating the models that can be applied to assess potential interference from into U-NII devices into DSRC devices. In FY 2016, the analysis will examine potential interference from DSRC devices into U-NII devices.

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# Simulating Spectrum Utilization Scenarios

## Objectives

- *Develop realistic and reliable computer simulations to predict the interference power an LTE or radar receiver can tolerate*
- *Develop realistic and reliable computer simulations to predict aggregate interference power emitted by multiple simultaneous users of LTE devices*

## Problem

In today's accelerated spectrum management process, policy-makers and researchers alike are increasingly dependent on computer simulation of spectrum sharing scenarios that involve equipment that has not yet been manufactured or has never previously operated in the same or adjacent bands, networks that have not yet been built out, or too many cases to measure in a timely manner. Potential spectrum utilization scenarios of great interest today include placing broadband radio services (BRS) such as LTE in bands adjacent to bands occupied by federal radars or moving federal radars into bands already occupied by other radars. For all the reasons cited above, few or no field measurements have been taken that can be used to predict potential interference in these new scenarios. ITS is addressing this problem by developing computer simulation methods for predicting the interference power an LTE or radar receiver can tolerate (i.e., the IPC) and the probability that the aggregate LTE interference power will exceed it.

## Interference Protection Criteria Simulation

Radar receiver IPC measurements consist of setting the radar to an interference-free baseline state and measuring the degradation in the probability of detection by visually counting test targets on the radar display as interference power is increased. Typically, these measurements are accomplished by counting the detections made by a human radar operator—a time-consuming process that limits the number and range of experiments. In FY 2014 ITS created its first radar IPC simulation model. The model was superior to measurements that relied on human operators in that it allowed engineers to:

- Accurately estimate performance degradation by replacing subjective visual target counting with objective detected signal analysis.
- Accurately estimate the probability of false alarm so that the baseline state is definitively established. Previous IPC measurements were not able to determine the probability of false alarm.
- Access subsystem signals so that the effect of interference on the radar system can be studied.
- Emulate radar cross section fluctuation. Previous IPC measurements were not able to determine probability of detection with fluctuating radar cross section within a reasonable amount of time because of the large number of trials needed.

In FY 2015 ITS focused on increasing accuracy by refining the model and methods to minimize differences between measurement and simulation. The refined model includes signal processing paths for independent processing of estimates of the (1) signal, (2) noise, (3) interference, (4) composite noise and interference leading to an estimate of probability of false alarm, and (5) composite signal, noise, and interference leading to an estimate of probability of detection. This architecture allows engineers to precisely determine signal, noise, and interference powers and thus to accurately specify all IPC parameters.

Considerable effort was devoted toward more efficiently estimating probability of false alarm and devising a method for accurately emulating the constant false alarm rate (CFAR) function. Radars use this algorithm to detect target returns against a background of interference, clutter, and noise. ITS developed a Monte Carlo method for determining the optimum loss and delay to most accurately emulate the radar CFAR function. Figure 1 shows typical baseline CFAR behavior with 30 reference cells.

Significant progress was also made in establishing models and methods for determining LTE equipment IPC. Similar to our approach with the ATC radar, we are planning on refining these models and methods by comparing their results to previous IPC field measurements. A significant amount of time was spent studying the function of various LTE parameters and creating a spreadsheet of LTE equipment parameters that we can distribute to manufacturers to verify that simulated and field measurement parameters are set to the same values.

## Aggregate Interference Power

Future BRS system base stations are expected to densely blanket metropolitan areas. With as many as 18 simultaneous users per base station, there is some concern that the combined or aggregate power emitted by their equipment will be debilitating to other systems that operate at or near the BRS frequencies. In some spectrum utilization scenarios, the victim receiver may be a federal communications or radar device.

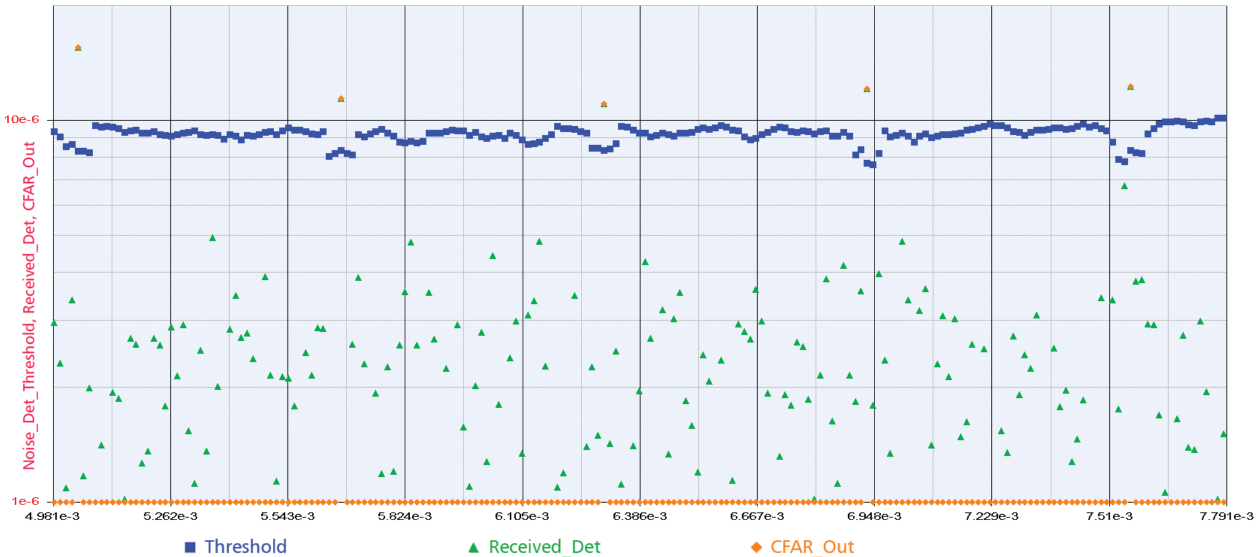



*Figure 1. Screen shot showing received signal (green), threshold signal (blue), and CFAR output (gold) over several pulse repetition intervals in baseline state. The threshold dips when the test cell contains the target allowing the signal to pass through the CFAR block and be detected. The dip is extended in time by the guard cells surrounding the test cells.*

In FY 2014 ITS began developing an aggregate interference model to predict the distribution of mean aggregate LTE power present at a victim receiver. These results are useful for establishing geographic zones which exclude BRS base stations and corresponding user equipment (UE) to protect incumbent radars. The initial model placed base stations at the center of hexagons that tessellated a model metropolitan area and determined UE power with omnidirectional antennas, free-space loss, and noise-limited uplinks.

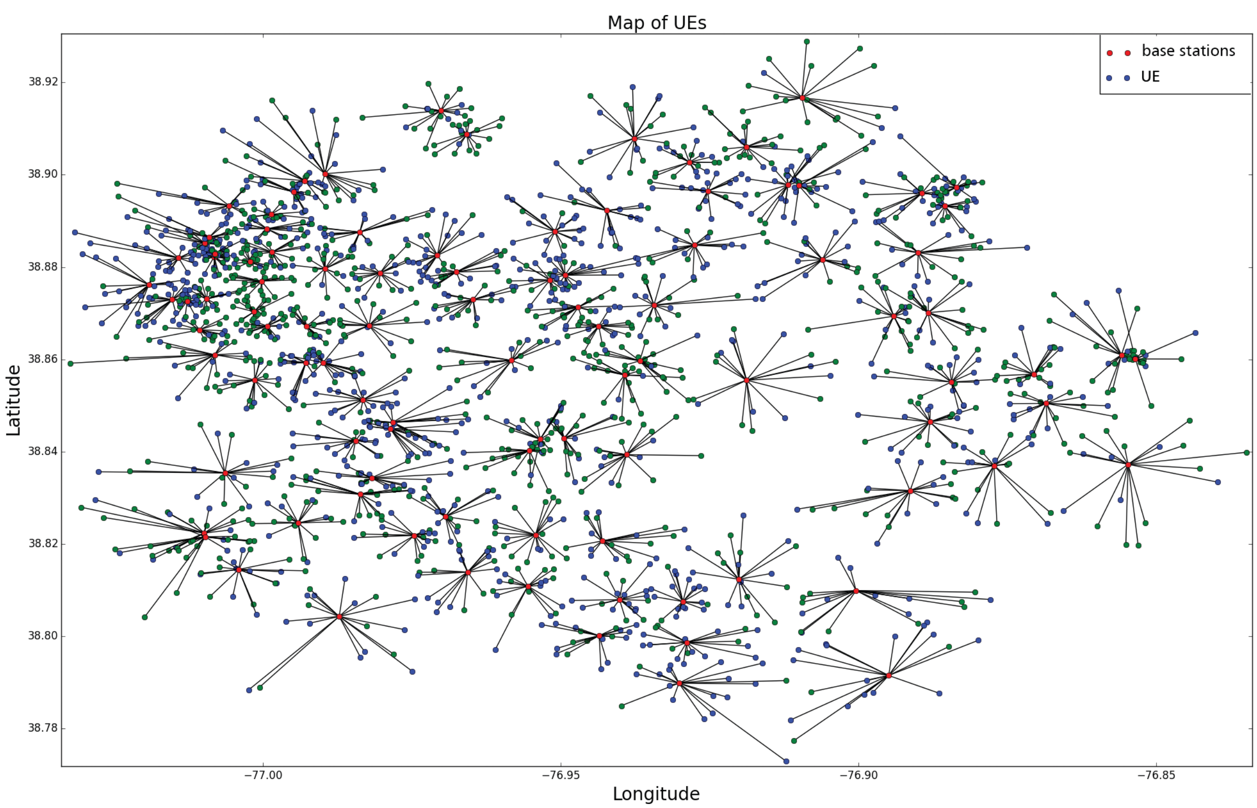



*Figure 2. Realistic mapping of UE pairing to base stations.*

In FY 2015 each of these approximations was made more realistic by using real base station locations and determining UE power with directional base station antenna patterns, ITM propagation loss, and self-interference limited uplinks. In the absence of tessellated coverage areas, considerable effort was needed to find an efficient method for pairing UEs to base stations. An example of this pairing is shown in Figure 2.

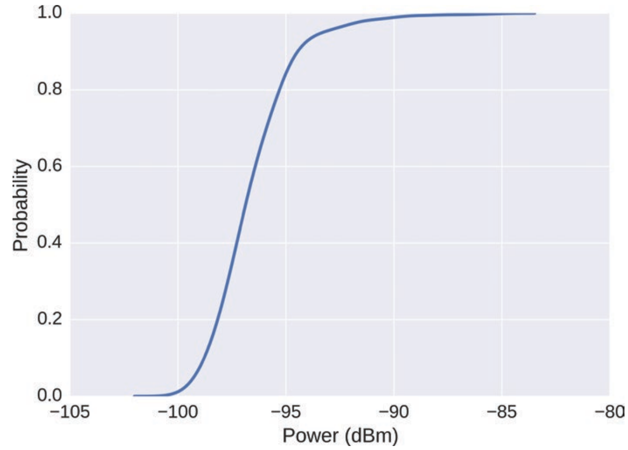



*Figure 3. Simulated CDF of aggregate UE power to a terrestrial receiver with a directional antenna.*

Figure 3 shows the cumulative distribution function (CDF) of aggregate UE power a terrestrial victim receiver with a directional antenna might experience. The CDF was created with 500 Monte Carlo trials. CDFs such as this one provide essential information for policy makers who are tasked with reviewing proposed base station locations or "layouts." This CDF tells the policy maker that if the victim receiver IPC is -95 dBm, the aggregate power will be less than the IPC 80% of the time but will exceed it 20% of the time. The location of base stations may have to be modified if these percentages impact the federal communication or radar system's mission.

While significant progress has been made on the aggregate model, we are planning to refine the model even more in FY 2016 by incorporating the effects of more realistic UE power random processes based on measured data and theoretical traffic, scheduling, and loading considerations.

*For more information contact Robert J. Achatz, (303) 497 3498, rachatz@its.bldrdoc.gov.*

# Web-based Propagation Analysis Services

Government operations, including those for public safety and national security, depend critically on the ability to successfully predict radio propagation in a variety of environments and conditions. Different propagation models are used to predict radio link behavior at different frequencies, antenna heights, antenna characteristics, and distances. The accuracy of a propagation prediction depends not only on the reliability of the model itself, but also on the suitability of the model for use in the particular case. ITS propagation modeling software has been programmed to include the capacity to perform propagation analysis using many different propagation models.

Advanced propagation prediction models that can successfully integrate geographic data and display coverage predictions are important tools for accurately predicting the performance of communication systems. Ideally, these models should be easy for non-specialists to access and use for operational and financial planning purposes. They should also be detailed and accurate enough for specialists to use in deployment.

Previous propagation modeling programs that ITS made available for government users required a concrete understanding of radio propagation and prediction concepts. More recently, many of these models have been ported to new programs that operate in a Windows® environment and integrate with the proprietary Esri™ geographic information system (GIS) program most commonly used by our sponsor agencies. This implementation required users to have licensed commercial software installed and some expertise in the use of that software, but was significantly easier to use. ITS now disseminates software applications that reduce dependency on licensed software applications, allowing end users to access the models through a web interface. Designing a web-based tool is consistent with the Federal Digital Government goals of making existing high-value data and content available through web APIs and using a shared platform approach to developing and delivering digital services to lower costs and reduce duplication.

## Propagation Modeling Website

### Objectives

- *Allow users to perform propagation prediction studies for High Frequency (HF) and Very High Frequency (VHF) applications using custom-tailored Propagation Modeling Website (PMW) software through a browser interface*
- *Enable compositing thousands of analyses to predict regional wireless network coverage for system planning and interference detection for national security and public safety*

### Overview

Accurate RF propagation modeling is an essential component of wireless communications planning, and accurate geographic information is a critical input for accurate modeling. To assist other agencies in the design of effective wireless systems, ITS has developed a web site with propagation modeling tools that use commercial GIS to both acquire geographic data and display geographic coverage areas. The Propagation Modeling Website (PMW) is a web-based GIS RF propagation modeling tool, customized to meet the propagation prediction needs of the Department of Defense (DoD) and National Weather Service (NWS) sponsors. PMW is presently available only to federal government agencies. The PMW covers radio frequencies from 1 MHz to 20 GHz.

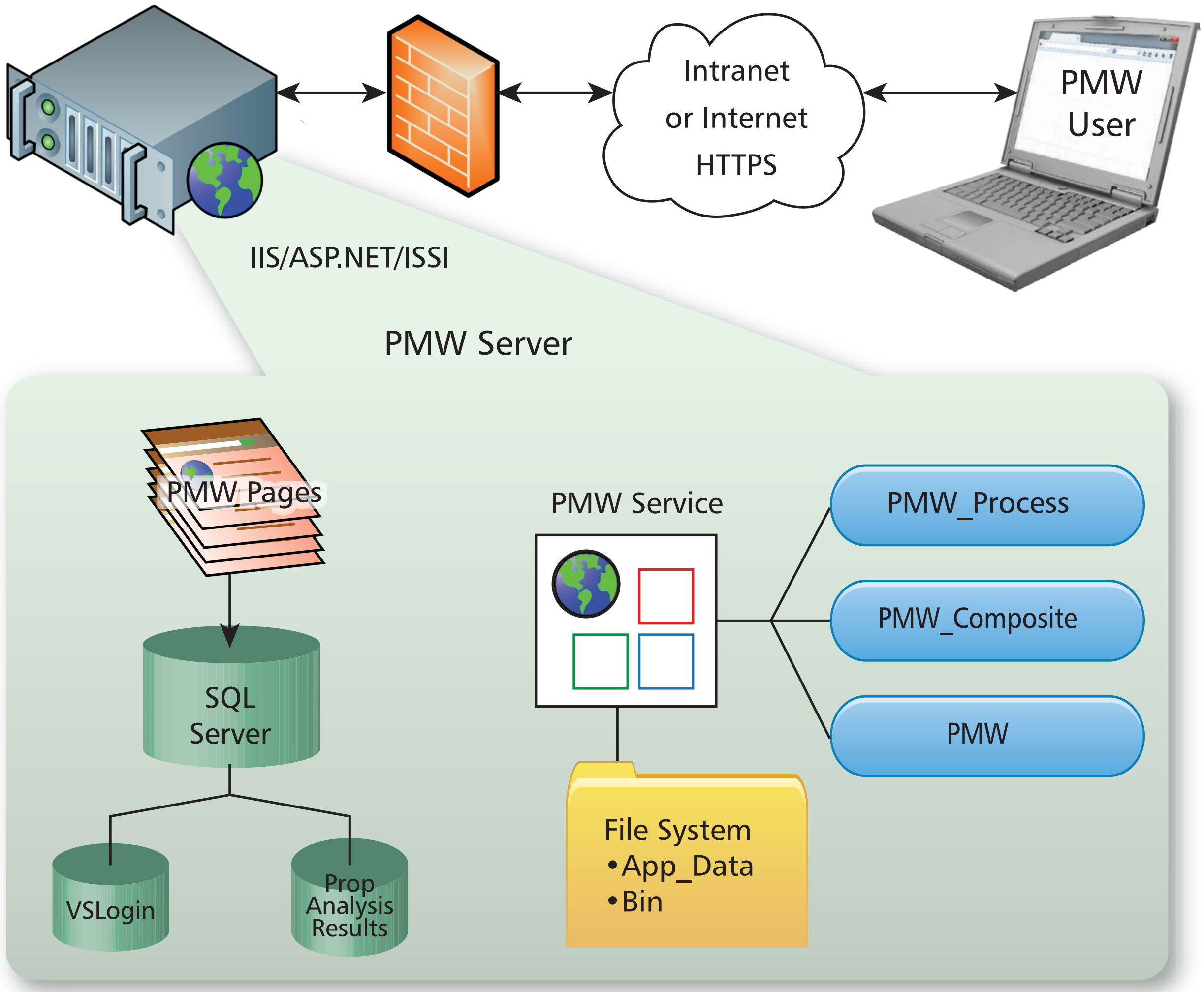
The PMW project builds on over 50 years of ITS expertise in evaluating and analyzing RF propagation models. Over the last seven years, ITS has been developing the newest generation of propagation prediction tools, the PMW web-based GIS solutions. The PMW provides intranet users with access to propagation models, a central imagery/data storage facility, and a central database location to store all propagation analyses, using just one set of licensed software, as illustrated in the diagram of the PMW architecture. The system enjoys streamlined maintenance, operation, and upgrades for ease of deployment, and ITS has a support system in place to deliver end-user help, upgrades, and enhancements.

In FY 2015, many enhancements were made to the software that might not be readily apparent to end users. The underlying analysis code was substantially rewritten to simplify and unify many of the common processes that the models rely on, so that integration of additional models will be simpler and faster. In addition, the database containing default values was replaced by a series of easy to edit .xml files. This allows a casual user to configure their own defaults without having to write database queries. The build and deployment processes were also streamlined, allowing ITS to take a more agile approach to software development.

PMW software development and maintenance is sponsored by various DoD agencies and the NWS.

### PMW Capabilities

PMW presently includes the capacity to perform RF propagation analysis using any of the following propagation models: TIREM 3.15; Longley-Rice 1.22; COST 231 Extended Okumura-Hata; Undisturbed Field/Mobile-to-Mobile; ICEPAC; low frequency/medium frequency (LF/MF), ICEWave, and ITURHFProp. The last three are new additions to the PMW modeling suite. In FY 2015, work also began on improving the range of features implemented from the LF/MF model, as well as adding the ITU P.2001 model (also called the Wide Band Propagation Model). Users can simultaneously run a batch of transmitters, specified in an Excel® transmitter file. Propagation analyses, using all nine of the currently available models, can be performed in either single or batch mode.




*The PMW architecture enables web-based access to a suite of RF propagation models and analysis tools.*

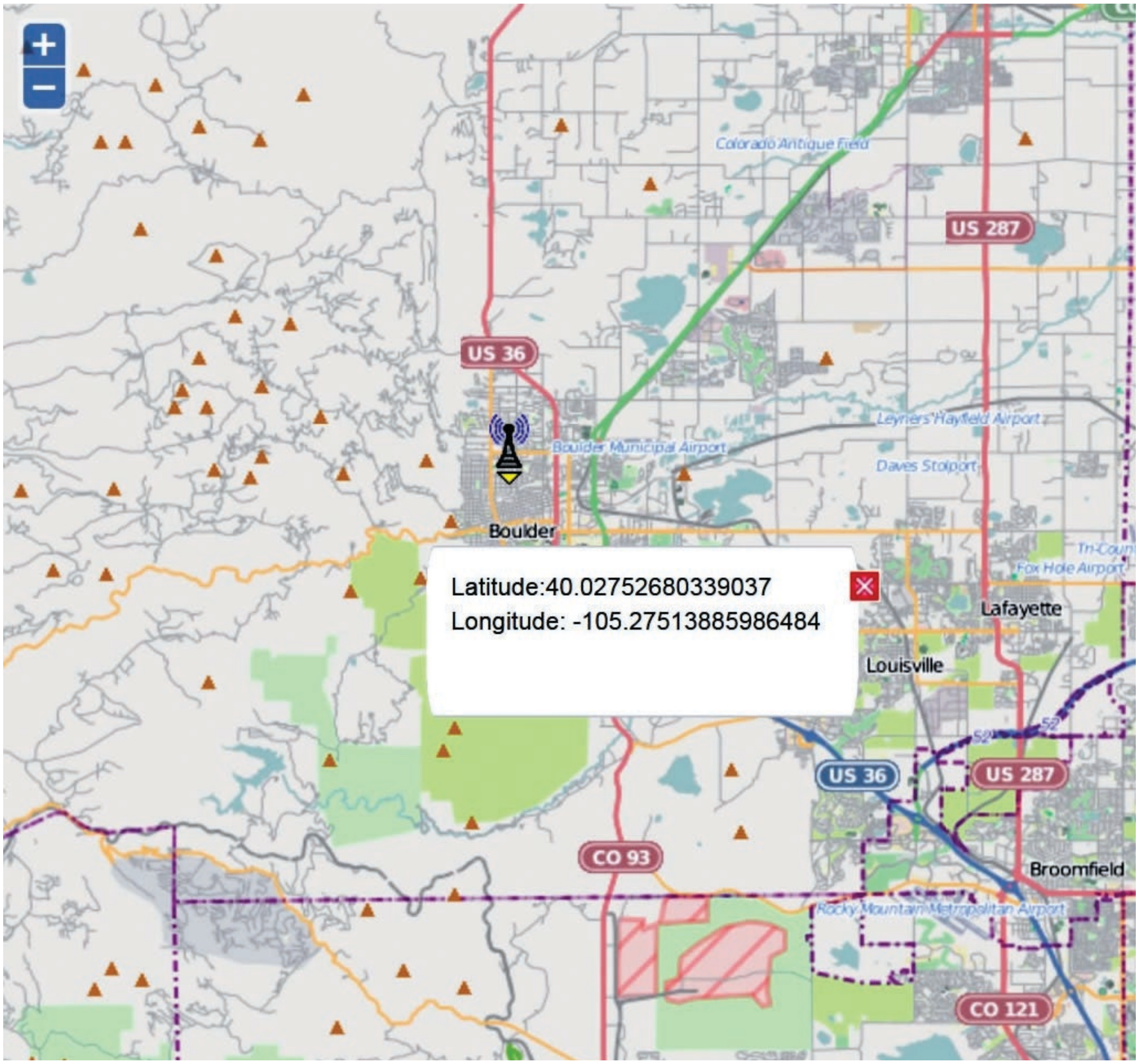
In single analysis mode, users can geographically select a transmitter from an embedded interactive map display. In batch mode, users can load an Excel® transmitter file and plot the desired transmitters on the map prior to running the analysis. This functionality was developed using open source products OpenStreetMap© and OpenLayers©. The PMW is delivered with five default zoom levels for the map. On request, it can be shipped with additional zoom levels, up to 14; the finest zoom level scales to 76 meters per pixel. Local installation of the PMW along with the geographic data and the server software is possible for users that cannot access the service over the Internet.

Users can export analyses for use with Esri's ArcGIS® Desktop application or any other GIS application that accepts PMW's various output formats. Because the PMW is modular in design, ITS engineers can enhance the PMW software to incorporate the specific needs of different sponsors.

The PMW incorporates a parallel-processed design for enhanced speed in running analyses. Depending on the user's hardware capabilities, the software can use parallel processing to decrease propagation analysis time proportionally to the number of computer cores. The PMW also provides the ability to create analysis composites for thousands of transmitters and export data analyses to Google Earth® (KML/KMZ).

To run an analysis with TIREM, Longley-Rice, ITURHFProp, IceWave, and ICEPAC models, users can choose from antenna pattern data included with the software or upload their own files to the site. TIREM and Longley-Rice models use SRTM1, SRTM2, DTED1, DTED2, GLOBE, or user-selected terrain files.

Over the next several years, as the PMW continues to mature, current and future sponsors may choose several software enhancements, including interference studies, the ability to plot completed analyses in




*Web map zoomed to level 12.*

the web map, additional input parameters like signal-to-noise ratio (SNR), composites for sectors of a cell tower, new terrain formats (HRTe, LiDAR, IFSAR, etc.), path profile, output reports, point-to-point propagation model mode, and other propagation models (IF-77, JEM, P.2001, and updated LF/MF and HF models).

The PMW currently operates on the sponsors' internal, secure networks or on a secure site hosted by ITS, allowing only the sponsors to have access to their data. Due to the large selection of GIS databases available, customers can choose to include terrain, satellite and aircraft imagery, ground transportation infrastructure, building data, and population distribution. By developing PMW, ITS helps Government agencies to efficiently manage their telecommunications infrastructure through sound system planning and interference detection for national security and public safety.

*For more information on the locally-hosted PMW contact George Engelbrecht, (303) 497-4417, gengelbrecht@its.bldrdoc.gov. For more information on the NWS PMW contact Mike Chang, (303) 497-4220, mchang@its.bldrdoc.gov.*

# Public Safety Communications Interoperability

The Government's interest in ensuring the availability of wireless communications for the safety of the public has been acknowledged since the earliest days of the 20th century. The first two-way wireless telegraphy transmission across the Atlantic took place in 1906; three years later, a liner involved in a collision off Nantucket Island sent the first wireless distress call, leading to the rescue of over a thousand people. After the sinking of the Titanic, when distress calls went unanswered for four hours because the closest radio operators were off-shift, the Wireless Ship Act of 1912 required that all large ships have 24 hour radio communication capability. That Act also delegated to the Department of Commerce the authority to enforce wireless communications laws, treaties, and conventions, and to regulate radio communications by issuing licenses to operate in order to prevent or minimize interference.

Since that time, the radio laboratories of the DoC have worked hand in hand with other government agencies at all levels to improve communications for public safety, national security, and emergency preparedness—from radio signaling for military operations in World War I to the first radio beacons for airway safety in the 1920s to World War II and the birth of radar to the advent of digital radio in the 1970s and 1980s to present-day nascent public safety broadband technologies. One hundred years after the Wireless Ship Act, Congress created the First Responder Network Authority (FirstNet) with a mandate to establish a nationwide, interoperable public safety broadband network, and allocated to FirstNet the spectrum in which to do so.[1]

ITS has worked with the NIST Communications Technology Laboratory (NIST/CTL) and its predecessors for decades to conduct research and contribute to standardization efforts to assist fire, emergency medical, national security, emergency preparedness, and law enforcement agencies to select and procure communications equipment that meets their needs. Since FY 2003, this work has been carried out through the Public Safety Communications Research (PSCR) program (www.pscr.gov), a joint effort that leverages the capabilities of NIST/CTL and ITS through collaborative research projects. PSCR is one of the largest sponsored programs at the Institute, with support from the Department of Homeland Security (DHS) Office for Interoperability and Compatibility (OIC), the DHS Office for Emergency Communications (OEC), and FirstNet.

PSCR

PSCR conducts broad-based technical efforts aimed at facilitating communications interoperability and information sharing within and among the various public safety communities. These wireless broadband users have unique needs compared to commercial wireless customers. Commercial wireless broadband networks are primarily constrained by capacity—the need to serve a relatively well concentrated population of customers using cellular base stations with a finite user capacity. Public safety networks, by contrast, typically serve a small number of highly mobile users but must provide service anywhere—incidents are obviously not constrained to occur only within areas of high population density—so expanding coverage is often more critical than expanding capacity. Public safety users also have unique needs with respect to quality and network management. Signal degradation that is a nuisance to a civilian user may be life-threatening in a public safety emergency. During a large-scale emergency, public safety networks must allow first responders from multiple services and jurisdictions to communicate, while giving the incident commander control over resource prioritization.

The public safety community chose LTE as the most promising technology to assure robust and efficient public safety broadband transmissions. ITS research in the PSCR program explores the ways in which both

1. Title VI—Public Safety Communications and Electromagnetic Spectrum Auctions of the Middle Class Tax Relief and Job Creation Act of 2012, enacted as Public Law 112-96 on February 22, 2012 and codified at 47 U.S.C. §1401–1473, created the First Responder Network Authority (FirstNet) and directed the FCC to grant a single license to FirstNet for the use of both the 700 MHz D block (758-763 MHz / 788-793 MHz, reallocated to public safety) and previously allocated public safety broadband spectrum.

public safety and commercial LTE networks and equipment can be optimized for public safety users. In the process, the program is developing new tools for active network testing which will be more widely applicable to inform design decisions for any high-speed wireless data system. The results of this research supports and informs the requirements gathering and standards development effort that targets inclusion of public safety requirements in commercial standards so that public safety agencies can benefit from the competitive commercial market in cost-effectively acquiring communications equipment.

In FY 2015, PSCR research focused on exploring LTE network architecture, capabilities, and relationships as applied to priority services for public safety users; testing strategies for extending LTE coverage both over large geographic areas and into buildings in urban areas; quantifying speech intelligibility of digital speech and audio coders; and continuing to promote public safety's needs in international standards bodies.

# LTE Priority for National Security/Emergency Preparedness

## Objective

- *Evaluate current commercial LTE Next Generation Network Priority Services mechanisms to ensure emerging technologies preserve robust and reliable public safety communications functions*

## Overview

The Government Emergency Telecommunications Service (GETS) and the Wireless Priority Service (WPS) programs provide public safety, national security, and emergency response users an alternative method for call completion when either a public switched telephone network or a commercial wireless network is congested and the probability of completing a normal call is reduced. WPS users dial a special access code before their destination phone number on a registered wireless device, while GETS users dial a specific access telephone number followed by their 12 digit personal identification number (PIN) and intended destination number.

Both WPS and GETS are administered by the Department of Homeland Security's Office of Emergency Communication (DHS/OEC) and implemented via contracts with the major wireline and wireless carriers. WPS is not yet implemented in LTE. Mobile network operators (MNOs) have proposed a mix of priority mechanisms to deliver the WPS functionality that emergency users of 2G and 3G wireless have come to rely on. DHS/OEC has asked ITS to explore the technical parameters of the next generation (4G or LTE) of WPS to validate designs proposed by MNOs before they are implemented. Proprietary details of a carrier's proposed deployment are analyzed, tested, and reported to DHS/OEC. DHS/OEC uses this information to work with MNOs to obtain the best implementation possible. Later phases of this project will test implementations and provide data that can be used by DHS/OEC to release a technology roadmap for priority services to enhance these LTE emergency communications services, referred to as Next Generation Networks Priority Services (NGN-PS). In FY 2014, ITS built a PSCR NGN-PS test bed to analyze priority mechanisms as currently proposed for commercial LTE equipment. This foundational work informs a larger, multi-year project goal of providing technical advice to DHS/OEC as they roll out LTE implementations of the WPS.

## FY 2015 Research

In FY 2015, the PSCR project team performed a functional evaluation of a number of NGN-PS mechanisms by following protocol messaging through a typical LTE call flow. In the first phase of testing, NGN-PS messaging was evaluated in an entirely simulated environment. The simulated LTE network contained representations of User Equipment terminals (UEs—e.g., mobile phones), an Evolved NodeB (eNodeB—i.e.,

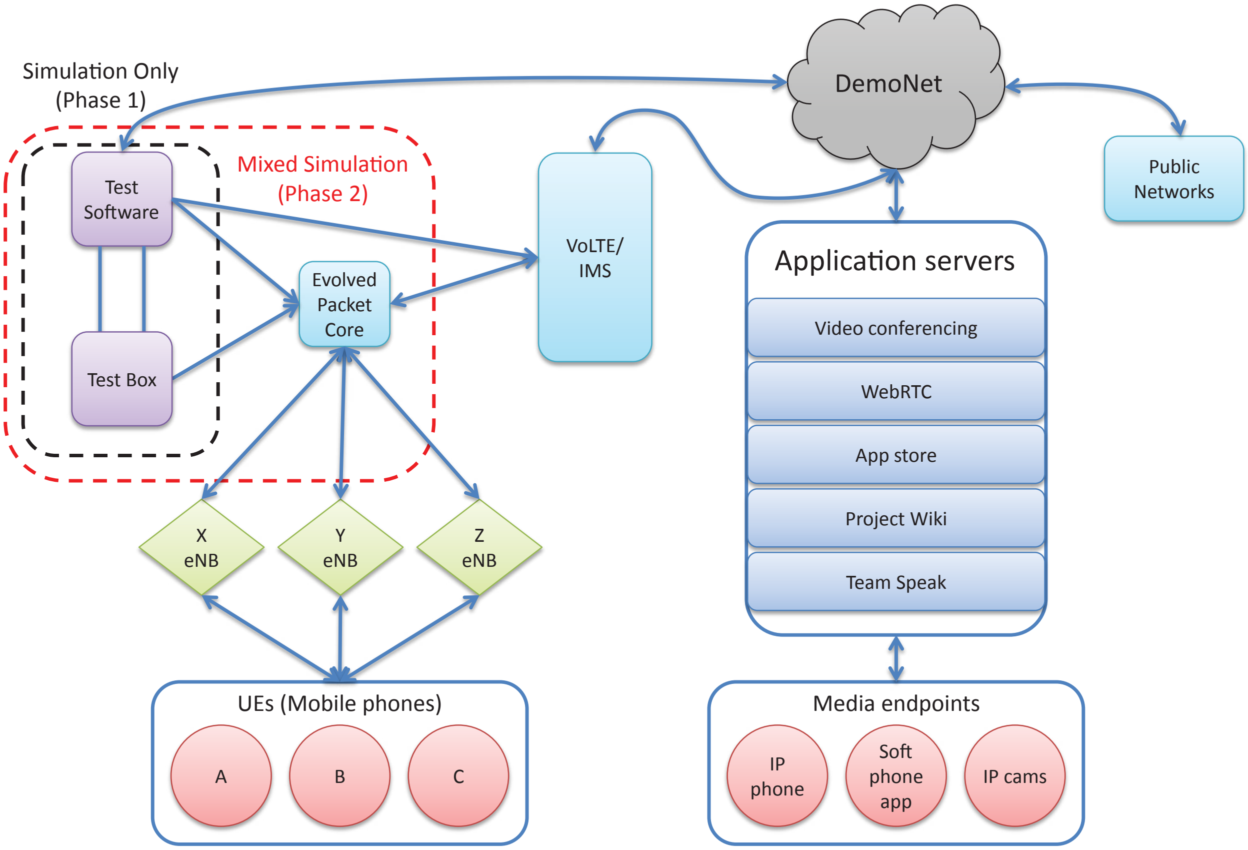



*Figure 1. Schematic of the PSCR NGN-PS test bed.*

base station), an Access Point Name (APN), and Packet Data Network (PDN). These were entirely simulated within a piece of test equipment, connected to a commercial Evolved Packet Core (EPC) and managed using a proprietary software application. In the second phase of testing, the test equipment provided traffic to and from a device under test via standardized LTE interfaces. This method can be used to test a single network element, a group of entities, or another vendor's entire EPC. The inherent flexibility in the test bed architecture allows very cost effective testing of the maximum number of scenarios and configurations to cover the majority of use cases. Figure 1 shows a graphical representation of both the test bed and testing phases of the project.

LTE attach procedure tests are derived from OEC's Government Industry Requirements (GIRs) for priority services, intended to assure that technical innovation adequately addresses the needs of the National Security/Emergency Preparedness (NS/EP) user community. The GIRs specify OEC's expectations about the number of users; the types of services (voice, video, data); the number of priority levels needed and processes for authorizing them, and performance and cost metrics. The study of NGN-PS mechanisms and interactions focuses on the end-user experience and the higher-level protocol traffic that goes with it when NS/EP users send and receive voice, video, and data. The simulated network incorporates past revisions of standards applicable to LTE as well as forward-looking features that have not yet made it into released standards. Both commercial and public safety band class eNBs and UEs are used in the test bed, and researchers have the ability to load any isolated network element found in a commercial Evolved Packet System (EPS).

## Future Work

In FY 2016, performance tests will be designed, set up, and conducted first for control plane (signaling information) testing then for user plane (user data) testing. Preparations will also begin for future research on secure voice/Commercial Solutions for Classified (CSfC).

Voice over LTE (VoLTE) is one of the most critical applications being studied. FY 2016 testing will use an IP Multimedia Subsystem (IMS) network VoLTE solution that has been acquired for the lab and will be deployed in the first quarter of FY 2016. Once this is implemented, testing on IMS VoLTE-dependent mechanisms will begin.

DHS/OEC has identified control plane testing as their top priority for the next fiscal year, with performance oriented examinations of High Priority Access, Automatic Access Class Barring, and Operational Measurements to be completed as soon as possible. Since the majority of resource decisions are performed and implemented at the control plane level, PSCR/ITS will have to have completed testing in these areas so that it can advise DHS/OEC if the MNOs' proposed solution will satisfy the GETS/WPS Government Industry Requirements documents. After the control plane testing is complete, the project will concentrate on the user plane.

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# Extended Cell Testing

## Objectives

- *Use standards-based advanced LTE features to extend the cell radius of a single sector band class 14 LTE system up to 62 miles*
- *Test and evaluate coverage and performance of extended cell and disseminate results to stakeholders*

## Overview

While FirstNet's nationwide public safety broadband network (NPSBN) is not expected to be substantially operational until 2022, some public safety organizations throughout the country are already beginning to deploy band class 14 LTE networks, working closely with FirstNet to ensure future compatibility with the NPSBN. PSCR is testing and evaluating how these networks can be best configured to support FirstNet's requirement to provide nationwide coverage. Public safety LTE operates on 10 MHz channels centered at 763 MHz on the downlink and 793 MHz on the uplink. Radio waves in this spectrum can propagate over larger geographic areas with less infrastructure than those in higher bands. To provide service to rural areas where user density is lower, a potential solution is to increase the size of each cell beyond the typical LTE cell radius of 9.6–13 km (6–8 miles). An extended cell solution can provide needed coverage in rural areas with fewer towers, reducing deployment costs.

## Extended Cell Implementation

To increase the cell radius beyond the typical range, two modifications to the eNodeB side of the link were implemented. First, the coverage area was increased by deploying the eNodeB and antenna at a greater height. Second the LTE Physical Random Access Channel (PRACH) preamble format was modified. The LTE 3GPP standards specify four preamble formats to accommodate longer round trip propagation delay in large cells. The ones of interest for extended cell are PRACH preamble format 1, which supports a cell radius of up to 77 km (48 miles), and format 3, which supports a radius up to 100 km (62 miles).

PSCR deployed a single sector band class 14 LTE system on a 305 meter (1000 foot) tower in Erie, CO, shown in Figure 1. The extended cell project consisted of two phases using different PRACH implementations, eNodeB antenna deployment heights, antenna configurations, and UE transmit power levels. Performance and coverage differences were measured to demonstrate the improvements that can be achieved.

The Phase 1 system consisted of a single sector eNodeB with a 90° azimuth (pointing directly east) and an antenna height of 85 m (280 ft). It incorporated PRACH preamble format 1 (77 km/48 mi) cell size. Measurements were performed on the downlink only and were captured with measurement software that interfaced with a Power Class 3 UE capable of +23 dBm as the test instrument. Phase 1 was completed in the fourth quarter of 2013.

Phase 2 of the project leveraged the effort from Phase 1. It also used a single sector eNodeB, but with a 5° azimuth and measurements were taken along an alternative drive test route to avoid interfering with a nearby operational band class 14 LTE network. The eNodeB antenna was deployed at 280 m (920 ft) and incorporated PRACH preamble format 3 to provide an increased coverage distance of 100 km (62 mi). Other modifications included the addition of two more receivers at the eNodeB, use of both a normal power UE (+23 dBm transmit power) and a Power Class 1 high power UE capable of +31 dBm transmit power, and the ability to log data on both the uplink and downlink. On the downlink, data was captured with measurement software that interfaced with the band class 14 UE whereas uplink data was measured separately at the eNodeB. The Phase 2 modeled coverage area and drive test route is shown in Figure 2. Phase 2 was completed in the first quarter of 2015.

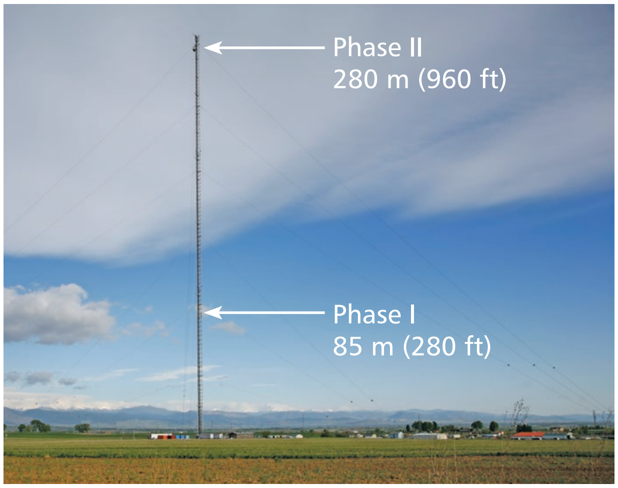



*Figure 1. Tower used for LTE extended cell testing. Photo by Ron Carey.*

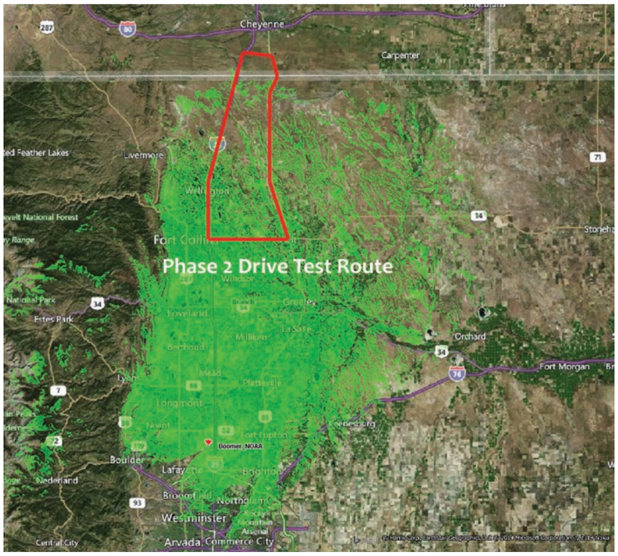



*Figure 2. Phase 2 modeled coverage area (shown in green) for RSRP ≥ -110 dBm and drive test route (red line).*

## Measurements

Measurements were conducted for both phases using an LTE UE with external antennas mounted on the roof of the measurement vehicle. Phase 1 used a directional antenna, but phase 2 achieved good results with an omni-directional roof-mounted antenna. A series of uplink and downlink throughput measurements were taken while driving and at static locations. Key testing objectives included determination of the maximum cell radius that the system is capable of operating, as well as the data throughput performance of the network at the cell edge. The LTE reference signal received power (RSRP) was a parameter used for signal strength and coverage area predictions. Propagation was predicted using modeling parameters matched to the actual system hardware and specifications, and measured data was compared to predicted cell coverage to validate the model and to compare phase 1 and phase 2 performance and cell edge performance.

Measurement results were presented at the 2014 Public Safety Broadband Stakeholder Conference, the APCO International 2014 Annual Conference and Expo, and the 2015 Public Safety Broadband Stakeholder Conference.

*For more information contact Christopher Redding, (303) 497-3104, credding@its.bldrdoc.gov*

# Public Safety Broadband In-Building Testing

## Objectives

- *Investigate in-building coverage characteristics of public safety band class 14 LTE systems*
- *Investigate ways to improve indoor performance of public safety band class 14 LTE systems*
- *Disseminate initial actionable recommendations for improving indoor performance of public safety band class 14 LTE systems*

## Background

It is essential for public safety first responders to be able to communicate within and into buildings. Building walls reduce radio signal power in complex ways, creating difficult and sometimes life-threatening wireless communication challenges. The power of a signal decreases each time it passes through a wall by an amount that depends on the frequency of the radio wave, the type of material, and the angle of incidence. Building materials may also reflect and redirect signals, while hallways and doorways may allow signals to propagate farther than expected. With the advent of broadband LTE public safety systems, it is critical to understand how to ensure reliable, high-quality in-building communications using those systems.

## Tests and Measurements

Engineers and researchers from ITS and the University of Colorado performed a comprehensive series of in-building measurements in FY 2014. The purpose of this work was to investigate both the in-building coverage characteristics of public safety band class 14 LTE systems and ways to improve indoor performance. In all the testing, a 10 MHz LTE bandwidth was used on both the downlink and uplink channels. The center frequencies of the downlink and uplink channels were 763 MHz and 793 MHz, respectively.

Two measurement campaigns were conducted on the University of Colorado Boulder campus: the first at the Discovery Learning Center (DLC) and the second at the Coors Event Center (CEC). These structures are well suited for such a study, both because of their structure and design and because they are located well within the coverage area of PSCR's over-the-air network operating in the public safety broadband spectrum. The PSCR Broadband Demonstration Network covers most of the city of Boulder, Colorado. The network was used as a baseline to study methods for improving indoor coverage.

Three approaches for coverage improvement at the DLC were investigated: (1) a cell-on-wheels (COW) placed in close proximity to a building and beaming LTE energy directly into the building, (2) a small cell feeding two discrete antennas (SCDA) placed inside a building, and (3) a small cell feeding a distributed antenna system (SCDAS) installed in the ceilings in a section of the DLC only.

Measurements were performed using a combination of a backpack-mounted system and a tablet computer shown in Figure 1. Two independent LTE data streams were collected using a combination of a vendor-supplied LTE Modem (UE) and an LTE scanner while the researcher walked through the building, modeling the path that a first responder might take in response to an incident. The data streams were, in turn, directed to a tablet computer and stored for subsequent post processing. The data obtained enabled reliable estimates of in-building coverage to be made in terms of both data and radio signal performance. Signal strength was one of several parameters measured at multiple points along the path, and it was plotted on a building plan. Figure 2 shows the LTE reference signal received power (RSRP) that was measured in the CEC stadium. With external coverage provided by the PSCR macro network, coverage was very weak, as shown by the amber and red data points plotted on the figure on the left. The figure on the right shows a significant improvement in signal levels over the same walk path when the small cell provides interior coverage.

### Related Publication:

*Robert T. Johnk, Mitchell Powell, Jaydee L. Griffith, Mark A. McFarland, Kenneth R. Baker, Prachee Daithanker, Saman Samdian, Lavanya Gopal, Sai Gavva, "In-Building LTE Testing at the University of Colorado," NTIA Technical Report TR-15-518, July 2015. Available http://www.its.bldrdoc.gov/publications/2807.aspx.*

*Figure 1. Backpack measurement system in action at the DLC.*

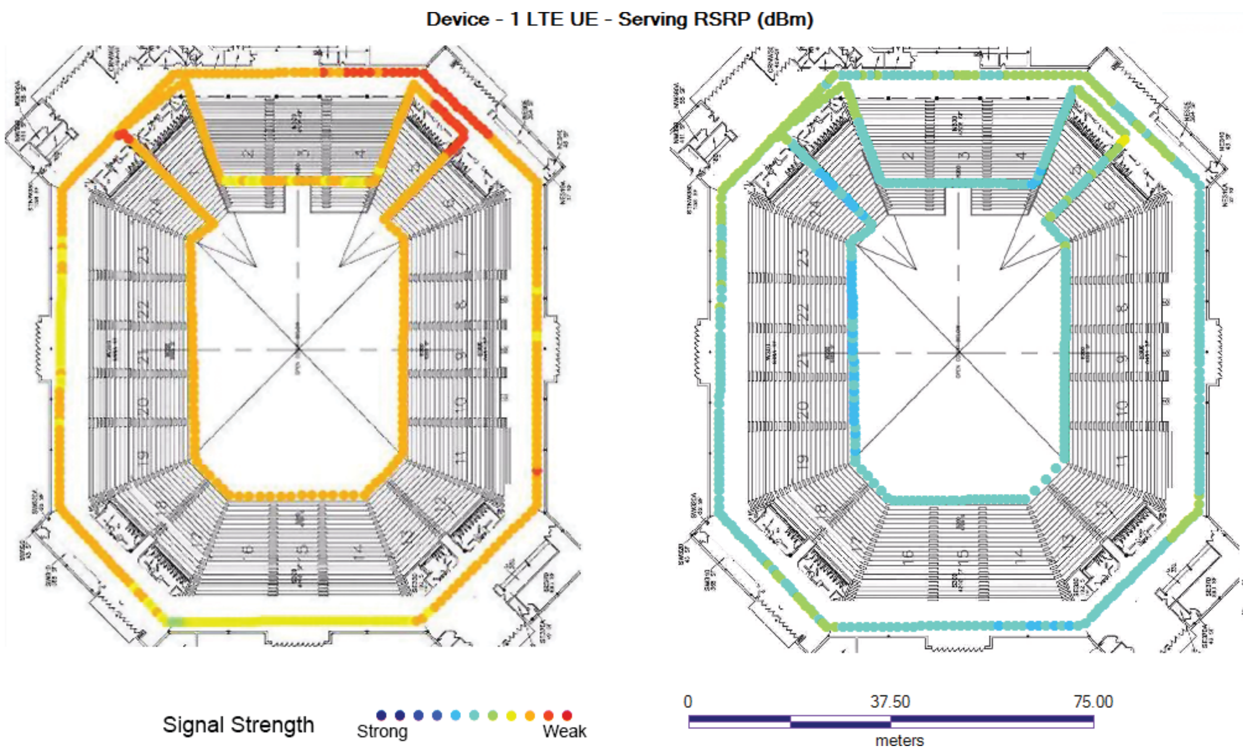



*Figure 2. At left, plot of the CEC stadium reference signal received power (RSRP) along a walk path for a downlink data flow using UDP protocol with the PSCR macro network at 40 W, where blue indicates a strong signal and red weak or no signal. At right, RSRP along the same walk path significantly improves with the addition of a small cell powered at 1 W.*

## Results

In FY 2015, the measurements were analyzed and a comprehensive summary of the work was published in an NTIA Technical Report. Test results indicated that the PSCR macro network did not provide complete coverage of either the Discovery Learning Center or the Coors Event Center. A significant improvement in indoor coverage and system performance was observed when a small cell and COW were used individually or in combination. All in all, the report highlights the fact that the macro network does not provide complete indoor coverage and that some form of in-building support is needed to achieve a high level of performance and guarantee coverage for first responders throughout a building.

This work was funded by the Department of Homeland Security's Office for Interoperability and Compatibility (OIC), which leads the DHS effort to enable interoperable emergency communications among 60,000 federal, state and local public safety agencies. Via DHS and FirstNet, all of these agencies will benefit from the recommendations produced by this research.

*For more information contact Dr. Robert Johnk, (303) 497-3737, bjohnk@its.bldrdoc.gov*

# Speech Intelligibility Testing for Mission Critical Voice

## Objective

- *Quantify speech intelligibility associated with a range of LTE-compatible digital audio coding algorithms in various acoustic noise environments.*

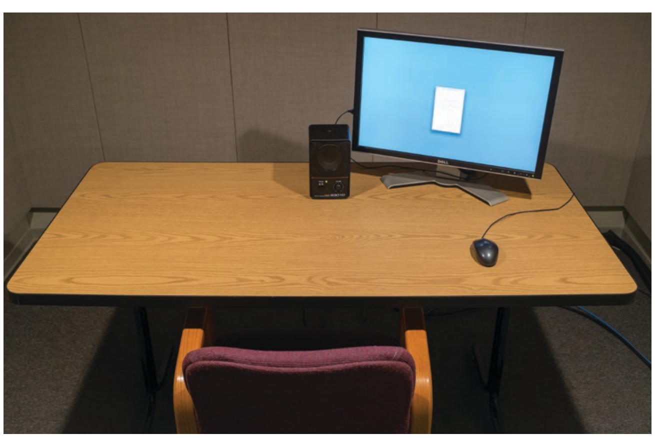
## Overview

In FY 2015 staff designed, implemented, and analyzed a detailed study of speech intelligibility for some of the various digital speech and audio codecs that can be used to provide mission-critical voice over LTE based radio networks. This study focused on the speech intelligibility produced by these codecs as a function of the acoustic noise environment. Noise is indeed a critical factor in mission-critical voice communications and preserving intelligibility when noise is at its worst (firefighting operations, sirens, alarms, etc.) can potentially be a matter of life and death.

The work was funded by DHS/OIC and motivated by high-level requirements for mission-critical voice networks for public safety that were set out by the National Public Safety Telecommunications Council.[1] A key premise of the work was that intelligibility measurements would be referenced to the time-honored standard of intelligibility set by analog FM land-mobile radio.

## Testing

In the first phase of this work, staff created speech and noise recordings. These included 54 different noise environments and 1200 different test sentences that followed the modified rhyme test (MRT) paradigm. The recordings were processed using 83 different narrowband, wideband, and fullband digital audio codec modes and by the analog FM reference as well. ITS staff then used an objective estimator of speech intelligibility to gain preliminary insights into the intelligibility of the various codec modes relative to that of analog FM. These results allowed for the design of a practically sized MRT involving six challenging yet relevant noise environments and 28 codec modes.



*Setup for speech intelligibility testing in a standards-compliant sound isolation booth in the ITS lab. Photo by A. Catellier.*

Thirty-six subjects from the public safety community participated in the MRT resulting in 432 trials for each of the 168 conditions under test (72,576 total trials.) The study was made possible through the participation of these subjects, who had an average of 19 years of experience and represented the disciplines of dispatch, fire service, law enforcement, emergency medical services, and disaster management.

1. National Public Safety Telecommunications Council, Broadband Working Group, "Mission Critical Voice Communications Requirements for Public Safety," August 2011. Accessed http://www.npstc.org/download.jsp?tableId=37&column=217&id=2055&file=Mission Critical Voice Functional Description 083011.pdf December 22, 2015.

### Results

MRT results show strong dependence on noise environments. In a quiet environment 21 codec modes matched or exceeded the intelligibility of the analog FM reference. For 19 codec modes, intelligibility ratings were no lower than analog FM in at least five of the six noise environments. This list includes three narrowband, eleven wideband, and five fullband codec modes with data rates ranging from 6.6 to 48 kbps. But when all six noise environments were considered, only six codec modes consistently produce intelligibility no lower than analog FM. The data rates for these six codec modes ranged from 16.4 to 32 kb/s. Full details are available in NTIA report 15-520, which is presently informing discussions surrounding the adoption of standards for speech coding for mission-critical voice over LTE.

**Related Publication:**

*Stephen D. Voran and Andrew A. Catellier, "Speech Codec Intelligibility Testing in Support of Mission-Critical Voice Applications for LTE," NTIA Technical Report TR-15-520, July 2015. Available http://www.its.bldrdoc.gov/publications/2811.aspx.*

*For more information contact Stephen D. Voran, (303) 497-3839, svoran@its.bldrdoc.gov*

## Public Safety Broadband Requirements and Standards

### Objectives

- *Identification of public safety broadband communications requirements*
- *Representation of the First Responder Network Authority in standards development*

### Overview

In 2010 the FCC published the National Broadband Plan, which outlines how broadband spectrum will be utilized in the future. The Plan also proposed the development and implementation of a nationwide interoperable public safety broadband communications network, and the development of "common standards for interoperability and operating procedures to be used by the public safety entities licensed to construct, operate and use this nationwide network."[1] In order to assure that the nationwide network would be interoperable across agencies, jurisdictions, and regardless of manufacturer, PSCR actively participated in the requirements gathering and standards development process on behalf of public safety. Following the creation of FirstNet, the PSCR standards team now directly represents FirstNet, and thus all public safety in the United States, in all broadband standards development. Coordinated implementation of a public safety broadband network under a single network operator—FirstNet—presents a unique opportunity for public safety to define their requirements before deployment and to potentially preemptively eliminate the interoperability problems that have plagued public safety in land mobile radio.

### Activities

PSCR has been active in the requirements gathering and standards development process for public safety broadband communications since its inception in 2003. PSCR actively participated in the Telecommunications Industry Association (TIA) standards process for land mobile radio and has long-standing relationships with many public safety organizations that focus on defining requirements for public safety communications. PSCR is uniquely positioned to represent public safety as new broadband technologies are tested in PSCR's Demonstration Network and as the nationwide network is built out.

1. Federal Communications Commission, "Connecting America: The National Broadband Plan," March 2010, p. 317. Accessed https://transition.fcc.gov/national-broadband-plan/national-broadband-plan.pdf December 22, 2015.

- PSCR led the creation of the SAFECOM Statement of Requirements in 2004, which was a spectrum and technology agnostic perspective of advanced public safety communications
- PSCR led the National Public Safety Telecommunications Council's (NPSTC) Broadband Working Group to develop a 700 MHz Broadband Statement of Requirements in 2007
- PSCR led the NPSTC Broadband Task Force Technology Working Group, which addressed interoperability issues and delivered its report and recommendations in August 2009
- PSCR led the NPSTC Broadband Working Group in the creation of the qualitative Mission Critical Voice Requirements document in 2011
- PSCR led the NPSTC Broadband Working Group in the creation of the Local Control and Priority & Quality of Service Requirements documents in 2012
- PSCR led the NPSTC Broadband Working Group in the creation and delivery of the Public Safety Launch Requirements to the FirstNet Board in 2012
- PSCR led the NPSTC Broadband Working Group in the creation and delivery of the Mission Critical Push To Talk over LTE Requirements to the FirstNet Board in 2013
- PSCR led the NPSTC Broadband Working Group in the creation and delivery of the Definition of Public Safety Grade Systems and Facilities to the FirstNet Board in 2014
- PSCR led the NPSTC Broadband Working Group in the creation and delivery of the Public Safety Console for LTE Requirements to the FirstNet Board in 2014

In its standards development efforts, PSCR also represents FirstNet as a member of the organizations that are collectively responsible for developing the standards for the LTE technology selected by public safety for 700 MHz broadband—the 3rd Generation Partnership Project (3GPP, a collaboration among six telecommunications standards bodies to produce globally-applicable cellular system specifications); the Alliance for Telecommunications Industry Solutions (ATIS, the founding North American Organizational Partner of 3GPP); the Open Mobile Alliance (OMA, a standards body which develops open standards for the mobile phone industry); and the GSM Association (GSMA, an international association of mobile operators and related companies that supports GSM mobile telephone standardization).

As a result of PSCR's involvement, public safety was identified as the top priority in 3GPP for Release 12. PSCR currently represents FirstNet in ensuring Release 12 LTE products contain two critical features for public safety: efficient group communications capabilities and direct mode capability. Additionally, PSCR is representing FirstNet in 3GPP to ensure that Release 13 LTE products have a mission critical push to talk over LTE capability, and is working with DHS/OIC for the standardization of video for public safety over LTE in Release 14.

As part of its requirements and standards work, PSCR is coordinating with public safety organizations in the United Kingdom, continental Europe, Canada, and Australia as they begin to develop public safety broadband efforts for their first responders.

## Value to Public Safety

Broadband technology presents a significant opportunity for public safety agencies to use a nationwide interoperable communications network that meets the unique needs of first responders and is deployed by a single network operator (FirstNet). There are as many as five million public safety users in the country. The newly available 700 MHz spectrum will let public safety adopt broadband technologies that support high-speed data transmission across long distances, creating access to video, mapping, GPS applications, and more. It is crucial that public safety's requirements be incorporated into standards so that federal grant dollars and taxpayer dollars are spent only on equipment that is interoperable and allows first responders to better carry out their mission of protecting lives and property.

## Principal Relevant Requirements and Standards Documents

**U.S. Department of Homeland Security Office of Emergency Communications (OEC) SAFECOM**

- SAFECOM Statement of Requirements (SoR) for Public Safety Communications Interoperability (2006–2008)

**National Public Safety Telecommunications Council.**

- NPSTC Public Safety 700 MHz Broadband Statement of Requirements (SoR) (2007)
- NPSTC Broadband Task Force Requirements
- NPSTC Mission Critical Voice Communications Requirements for Public Safety Functional Description (2011)
- NPSTC LC21 "Local Control in the Nationwide Public Safety Broadband Network," Rev. F, March 19, 2012
- NPSTC "Priority and QoS in the Nationwide Public Safety Broadband Network," Rev 1.0, April 17, 2012
- NPSTC Public Safety Broadband High-Level Launch Requirements, Statement of Requirements for FirstNet Consideration (December 7, 2012)
- NPSTC Public Safety Broadband Push-to-Talk over Long Term Evolution Requirements A NPSTC Public Safety Communications Report (July 18, 2013)

**3GPP SA1 WG**

- 3GPP TS22.278 Service requirements for the Evolved Packet System (EPS) (Release 13) V13.2.0 (2014-12)
- 3GPP TS22.115 Service aspects; Charging and billing (Release 13) V13.3.0 (2015-03)
- 3GPP TS22.468 Group Communications System Enablers for LTE (GCSE_LTE) (Release 13) V13.0.0 (2014-12)
- 3GPP TS 22.179 Mission Critical Push To Talk (MCPTT) over LTE; Stage 1 (Release 13) V13.2.0 (2015-06); V13.1.0 (2015-03); 13.0.1 (2015-01); 13.0.0 (2014-12)
- 3GPP TR 22.879 Feasibility Study on Mission Critical Video Services over LTE; (Release 14) V1.1.0 (2015-09); V0.2.0 (2015-08)
- 3GPP TR 22.880 Feasibility Study on Mission Critical Data Communications; (Release 14) V1.0.0 (2015-09); V0.2.0 (2015-08)

**3GPP SA6 WG**

- 3GPP TR 23.779 Study on application architecture to support Mission Critical Push To Talk over LTE (MCPTT) services (Release 13) V13.0.0 (2015-09); V2.0.0 (2015-09); V1.1.0 (2015-08); V1.0.0 (2015-06); V0.8.0 (2015-06); V0.7.1 (2015-05); V0.7.0 (2015-04); V0.6.0 (2015-03); V0.5.1 (2015-02); V0.5.0 (2015-02); V0.4.0 (2014-12)
- 3GPP TS 23.179 Functional architecture and information flows to support mission critical communication services; Stage 2 (Release 13) V1.1.0 (2015-10); V1.0.0 (2015-09);V0.4.0 (2015-08); V0.3.0 (2015-08); V0.2.0 (2015-07); V0.1.1 (2015-06); V0.1.0 (2015-06)

**3GPP SA2 WG**

- 3GPP TS 23.303 Proximity based services (ProSe); Stage 2 (Release 13) V13.1.1 (2015-09); V13.1.0 (2015-09); V13.0.0 (2015-06); (Release 12) V12.6.0 (2015-09); V12.5.0 (2015-06), V12.4.0 (2015-03); V12.3.0 (2014-12)
- 3GPP TS 23.468 Group Communications System Enablers for LTE (GCSE_LTE); Stage 2 (Release 13) V13.2.0 (2015-09); V13.1.0 (2015-06); V13.0.0 (2015-03); (Release 12) V12.6.0 (2015-09); V12.5.0 (2015-06); V12.4.0 (2015-03); V12.3.0 (2014-12)
- 3GPP TR 23.797 Study on architecture enhancements to support isolated Evolved Universal Terrestrial Radio Access Network (E-UTRAN) operation for public safety (Release 13) V13.0.0 (2015-06); V1.0.0 (2015-06); V0.3.0 (2015-06); V0.2.0 (2015-06); V0.1.0 (2015-02);

**3GPP SA3 WG and LI**

- 3GPP TR 33.833 Study on security issues to support Proximity Services (Release 13) V1.5.0 (2015-09); V1.4.0 (2015-05); V1.3.0 (2015-02)
- 3GPP TR 33.879 Study on Security Enhancements for Mission Critical Push To Talk (MCPTT) over LTE (Release 13) V0.3.0 (2015-09); V0.2.0 (2015-05); V0.1.0 (2015-02)
- 3GPP TR 33.897 Study on isolated E-UTRAN operation for public safety; Security aspects (Release 13) V1.0.0 (2015-09); V0.1.0 (2015-05)
- 3GPP TS 33.179 Security of Mission Critical Push To Talk over LTE (Release 13) V0.1.0 (2015-09)
- 3GPP TS 33.107 3G security; Lawful interception architecture and functions (Release 13) V13.0.0 (2015-09) (See Clause 16 and 17)
- 3GPP TS 33.106 3G security; Lawful interception requirements (Release 13) V13.1.0 (2015-09); V13.0.0 (2015-06)
- 3GPP TS 33.246 Security of Multimedia Broadcast/Multicast Service (MBMS) (Release 13) V13.0.0 (2014-12) (See Annex N)

**3GPP SA4 WG**

- 3GPP TS 26.179 Mission Critical Push To Talk; Codecs and media handling (Release 13) V0.1.0 (2015-10); V0.0.4 (2015-10); V0.0.3 (2015-10); V0.0.1 (2015-07)

**3GPP RAN 1 WG, RAN 2 WG**

- 3GPP3GPP TS 36.300 Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (Release 13) V13.1.0 (2015-09); V13.0.0 (2015-07)

- 3GPP TS 36.302 Evolved Universal Terrestrial Radio Access (E-UTRA); Services provided by the physical layer (Release 12) V12.5.0 (2015-09); V12.4.0 (2015-07); V12.3.0 (2015-03); V12.2.0 (2015-01)
- 3GPP TS 36.304 Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) procedures in idle mode (Release 12) V12.6.0 (2015-09); V12.5.0 (2015-07); V12.4.0 (2015-03); V12.3.0 (2015-01)
- 3GPP TS 36.306 Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio access capabilities (Release 12) V12.6.0 (2015-09); V12.5.0 (2015-07); V12.4.0 (2015-03); V12.3.0 (2015-01)
- 3GPP TS 36.321 Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification (Release 12) V12.7.0 (2015-09); V12.6.0 (2015-07); V12.5.0 (2015-03); V12.4.0 (2015-01)
- 3GPP TS 36.322 Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Link Control (RLC) protocol specification (Release 12) V12.3.0 (2015-09); V12.2.0 (2015-03); V12.1.1 (2015-01)
- 3GPP TS 36.323 Evolved Universal Terrestrial Radio Access (E-UTRA); Packet Data Convergence Protocol (PDCP) specification (Release 12) V12.4.0 (2015-09); V12.3.0 (2015-03); V12.2.0 (2015-01)
- 3GPP TS 36.331 Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification (Release 12) V12.7.0 (2015-09); V12.6.0 (2015-07); V12.5.0 (2015-03); V12.4.0 (2015-01)
- 3GPP TR 36.890 Study on Support of single-cell point-to-multipoint transmission in LTE (Release 13) V13.0.0 (2015-09); V1.0.0 (2015-09); V0.3.0 (2015-09); V0.2.2 (2015-09); V0.2.1(2015-09) ); V0.2.0 (2015-05); V0.1.1(2015-05) ); V0.1.0 (2015-05); V0.0.2(2015-03); V0.0.1 (2015-03)
- 3GPP TR 36.881 Study on latency reduction techniques for LTE (Release 13) V0.4.0 (2015-10); V0.3.1 (2015-10); V0.3.0 (2015-09); V0.2.2 (2015-09); V0.2.1(2015-09) ); V0.2.0 (2015-09); V0.1.1(2015-09) ); V0.1.0 (2015-09); V0.0.2(2015-09); V0.0.1 (2015-09)
- 3GPP TR 36.885 Study on LTE-based V2X Services (Release 14) V0.1.0 (2015-11); V0.0.2 (2015-09); V0.0.1 (2015-09)
- 3GPP TR 37.857 Study on Indoor Positioning Enhancements for UTRA and LTE (Release 13) V13.0.0 (2015-09); V1.0.1 (2015-09); V1.0.0 (2015-09); V0.6.0 (2015-09); V0.5.0 (2015-09); V0.4.0 (2015-09); V0.3.0 (2015-06); V0.2.1 (2015-05); V0.2.0 (2015-05); V0.1.1(2015-05) ); V0.1.0 (2014-12)
- 3GPP TS 36.305 Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Stage 2 functional specification of User Equipment (UE) positioning in E-UTRAN (Release 12) V12.2.0 (2015-01)
- 3GPP TS 36.355 Evolved Universal Terrestrial Radio Access (E-UTRA); LTE Positioning Protocol (LPP) (Release 12) V12.4.0 (2015-03); V12.3.0 (2015-01)

3GPP CT1 WG

- 3GPP TS 24.301 Non-Access-Stratum (NAS) protocol for Evolved Packet System (EPS); Stage 3 (Release 13) V13.3.0 (2015-09); V13.2.0 (2015-06); V13.1.0 (2015-03); V13.0.0 (2014-12)
- 3GPP TR 24.980 Recommended Minimum Requirements for support of MCPTT Service over the Gm reference point (Release 13) V0.1.0 (2015-10)
- 3GPP TS 24.333 Proximity-services (ProSe) Management Objects (MO) (Release 13) V13.0.0 (2015-09); (Release 12) V12.3.0 (2015-06); V12.2.0 (2015-03); V12.1.0 (2014-12)
- 3GPP TS 24.334 Proximity-services (ProSe) User Equipment (UE) to ProSe function protocol aspects; Stage 3 (Release 13) V13.1.0 (2015-09); V13.0.0 (2015-06)
- 3GPP TS 24.379 Mission Critical Push To Talk (MCPTT) call control protocol specification (Release 13) V0.2.2 (2015-09): V0.2.1 (2015-09); V0.2.0 (2015-09); V0.1.0 (2015-09)
- 3GPP TS 24.380 Mission Critical Push To Talk (MCPTT) floor control protocol specification (Release 13) V0.3.1 (2015-10); V0.3.0 (2015-10); V0.2.2 (2015-09): V0.2.1 (2015-09); V0.2.0 (2015-09); V0.1.0 (2015-09)
- 3GPP TS 24.381 Mission Critical Push To Talk (MCPTT) group management protocol specification (Release 13) V0.3.0 (2015-10); V0.2.2 (2015-09): V0.2.1 (2015-09); V0.2.0 (2015-09); V0.1.0 (2015-09)
- 3GPP TS 24.382 Mission Critical Push To Talk (MCPTT) identity management protocol specification (Release 13) V0.1.1 (2015-10); V0.1.0 (2015-09)
- 3GPP TS 24.383 Mission Critical Push To Talk (MCPTT) Management Object (MO) (Release 13) V0.2.2 (2015-09): V0.2.1 (2015-09); V0.2.0 (2015-09); V0.1.0 (2015-09)

# Enhancing Spectrum Utilization

ITS is recognized nationally and internationally as a leading expert in spectrum utilization technical studies. Research to enhance spectrum utilization addresses the long term goal of improving telecommunications technologies so that more users can effectively operate in limited and shared spectrum. Radio waves are made to carry information by varying the wave's amplitude, frequency, and phase within a frequency band. They range from hundreds of meters to about one millimeter in length, corresponding to about 3 kHz to 300 GHz in frequency, and there are significant variations in the behavior of waves of different frequencies. This is why certain frequencies are more desirable "real estate" for certain purposes. The most desirable spectrum real estate is often referred to as "beachfront" spectrum.

To discover innovative ways to insert more information streams into every segment of the spectrum, and to make those streams resilient and robust no matter what frequency they travel on and which services they share spectrum with, we must continuously deepen our understanding of the behavior of radio waves and the radio environment. Fundamental research provides the technical foundation necessary to "unlock the value of otherwise underutilized spectrum and open new avenues for spectrum users to derive value through the development of advanced, situation-aware spectrum-sharing technologies."[1]

## FY 2015 Research to Enhance Spectrum Utilization

The Center for Advanced Communications (CAC) was created in response to a Presidential directive to "create and implement a plan to facilitate research, development, experimentation, and testing by researchers to explore innovative spectrum-sharing technologies."[1] CAC was chartered in 2013 to investigate and initiate collaborative research efforts that align the world-class research capabilities of ITS and NIST, using the highly successful Public Safety Communications Research (PSCR) program as a model. ITS's long history of theoretical and applied telecommunications research is complemented by NIST's core competencies in metrology (measurement science) and development of standards and compliance metrics for emerging technologies. CAC projects in FY 2015 focused on developing technologies and best practices for continuous spectrum monitoring and on developing technologies capable of operating in frequency bands that cannot now easily or cost-effectively be used for cellular services.

As radio services are being forced to operate in narrowing slivers of increasingly crowded spectrum, ensuring the quality of the service that reaches the end user presents increasing challenges. ITS performs research to support development and standardization of methods for assessing and improving the quality of delivered transmissions to enhance the user experience. End-to-end performance of the network is influenced by many interrelated physical factors, but the user's perception of that performance may also be influenced by entirely different factors unrelated to the radio channel. Research to enhance user experience addresses user perception through subjective testing that directly collects end user input on the received quality of images and audio and video streams.

Spectrum utilization measurements and analyses describe spectrum usage by individual and aggregate spectrum systems. While EMC studies characterize the radio emissions of different devices, spectrum measurements characterize the radio space in which they operate. This information about current occupancy of the existing radio spectrum environment is used to identify opportunities for increased utilization as well as to describe the background radio noise against which intentional transmissions will have to be made secure and resilient. Radio frequency spectrum measurements were taken in FY 2015 to support several EMC studies for spectrum sharing through more accurate characterization of emissions from different radio devices. Other measurements were taken to inform the development of propagation models that can accurately account for the impact of clutter (vegetation and man-made objects) on propagation.

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1. The White House, Presidential Memorandum: Unleashing the Wireless Broadband Revolution, June 28, 2010. Accessed http://www.whitehouse.gov/the-press-office/presidential-memorandum-unleashing-wireless-broadband-revolution January 9, 2014.

**At a Glance: FY 2015 ITS SDO Participation**
**36 positions on 32 different bodies in 6 SDOs, including 14 Chair/Co-chair/Vice Chair positions**

Technical standards establish common norms for technical systems—uniform engineering criteria, methods, processes, and practices that promote competition and interoperability. In cooperation with other interested U.S. government agencies and industry groups, ITS researchers contribute to the development of national and international telecommunication standards that enable emerging technologies to enhance spectrum utilization. ITS submits, and coordinates the formal review and approval of, recommendations to, for example, define the parameters of permissible emissions from different transmitters to reduce the probability of interference with others or define the characteristics of transmission envelopes so that devices from different manufacturers can interoperate predictably. Under agency reimbursable agreements, ITS staff also continue to support other federal agencies with development of telecommunication specifications, standards, proof of concept and demonstration measurements, interoperability analyses, technical and economic impact assessments, and prototype development. Positions held by ITS staff in national and international SDOs are listed on page 82.

CAC
Center for Advanced Communications

# CAC: Next Generation Technology

## Spectrum Monitoring Pilot Program

### Objectives

- *Develop an infrastructure and standards to acquire and amass spectrum monitoring data and make it available to the spectrum community in near real time via the Internet*
- *Establish best practices for the acquisition of spectrum data*
- *Establish and maintain a small network of ITS spectrum monitors in high-priority scenarios to support spectrum rulemaking, engineering, management, and enforcement*

### Overview

One of the first projects undertaken under the umbrella of the CAC was a joint ITS-NIST research effort to develop and demonstrate the ability to conduct spectrum monitoring over the entire lifecycle of new radio technologies, from the earliest proposals for spectrum sharing, to conformity assessment of newly deployed systems, to longer term surveillance testing that regulators may use to support enforcement actions. The Spectrum Monitoring Pilot Program was initiated in 2013 to investigate the efficacy of spectrum monitoring in support of research and spectrum regulatory proceedings.

Measured spectrum occupancy is useful information for planning, engineering, and enforcing new spectrum sharing and relocation scenarios. With some standardization and the development of best practices to ensure data quality, measured spectrum data could be made available alongside license and assignment data to improve the quality and quantity of information available for planning by policy makers, spectrum managers, and investors. In the engineering phase of a transition process, real-time and historical measured spectrum data could be used to check assumptions, validate propagation and usage models, and field test dynamic coordination schemes and technologies. After a sharing or relocation authorization, open and transparent use of relevant spectrum data can play a critical role in interference resolution and enforcement in the increasingly dynamic and complex interference environment.

Long-term and continuous acquisition of spectrum data, i.e., spectrum monitoring, is currently being performed by industry, academia, and government for a variety of purposes. There has been little effort, however, to collect, extend, and curate this information for the benefit of all. The organizations acquiring spectrum data use a wide variety of data types to suit their purposes. The means of acquiring the data also varies and there is no one-size-fits-all approach. With all these disparate sources, types, and methods, there is a need for infrastructure and standardization to aggregate and achieve full collective value of the data.

## Measured Spectrum Occupancy Database (MSOD)

To meet the first objective of this project, ITS is developing a distributed Measured Spectrum Occupancy Database (MSOD) architecture in collaboration with NIST/CTL. The architecture will enable industry, academia, and government agencies to host MSOD instances and contribute spectrum data to the overall program. MSOD will allow access to spectrum occupancy information through a web-based user interface. Users will be able to query MSOD via a web service or view and download data with a browser-based data visualization application. In the visualization tool, spectrum occupancy statistics over long time intervals will be available to inform policy discussions. Near-real-time amplitude versus frequency data will also be available for spectrum coordination and enforcement purposes.

## RF Sensor Development and Deployment

Toward the second objective, we are also pursuing RF sensor development and deployment. Sensor hardware and software are being designed to detect well-defined system transmissions in specified frequency bands, e.g., LTE at 0.7 and 1.7 GHz and pulse radar at 3.0 and 3.5 GHz. Novel aspects of the sensor designs include: (1) local calibrations to indicate the health of sensors in the field and to measure system noise level; (2) a standard format for the transfer of calibrated measurements from the sensor to the repository; and (3) benchmark tests on commercial-off-the-shelf (COTS) sensors and software defined radios (SDRs) to assess capabilities and limitations. For enforcement purposes, ITS is investigating signal processing techniques for spectrum forensics, e.g., direction finding, time-synchronization to, and demodulation of LTE control channels. Two radar sensor prototypes have been deployed at Virginia Beach (August 2014) and San Diego (July 2015) to monitor the 3.5 GHz maritime radar band on a continuous basis. In FY 2016, ITS plans to build and deploy four additional 3.5 GHz sensors at Key West, San Francisco, Cape Cod, and northern California/Oregon.

### Related Publications:


- *M.G. Cotton, M.M. Souryal, J.A. Wepman, M. Ranganathan, J.E. Kub, S.R. Engelking, Y. Lo, H.E. Ottke, R.F. Kaiser, D.J. Anderson, "An Overview of the NTIA/NIST Spectrum Monitoring Pilot Program," International Workshop on Smart Spectrum at IEEE WCNC 2015, New Orleans, LA, March 9-12, 2015. Available http://www.its.bldrdoc.gov/publications/2794.aspx.*
- *J.A. Wepman, B.L. Bedford, H.E. Ottke, M.G. Cotton, "RF Sensors for Spectrum Monitoring Applications: Fundamentals and RF Performance Test Plan," NTIA Technical Report TR-15-519, August 2015. Available http://www.its.bldrdoc.gov/publications/2808.aspx*
- *M. Souryal, M. Ranganathan, J. Mink, and N. El Ouni, "Real-Time Centralized Spectrum Monitoring: Feasibility, Architecture, and Latency," in Proc. IEEE DySPAN, Sept. 2015.*


*Spectrum monitoring radar sensor deployed at San Diego. Photo by Mike Cotton.*

*For more information contact Michael Cotton, 303-497-7346, mcotton@its.bldrdoc.gov*

CAC
Center for Advanced Communications

## Millimeter Wave Research

### Objective

- *Establish the scientific foundations for expanding wireless connectivity into the millimeter wave spectrum*

Looking to the fifth-generation, or 5G, cellular network of the future, this CAC project performs fundamental research needed to develop the technology to extend wireless connectivity into the millimeter wave portion of the radio spectrum. Millimeter wave, or extremely high frequency (EHF), spectrum includes frequencies from 30 GHz to 300 GHz, which are not currently being used for cellular broadband. This spectrum can offer 1,000 times the bandwidth of the existing cellular radio spectrum and move data 100 times faster—but it also has a much shorter range and is more easily blocked or deflected.

Using this spectrum for high capacity, low latency broadband applications requires entirely new technologies and methodologies for wireless devices. To reduce interference and compensate for millimeter wave propagation impairments, millimeter wave 5G systems will use complex antenna arrays to transmit and receive signals in many directions using narrow beams and small antenna apertures. Industry needs accurate models of how radio waves behave at these frequencies to develop those technologies. In a joint effort, ITS and NIST/CTL researchers are performing fundamental research into measurement, analysis, and statistical representations of millimeter wave propagation channels. ITS has been working to support this research for several years by designing and validating a channel probe capable of measuring mobile radio parameters in the millimeter wave frequencies.

In FY 2013 and 2014, ITS led development of a robotically controlled channel sounder capable of measuring mobile radio parameters at 83.5 GHz with 2 GHz of instantaneous bandwidth. A custom designed, 16 element, omnidirectional antenna array capable of switching antenna elements in 25 nanoseconds enables the sounder to measure signals from different angles of arrival within the coherence time of the mobile channel. In FY 2015, measurements were taken to calibrate the amplitude and phase response for all 16 multiplexor channels. In addition to the laboratory calibration (Figure 1), the system was mounted on a robot capable of autonomous navigation (Figure 2). Using this configuration, indoor mobile measurements were made in a conference room and in hallways for obstructed, non-line-of-sight (NLOS) and unobstructed, line-of-sight (LOS) paths (Figure 2).This allowed collection of 83 GHz propagation data as well as the position, velocity, and heading of the measurement system, which are necessary for analyzing mobile channels.

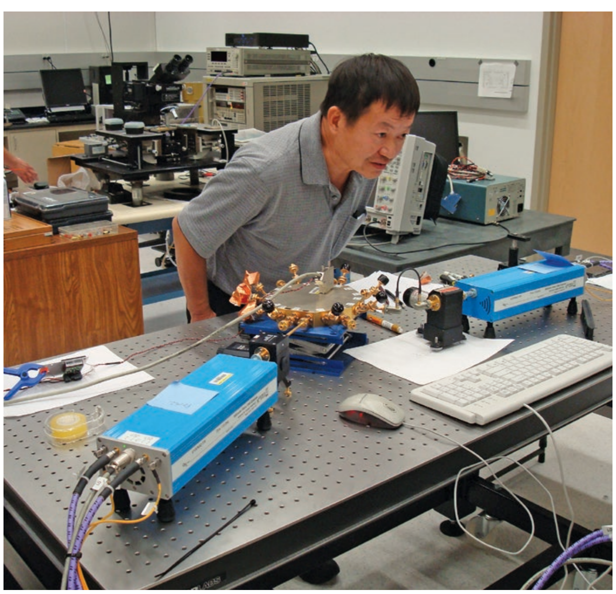


*Figure 1. ITS engineer Yeh Lo observes data being collected during bench calibration of the 83.5 GHz channel sounder. Photo by Peter Papazian.*

Geometric propagation parameters including angle of arrival, delay, and Doppler effects were collected and will be used to develop omnidirectional path loss models at 83.5 GHz. This data is being shared with the 5G mmWave Channel Model Alliance, a group convened by NIST to allow international researchers from government, industry, and academia to openly share measurement and modeling data and methods. Channel models are a starting point for standards activities, and international standards for millimeter wave technologies will be fundamental to commercialization.

A similar system for measurements at 28–38 GHz was designed and procured in FY 2014. In FY 2015, preliminary testing was completed on the 28–38 GHz system and design specifications were finalized and procurement completed for a similar 60 GHz system. The 60 GHz system is also designed to collect angle of departure data necessary for the development of next generation millimeter wave geometric channel models. Both of these systems will be deployed for indoor and outdoor measurements in FY 2016.

Nascent next generation technologies for short range indoor communications systems to support high bandwidth, high demand unlicensed commercial wireless applications in the millimeter wave spectrum will need robust beam steering and multiple-input and multiple-output (MIMO) methods for reliable operation. Millimeter-wave channel models based on accurate mobile measurements provide the propagation models that are the first step towards standardization of these and other building blocks of the 5G millimeter wave cellular network.

*Figure 2. The robot carries all the components of an automated measurement system, including the omnidirectional antenna perched on top of the rack. It moves autonomously along a pre-programmed path, while the system collects data on signals being transmitted from up to 150 m away. Photo by P. Papazian.*

# Enhancing User Experience

The user experience of a telecommunications service is governed by many factors at multiple levels. An engineering perspective illuminates the numerically quantifiable factors that influence how accurately and reliably digital representations of speech, video, images, text messages, etc. are moved between users. Examples of these factors include channel bandwidth and losses; the properties of encoding, decoding, and loss concealment algorithms; and attributes of users' devices. Important as they are, these factors do not stand alone. Indeed, they are most advantageously interpreted in the context of the additional, more difficult to quantify, factors related to users themselves. These may include user perception and judgment, the purpose for which the service is used, the way in which it is used, and the environment in which it is used.

The ITS Audio and Video Quality Research programs acknowledge and address this dichotomy while developing and standardizing methods for assessing and improving the user experience of telecommunication services. These programs, which are both long-standing and internationally renowned, conduct research and development leading to implementation, publication, and standardization of perception-based tools for assessment and optimization of video and audio communication systems. Their goal is to develop tools to monitor and optimize the user experience of audio and video information on communication channels, especially in light of bandwidth constraints and time-varying channel quality. Their work provides important information for network and equipment designers as well as reliable technical input to standards bodies.

Great strides have been made in recent years towards developing automated tools for assessing user experience, but subjective testing is still a very important tool. ITS considers the ultimate arbiter of the performance of a telecommunications service for inter-human communication to be the end user, the listener or viewer of the audio or video content transmitted over that network. ITS uses subjective testing to assess the success of emerging audio and video coding and transmission technologies and to support the development and validation of automated assessment tools.

# User Experience of Telecommunication Speech

## Objectives

- *Improved telecommunication speech experience, for example reduction of the background noise and other artifacts that can obscure intelligibility in mobile calls*
- *Tools that accurately quantify user experience of telecommunication speech services*

The quality of speech sent over a telecommunication system depends on a variety of factors, such as the background noise in the environment, the algorithms used to digitally code the speech signal, the bandwidth used in transmitting the speech signal, as well as others. For any set of factors, the user is concerned with the overall experience—the quality and intelligibility of the speech. The user experience can be enhanced through algorithms that robustly adapt to variations in the environmental factors listed above. Such adaptability allows telecommunications speech transmission to be well-matched to channel conditions even though those conditions are continually evolving, thereby enhancing the user experience.

The ITS Audio Quality Research Program supports community-wide efforts towards robust and adaptable telecommunication speech services. The program identifies, develops, and characterizes algorithm innovations in these areas, seeking to enhance the user experience through higher, more consistent speech quality, better intelligibility, or combinations of these two. The program also seeks to improve tools and techniques for quantitatively characterizing the user experience of speech quality and speech intelligibility, both through subjective testing and by means of signal processing algorithms.

The program has made numerous contributions that address wide-ranging aspects of this topic. Many of these contributions are documented in a healthy list of NTIA Technical Reports, peer-reviewed publications, and standards contributions. FY 2015 was no exception.

In the most significant major program, staff analyzed a key factor in noise reduction systems, developed relationships between the dimensions of a multi-dimensional subjective testing scale, and conducted investigations to determine speech intelligibility levels for LTE-compatible speech coders operating in noisy environments such as those often encountered in public safety operations. As in the past, each work effort is described in a detailed technical presentation so that all stakeholders can benefit from descriptions of the process engaged, the results obtained, and the insights drawn from those results. The interested reader is referred to http://www.its.bldrdoc.gov/audio for full details.

ITS staff investigated the additivity of spectral magnitudes, a key factor in noise reduction systems. Noise reduction systems are critical to a quality user experience as mobile users expect to be heard from cars, trains, restaurants, sporting events, and everything in between, in spite of the fact that noise conditions may make any communication difficult, and telecommunication especially difficult.

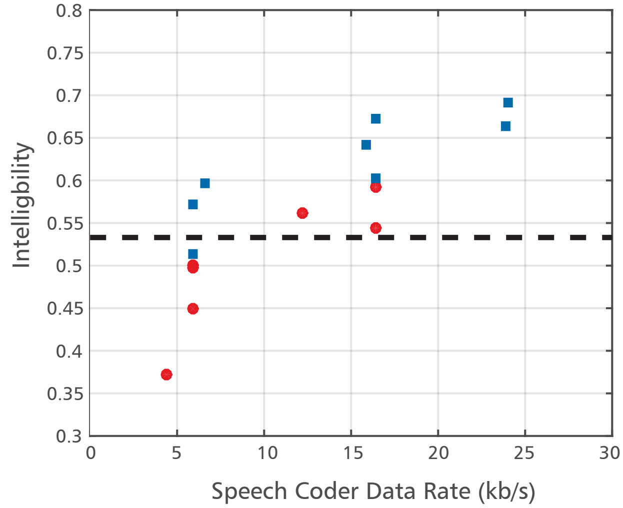
Many standardized subject testing scales exist, and some tests even seek to assess multiple dimensions of user experience in an efficient way. ITU-T Recommendation P.835 requires subjects to individually rate the quality of speech and background noise, and also to render a judgment of overall quality. Program staff conducted a standardized speech quality test in the ITS Audio Quality Laboratory. Subsequent analysis yielded a simple mathematical relationship between overall quality ratings and the individual ratings of speech quality and noise quality. Staff developed and presented a rigorous mathematical formulation of this result. This work provides fundamental insights

### Related Publications:

- *S.D. Voran and A.A. Catellier, Speech Codec Intelligibility Testing in Support of Mission-Critical Voice Applications for LTE, NTIA Technical Report TR-15-520, September 2015, Available http://www.its.bldrdoc.gov/publications/2811.aspx*
- *S.D. Voran, "Exploration of the Additivity Approximation for Spectral Magnitudes," 2015 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics, New Paltz, NY, Oct. 19, 2015. Available http://www.its.bldrdoc.gov/publications/2813.aspx*

into human judgments of media quality, and it also enables ITS and other labs to develop more efficient testing protocols.

Program staff also designed, conducted, and analyzed a major investigation of speech coder intelligibly. This work was motivated by a pressing practical question: Which of the LTE-compatible speech coding modes can provide speech intelligibility as good as or better than the intelligibility that Public Safety users experience with analog FM radios? For a realistic test, it was critical to include noise environments representative of those in which Public Safety users must often operate. Example results are shown in the figure. Staff documented the work and the results in a highly detailed NTIA report that has become critical input to a Public Safety speech coder selection process.




*Example intelligibly results for a selection of narrowband (red circles) and wideband (blue squares) speech coders tested in the presence of very loud rescue saw noise. The reference level measured for analog FM is shown by the dashed black line. In this example, intelligibility generally increases with speech coder data rate and, in any rate neighborhood, wideband modes generally offer higher intelligibility than narrow band modes. Above 10 kb/s all coder modes compare favorably with analog FM.*

Throughout FY 2015, program staff performed speech and audio quality testing using both objective and subjective techniques, supporting this and other ITS programs. Laboratory facilities were upgraded and staff continued to draft technical documents detailing research results. Staff also served in numerous peer reviewer and editor capacities for the technical paper publication process in support of the international speech and audio research community.

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## Video Quality Research

### Objectives

*Develop and disseminate knowledge, techniques, and tools that will:*

- *Enable subjective video quality testing of new technologies*
- *Allow industry to develop improved video systems*
- *Encourage the development of international standards related to video quality issues*

### Background

Cisco statistics indicate that video will be responsible for 80–90% of global internet traffic by 2019.[1] Video content is embedded on many web sites, delivered over the Internet, streamed to mobile devices, delivered on-demand, and used for real time monitoring in increasingly diverse applications. As with audio transmission, user experience of video transmission is influenced by the encoding and decoding algorithms, the environmental conditions, the limitations of the viewing device, and the user's purpose for viewing. For example, an individual watching an entertainment video on a large screen TV will have different expectations than a security officer trying to read a license plate number on a closed circuit monitor. As the

1. Cisco Visual Networking Index: Forecast and Methodology, 2014–2019 (May 2015). Accessed http://www.cisco.com/c/en/us/solutions/collateral/service-provider/ip-ngn-ip-next-generation-network/white_paper_c11-481360.html December 4, 2015

*Figure 1. Images were collected from 23 cameras, ranging from a 1 megapixel (MP) mobile phone to a 20 MP digital single-lens reflex camera (DSLR). The picture taking procedure matches prevalent consumer behaviors for the mobile phone cameras that dominate today's market. This implies handheld cameras, automatic settings, and a mixture of artificial and natural lighting. Note the variation in picture quality between pairs of images. The two images at upper right are courtesy Denver Botanic Gardens.*

diversity of devices and display sizes continues to increase along with the variety of purposes for which video can be used, new standardized and repeatable methods of subjective testing are needed to support the development of new coding algorithms that are robust to a wide variety of environmental conditions and equipment configurations. The work of the Video Quality Research program emphasizes international standardization and technology transfer, because U.S. industry benefits from the availability of new algorithms and products to support increased quality and efficiency of video transmission through wired and wireless services.

## Image Quality Subjective Testing

In FY 2015, ITS and Intel entered into a CRADA to explore a subjective image quality experiment design that specifically targeted understanding consumer perception of visual quality. With this consumer-oriented goal in mind, images were captured from a large number of representative consumer devices, some samples of which are shown in Figure 1. This design choice is fundamentally different from previous work in the field, in that it is not based on simulated software impairments, but rather on naturally occurring artifacts due to the device and conditions. New subjective questions were posed, which allowed exploration of differences in the quality of experience (QoE) provided by various devices.

Subjective test data from 23 cameras were analyzed to highlight and demonstrate the unique capabilities provided by this method. This dataset and subjective ratings are available on the Consumer Digital Video Library (CDVL, www.cdvl.org). This work is a necessary step toward the development of automated algorithms that can predict the quality of a video stream with no extraneous information.

## Theoretical Subject Model

How accurately are people able to use a 5 level quality scale (excellent, good, fair, poor, bad) to rate videos? Put another way, how repeatable are an individual subject's scores? Several subjective experiments have asked subjects to rate the same video sequences multiple times. Analyses indicate that none of the

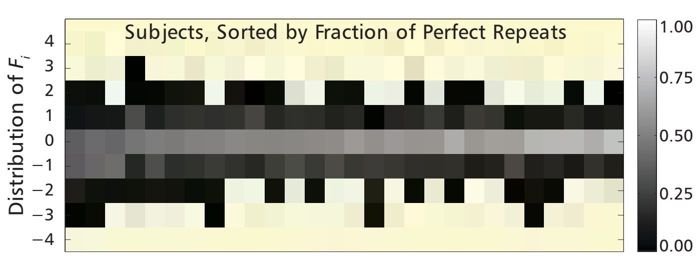


*Figure 2. Subjects viewed and rated the same set of video sequences multiple times. The histogram shows the distribution of differences between the rating each subject gave when they first saw a video and their subsequent ratings. No subject was able to perfectly repeat their ratings, even with coding-only impairments and a 5 level rating scale.*

subjects exactly repeated their prior scores, as shown in Figure 2. In collaboration with the Akademia Górniczo-Hutnicza (AGH) University in Krakow, Poland, ITS developed a theoretical model of subject rating behavior. This model allows us to understand the consequences of scoring imperfection on experiment design and analysis.

Three major factors influence accuracy: subject bias, subject inaccuracy, and stimulus scoring difficulty. These appear to be separate random effects and their existence is a reason why none of the subjects were able to perfectly repeat scores. The most important consequence is that subjects' scoring is a random process. This is expected behavior that must be accepted, not a flaw or fault that can be eliminated. These error terms explain behaviors of subjective test data that can be troubling to novices. Subjective testing remains the most accurate method to assess video quality. This is a critical tool for the assessment of new video technologies like 4K and wide color gamut television.

### Related Publications:

- *Lucjan. Janowski and Margaret Pinson, "The Accuracy of Subjects in a Quality Experiment: A Theoretical Subject Model," in IEEE Transactions on Multimedia, vol. 17, no. 12, pp. 2210-2224, December 2015. Available http://www.its.bldrdoc.gov/publications/2814.aspx*
- *Margaret H. Pinson, Lark Kwon Choi, Alan Conrad Bovik, "Temporal Video Quality Model Accounting for Variable Frame Delay Distortions," IEEE Transactions on Broadcasting, vol. 60, no. 4, pp. 637-649, Dec. 2014. Available http://www.its.bldrdoc.gov/publications/2816.aspx*

## Novel Experiment Design

Many video quality subjective experiments are designed to analyze quality differences among video clips produced by copying the same video scene many times, each with a different combination of video codec, bitrate, and environment. Fundamentally, the test measures whether viewers perceive a difference between two differently encoded versions of the same video clip, and, if so, which version gives the best user experience. Subjects are shown many versions of the same clip and give an opinion of each by assigning it a score. The scores of all subjects are analyzed to produce a mean opinion score (MOS). The MOS is assumed to predict the quality of the user experience when viewing any video scene encoded in that particular way.

One consequence of this experiment design is that each subject will view and rate the same video clip multiple times, occasionally as many as 25 times. Subject interviews reveal that some subjects change their scoring behavior in response to these repeated viewings—focusing on one portion of the sequence instead of paying attention to the whole. The question then arises as to whether repeated viewing of the same video scene changes the MOS, thus yielding a less accurate estimate of subject opinion. In FY 2015, ITS led an international study within the video quality experts group (VQEG) to seek an answer to this question by examining two alternative experiment designs that avoid clip reuse. Results are expected in FY 2016.

## Reliable Objective Video Quality Models

In FY 2015, ITS and University of Texas at Austin researchers published the results of an independent validation of the most recent objective Video Quality Model (VQM) developed by ITS. VQMs are computer algorithms that try to predict human perception of video quality as an inexpensive—but less accurate—alternative to subjective tests. They can be very useful to researchers who wish to limit expensive subjective tests of products under development to the most likely candidates for success. VQMs developed at ITS over 20 years and adopted into international standards are offered royalty-free at www.its.bldrdoc.gov/vqm.

A recent challenge to VQMs is the broad variety of time alignment errors introduced by modern video compression and transmission systems. It is difficult to predict the impact of different types of objectively measurable frame delays on subjective quality perception. In 2011, ITS proposed a promising new VQM with a set of variable frame delay (VFD) parameters that could be mapped to subjective quality and invited other researchers to independently test it. The University of Texas at Austin performed correlation analysis and statistical hypothesis testing with their own database of video sequences and subjective scores. Their results, published in December 2014, show that VQM_VFD substantially outperforms other objective models in accurately predicting the impact of variable delays on user experience.

### Leadership

VQEG determines whether objective video quality models are accurate enough for industry to trust. ITS helped establish VQEG in 1997 and continues to participate in VQEG by:

- Co-chairing VQEG meetings
- Providing independent oversight to promote fairness and accuracy
- Analyzing data from VQEG sponsored subjective tests
- Writing subjective test plans and reports

More information can be found on the Video Quality Research home page at http://www.its.bldrdoc.gov/n3/video.

## Consumer Digital Video Library

### Objective

- *Disseminate high quality, uncompressed video sequences to encourage novel research and development on future video technologies*

Finding—and getting rights to use—relevant test video is an obstacle to some interesting research topics. The Consumer Digital Video Library web site (CDVL, www.cdvl.org) was created to address this problem. ITS developed, hosts, and supports the CDVL web site. The CDVL makes high quality, uncompressed video clips available for download, free. Clips hosted on CDVL are ideal for use by the education, research, and product development communities. CDVL content allows academia and industry to:

- Develop new products
- Choose video equipment
- Improve video coding algorithms
- Optimize video system performance
- Train objective video quality models
- Conduct subjective video quality tests

In FY 2015, Netflix made available a 7 minute 4K video sequence on CDVL: *El Fuente*. This studio quality video sequence enables research into the impact of longer video sequences on video quality of experience. The increased bandwidth requirements of 4K provide new challenges for Internet transmission.

In 2015, 212 people downloaded video from CDVL. The research impact can be seen in the 73 IEEE publications (2008–2015) that reference the CDVL Web site.

*"Professional crew, on behalf of Netflix who owns its rights ... filmed [the El Fuente] video sequence in Mexico, depicting various scenes from everyday life. Netflix makes this content available to the research community for research and development purposes. The video frame size is 4096 × 2160, square pixel aspect ratio, frame rate is 59.94 fps (60,000/1,001 frames per sec.)." Ioannis Katsavounidis, Sr. Research Scientist, Encoding Technologies, Netflix, Los Gatos, CA, July 28, 2015.*

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# Radio Frequency Measurements

RF measurements of spectrum occupancy and device emissions provide information about the electromagnetic radiation actually present in a certain frequency band in select locations: how many signals, the extent of coverage, how often signals occur, and on what frequencies. In response to the 2013 Presidential Memorandum on Expanding America's Leadership in Wireless Innovation,[1] NTIA/OSM is conducting a quantitative assessment of federal spectrum usage in five frequency bands totaling 960 MHz of spectrum to support acceleration of shared access to spectrum. The assessment is derived from the Table of Frequency Allocations, propagation models, and agency estimates of usage patterns. Measurements of actual spectrum usage that identify active and passive users and their spatial and temporal characteristics can provide greater understanding to complement the OSM study and enable increased spectrum sharing.

Besides facilitating quantitative assessment, spectrum and propagation measurements are critical for validating the propagation models that underpin spectrum management decisions on spectrum reallocation or spectrum sharing. This is especially true for propagation models at frequencies above 1 GHz. Existing models need substantial improvement in several microwave frequency bands that are candidates for near-term spectrum sharing, including 1300 MHz, 1700 MHz, 3.5 GHz and 5 GHz. Data need to be taken in these bands for both indoor-to-indoor and outdoor-to-indoor propagation paths. The economic impact of spectrum sharing in these bands is on the order of tens of billions of dollars, both in one-time radio network deployment costs and in terms of long-term impact on the U.S. economy.

Spectrum and propagation measurements provide important information about the characteristics of transmitted signals in a particular band, both intended and unintended, their spatial extent, and their temporal and frequency characteristics. Measurements document transmitter emissions for compliance assessment and interference analysis and help determine the extent and characteristics of coverage. Reliable measurements also support propagation model development and validation, regulatory decisions, and telecommunications technology development. But unless a spectrum measurement is carefully designed using rigorous techniques, it may easily produce false spectrum occupancy and propagation loss estimates. For example, an entire band may appear occupied or the impact of potential interferers may be over overstated.

ITS and its predecessor organizations have a century of experience in building and using state-of-the-art spectrum measurement systems. Outputs have included broadband spectrum surveys, measurements of emissions from individual transmitters, resolution of radio interference problems, and documentation of transmitter emission compliance with federal standards such as the Radar Spectrum Emission Criteria (RSEC), all published in hundreds of NTIA Reports, ITU contributions, and other inputs to decision-makers in numerous federal agencies and private sector entities. The reported results of ITS RF measurements have had broad impacts on federal and private sector spectrum planning and use.

## ITS Radio Spectrum Measurements in FY 2015

### Objectives

- *Measurements of patterns of radio spectrum usage*
- *Detailed band-by-band measurements of occupancy*
- *Spectrum monitoring on a band-by-band basis*
- *Transmitter emission spectra determination*
- *Radio regulation compliance verification for transmitters*
- *Interference assessments and resolution*

1. The White House, Presidential Memorandum: Expanding America's Leadership in Wireless Innovation, June 14, 2013. Accessed https://www.whitehouse.gov/the-press-office/2013/06/14/presidential-memorandum-expanding-americas-leadership-wireless-innovatio December 22, 2015.

*ITS engineer John Carroll setting up a suitcase radio spectrum measurement system at a field site. Photo by Frank Sanders.*

In FY 2015, ITS performed a wide range of spectrum measurements while continuing to develop next-generation measurement system hardware and software. ITS performed RF measurements on several radar transmitters, including a new model of tactical ground-based military air surveillance radar and a major navy multi-mode radar. ITS and OSM measured emissions from these radars as part of a larger 3.5 GHz spectrum sharing investigation (see stories on pages 18 and 20). The ground-based radar was also measured for compliance with the NTIA RSEC; demonstrated compliance with the RSEC brought these radars to Stage IV (final-stage) spectrum certification, meaning that they can be deployed by their operating agencies on an effectively unlimited basis.

In FY 2015, ITS engineers also performed several investigations into 5 GHz Unlicensed National Information Infrastructure (U-NII) devices that share spectrum with federal radar systems using technology to detect and avoid radar signals to protect government operations. In April 2015, ITS became aware of reported interference between the Miami, Florida, Terminal Doppler Weather Radar (TDWR) and two wireless internet service providers (WISPs) using newly-certified, off-the-shelf U-NII equipment. ITS performed a comprehensive set of measurements on the devices in the laboratory to understand why these devices did not detect and avoid the Miami TDWR under updated FCC certification rules. The interference mechanism was identified and both the manufacturer and the FCC were notified of ITS's results. ITS also performed a detailed study examining the ability of existing, off-the-shelf U-NII devices to detect sub-microsecond and wideband frequency-modulated radar waveforms. These waveforms are similar to, but not exactly the same as, radar waveforms in the 5350 to 5470 MHz band that the FCC is examining for future spectrum sharing. This testing was undertaken to validate test procedures for future testing of prototype U-NII devices by gathering baseline data from existing technologies.

Other notable spectrum measurements performed in FY 2015 include an examination of the emissions of a portable LTE hotspot designed to operate in a new band for spectrum sharing, near 3.5 GHz. The LTE emissions were measured at a Navy research lab with an ITS suitcase measurement system. The collected data was referenced by the FCC in a Report and Order to set the LTE device out-of-channel emission limits.

## Expanding RF Measurement Capabilities

ITS engineers continued spectrum measurement system development in hardware and software. Two new spectrum and signal analyzers were procured in FY 2015 to add real-time spectrum analysis capabilities to the RSMS measurement platform (described on page 73). These will be used to develop advanced spectrum forensic techniques which will be critical for performing EMC analyses to mitigate interference problems. Handheld spectrum analyzers with built-in GPS functionality were also purchased for use in mobile propagation measurements. Other signal analyzers and signal generators were purchased to expand the RSMS inventory to make it possible to conduct spectrum or EMC measurements at multiple locations in parallel. Spectrum occupancy processing was added to the RSMS-5G software package. Using this new capability along with the RSMS-5G measurement scheduler, it is possible to collect spectrum data and compute occupancy over a long period of time to determine usage characteristics in a specific frequency band.

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## ITS/NIST Clutter Measurement Collaboration

### Objectives

- *Characterize a new continuous wave mobile spectrum measurement system*
- *Take and analyze mobile spectrum measurements to develop clutter metrics so that propagation prediction models may account for signal attenuation caused by vegetation and man-made objects*

### Problem

The presidential mandate to make 500 MHz of federal and non-federal spectrum available for expanded commercial wireless broadband use by 2020 did not come with a practical instruction manual. To determine exactly how and in which bands spectrum could feasibly be shared, the Commerce Spectrum Management and Advisory Committee (CSMAC)[1] formed five working groups with members from both federal agencies and commercial wireless operators. Working Group 5 (WG-5) explored the feasibility of DoD airborne operations communications systems sharing the 1755–1850 MHz band with commercial LTE systems. Sub-working groups were formed to study each of four different systems in the airborne operations category—air combat training systems, small unmanned aircraft systems, precision-guided munitions, and aeronautical mobile telemetry. The sub-working groups began issuing draft reports in mid-2013.

WG-5's March 2014 final report emphasized that "EMC analyses conducted thus far indicate that separation distances in the order of hundreds of kilometers would be necessary to ensure that federal and commercial LTE systems would not cause harmful interference to one another,"[2] making band sharing very problematic. Follow-on work was recommended to address ways to reduce protection/coordination zones that separate federal and commercial systems.

One recommendation was to perform additional study of radiowave attenuation due to vegetation and man-made objects (collectively called clutter). The effects of clutter were not included in any of the interference analyses performed by WG-5 because the group could not agree on a method to do so. The WG-5 ground-to-ground analyses took terrain effects into account using the Longley-Rice/Irregular Terrain Model (ITM). ITM was originally developed at ITS, has been extensively validated, and is now widely relied on by a variety of organizations. The air-to-ground analysis used the model from Recommendation ITU-R P.528, also based on an ITS-developed model (IF-77), but does not include terrain effects. Neither of these models include the effects of clutter, and the final WG-5 report emphasized the need for validated propagation models that takes both terrain and clutter into account, and the need for "ground truth" measurement data to validate those models.

### Approach

ITS began conducting exploratory work on incorporating clutter into EMC analyses for sharing in July 2013. The results of an initial study, completed and reported in FY 2014, led to agreement on reduced protection/coordination zones, greatly increasing the value of commercial licenses to operate in this band. The FCC auction of licenses in this and the related bands collectively known as the AWS-3 bands closed in January 2015 and produced nearly $45 billion in revenue. The initial study reinforced the need for a body of ground truth measured data from which clutter metrics could be reliably calculated and which could be used to validate the inclusion of those metrics into propagation models for different applications. It also highlighted the importance of including appropriate corrections for the relevant antenna gain patterns.

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1. The CSMAC is a body of spectrum policy experts from outside the federal government who offer the Assistant Secretary for Communications and Information at NTIA expertise and perspective on reforms to enable new technologies and services. Members are selected based on their technical background and expertise as well as NTIA's commitment to ensure diversity and balance in points of view.

2. Commerce Spectrum Management and Advisory Committee, CSMAC Working Group 5 Final Report: 1755-1850 MHz Airborne Operations, March 4, 2014. Accessed https://www.ntia.doc.gov/other-publication/2014/csmac-working-group-5-final-report November 30, 2015.

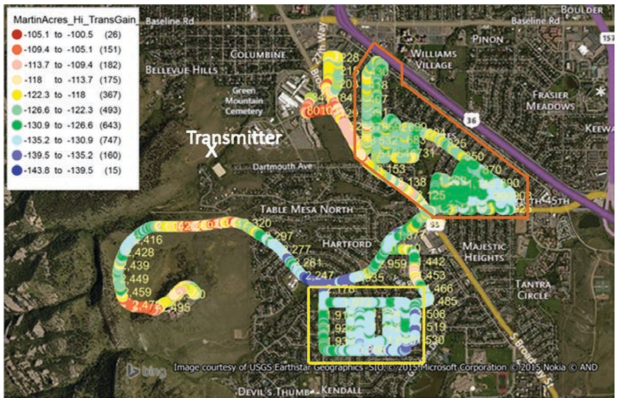


*Figure 1. The basic transmission gain for transmitter on the Green Mountain mesa is shown for a drive route near the Boulder laboratories. Neighborhoods outlined by the orange and yellow lines contained a uniform distribution of one-story homes and mature vegetation. Blue dots signify highest gain (most efficient transmission) and red lowest.*

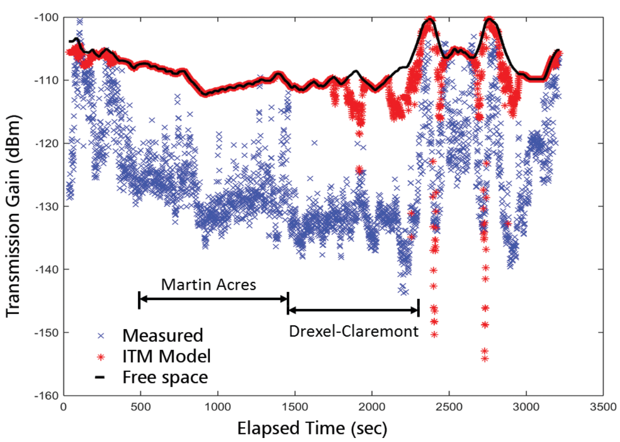


*Figure 2. Graph of elapsed time (sec) versus the measured basic transmission gain (blue x's), the ITM median basic transmission gain (red asterisks) and the free-space transmission gain (black line). The extent of the two neighborhoods, Martin Acres, and Drexel-Claremont, are shown on the plot. Clutter is defined as the difference between the ITM model and the measured data.*

In FY 2012, ITS designed and fielded a new continuous wave (CW) mobile propagation measurement system capable of measuring a number of important propagation parameters, including path loss. The designers were confident that reliable clutter metrics could be derived from the measured data collected by that system. In 2014, a collaborative project was initiated with NIST to leverage NIST's metrology expertise to characterize this ITS propagation measurement system, perform an uncertainty analysis, and explore the development of clutter metrics from the data it collects.

During the course of FY 2015, ITS worked with NIST mathematicians and statisticians to understand the characteristics of a vector spectrum analyzer (VSA) based CW measurement system. Initial measurements were made in the vicinity of the Boulder Laboratories. Figure 1 shows the basic transmission gain for a transmitting antenna on the Green Mountain Mesa west of the Boulder Laboratories along a drive route in two nearby neighborhoods (shown by the orange and yellow outlines) with a uniform distribution of trees and one-story homes. This drive route was used for many small studies to understand the measurement system's uncertainties.

## Results

Clutter metrics were obtained by subtracting the difference between the ITM model prediction and the measured data and computing a probability distribution. Figure 2 shows a plot of elapsed time in seconds versus the measured basic transmission gain, the ITM predicted median basic transmission gain, and the free-space predicted transmission gain. The extent of the two neighborhoods, Martin Acres and Drexel-Claremont, is shown. Clutter metrics obtained from these areas of the graph are shown in Figure 3.

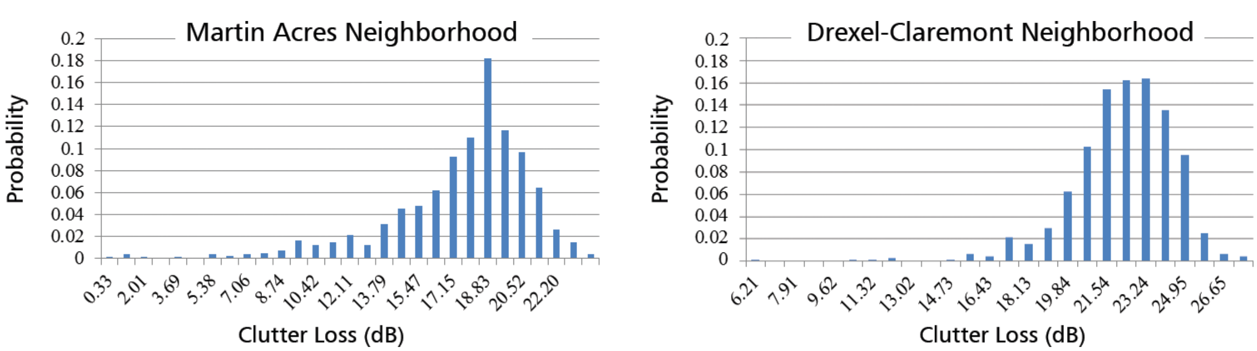


*Figure 3. Clutter metrics from the Martin Acres and Drexel-Claremont neighborhoods for a transmitter on Green Mountain mesa.*

A technical report to be released in early 2016 describes the measurement system and propagation measurements in the Martin Acres neighborhood, at Table Mountain near Boulder, in downtown Denver, and in San Diego, CA. It includes an uncertainty analysis of the VSA, which speaks to the reliability of the measurement system, as well as measurements and antenna pattern testing completed at the Table Mountain facility.

## SST&D Clutter Measurements, Phase I

### Objective

- *Refine and validate propagation clutter loss models*

The 2004 Commercial Spectrum Enhancement Act allows federal agencies to recover costs associated with engineering studies to determine the feasibility of spectrum sharing arrangements.[1] From these funds, DoD received approval to fund an overarching activity called the Spectrum Sharing Test & Demonstration (SST&D) Program. A major requirement of the SST&D Program is to improve measurements and models of propagation path losses between DoD operations and commercial operations.

The initial thrust of the SST&D program was to refine and validate the propagation clutter loss model that was developed to support the original CSMAC analysis that led to agreement on reduced protection/coordination zones in the AWS-3 bands (1695–1710 MHz, 1755–1780 MHz, and 2155–2180 MHz). That model included a clutter loss estimate of uniformly-distributed clutter losses of 10–20 dB and 0–10 dB, for urban/suburban and rural environments, respectively. These clutter losses were added as end point corrections to terrain-dependent path loss predictions and the revised predictions led to reductions in the coordination zones originally recommended by CSMAC.

The FCC established service, allocation, and technical rules for sharing in the AWS-3 bands that include requirements for commercial wireless broadband operators to coordinate with the federal agencies when seeking to build out systems in the 1695–1710 MHz and 1755–1780 MHz bands. The *Radio Frequency Coordination Portal* described on page 55 establishes a mechanism to handle requests for coordination in the first of those bands, but all federal agencies will need to perform the technical analysis to negotiate the sharing terms for each new entrant system. This adds urgency to the need to develop a validated clutter loss model to which many interested parties can lend confidence.

As part of the validation of the proposed propagation clutter loss model, the SST&D will measure clutter losses in locations representative of sites under consideration for wireless carrier coordination requests. Working in collaboration with the Defense Spectrum Organization (DSO), ITS developed a technical approach to refine the original clutter estimates. Work began in September 2015. Phase 1 of this effort involves clutter loss measurements and post-processing of measured data which will be used to validate and/or modify the end-point corrections to the terrain-dependent path loss predictions.

Initial propagation measurements were carried out in FY 2015. In San Diego, CA, measurements were taken at 1760 MHz, from two transmitting locations (downtown San Diego and the Point Loma/La Jolla area) as shown in Figure 1. Measurements in Denver, CO, were taken at 1761.5 MHz at three different transmitting locations, including the downtown Denver area, as shown in Figure 2. Measurements in and around both of these cities will enable DSO to refine the ground-to-ground clutter estimates used to evaluate coordination requests submitted by the commercial wireless carriers. These clutter estimates will be further refined in ongoing analysis under the SST&D program. Future measurement locations include the Washington, D.C., metropolitan area, Los Angeles, CA, and possibly other military installations as required by DSO. These estimates will also be compared to existing land-use, land-cover databases to understand how these databases could inform future estimates.

1. The Spectrum Relocation Fund was established by §204 of the Commercial Spectrum Enhancement Act of 2004 (CSEA), enacted as Public Law No. 108-494, and codified at 47 U.S.C. §928. CSEA was amended in 2012 and again 2015 to expand the types of engineering studies covered by the fund.


*Figure 1. Snapshots of San Diego measurement campaign. Push pins in Google Earth™ show transmitting locations from the CNM maintenance facility and the Navy submarine base; drive routes are shown by the purple traces. The transmitting truck is shown in the center photo and the receiving van is shown in the lower right photo. Map data ©2015 Google.*

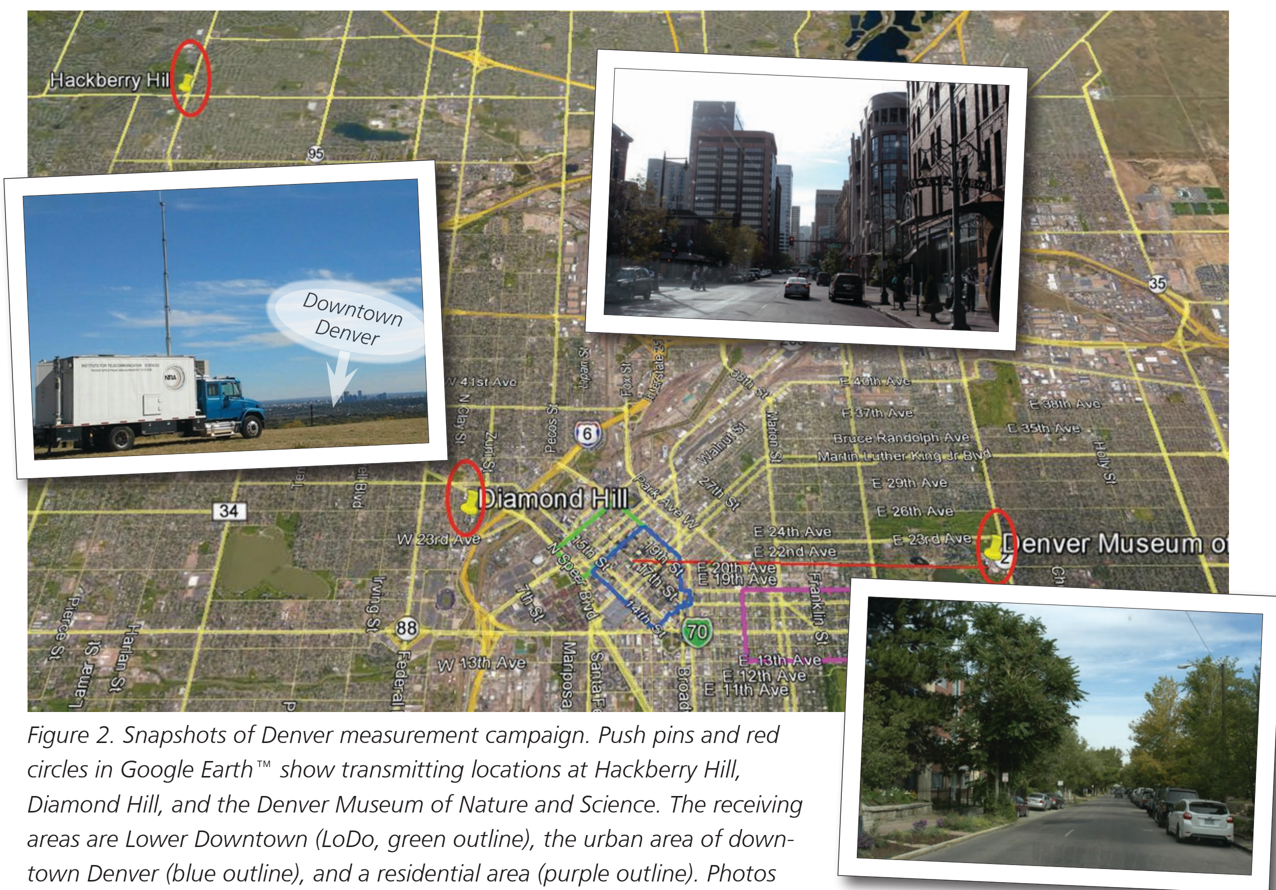


*Figure 2. Snapshots of Denver measurement campaign. Push pins and red circles in Google Earth™ show transmitting locations at Hackberry Hill, Diamond Hill, and the Denver Museum of Nature and Science. The receiving areas are Lower Downtown (LoDo, green outline), the urban area of downtown Denver (blue outline), and a residential area (purple outline). Photos show the transmitting truck at Hackberry Hill overlooking downtown Denver (left), the buildings in the urban corridor (center), and the residential neighborhood (right). Map data ©2015 Google.*

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# National and International Standards Development

ITS research also supports the development of national and international standards for radio devices and spectrum allocation. Strong and unbiased standards for propagation modeling, delineating interference protection criteria, and describing performance parameters for transmitting and receiving equipment are fundamental for advancing new technologies in a shared spectrum environment. In the International Telecommunication Union (ITU), spectrum sharing manifests as international coordination of spectrum use across borders and standards for fair competition in the global information and communications technology sector. ITS contributes to the development and application of national and international telecommunication standards by leading, participating in, and making technical contributions to national and international telecommunication standards development organizations (SDO), such as the 3rd Generation Partnership Project (3GPP), the ITU, and the Alliance for Telecommunications Industry Solutions (ATIS).

*Dr. John Howard Dellinger led the NBS Radio Section through its evolution into the Central Radio Propagation Laboratory, ITS's direct predecessor, from 1919 to 1949. He represented the U.S. at the 1927 International Radiotelegraph Conference in Washington, D.C., which laid the groundwork for the 1932 merger of the International Telegraph Conference and International Radiotelegraph Conference to form the ITU.*

ITS provides technical expertise and guidance in the development of telecommunications standards to these SDOs and, through interagency agreements, to other federal agencies as needed. ITS recommendations are highly valued both nationally and internationally. Other offices of NTIA participate in the same SDOs in different, non-technical capacities. In FY 2015, NTIA staff held 14 Chair, Co-chair, or Vice Chair positions in these bodies, providing technical leadership that is trusted by commercial-sector and international participants (see page 82 for a complete list). As representatives of the U.S. Administration, NTIA/ITS staff advocate globally for communications technology standards and policies that encourage competition and innovation.

ITS experts, working closely with policy experts from NTIA's Office of International Affairs, provide technical expertise to the ITU, a treaty organization that serves as a neutral venue for shaping global consensus on the standards that enable a seamless robust, and reliable, global communications system. The ITU holds the World Radiocommunication Conference (WRC) every two to three years to establish frequency allocations and regulatory procedures for the harmonious operation of global radiocommunication services. Global coordination of spectrum allocations ensures that services are not impaired by interference of competing signals and transmissions. ITU standards (called Recommendations) act as defining elements in the global infrastructure of information and communication technologies and play a critical role in advancing global interoperability and creating a level playing field in which companies can compete internationally.

Working with the U.S. ITU National Committees, ITS provides technical contributions and leadership to ITU-R (Radiocommunication Sector) and ITU-T (Telecommunication Standardization Sector) committees that develop technical Recommendations of importance to U.S. industry and government. ITU Recommendations are developed by consensus in Study Groups of public and private sector experts who provide input in the form of technical contributions. ITS also develops and coordinates approval of related U.S. voluntary consensus standards where appropriate. ITS founded and continues to play a significant role in the Video Quality Expert Group (VQEG), which is presently focused on collaborative efforts to develop new and improved methods for subjective and objective video quality assessment to submit to the ITU-T for standardization. Key national quality-of-service standards developed under the American National Standards Institute (ANSI) accredited Committee T1 for video, audio, and digital data also incorporate research results obtained at ITS.

# ITU-R Standards Activities

## Objectives

- *Develop and maintain internationally standardized RF propagation models*
- *Represent U.S. technical propagation issues before ITU-R SG3 and provide expert advice on the content and theoretical under-pinning for ITU-R documents*
- *Update RF propagation models to reflect advances in measurement and theory*
- *Contribute to domestic and international correspondence groups on propagation issues such as interference studies, earth-to-space links, and in-building communications*

## Background

The ITU-R has been called the single most important international telecommunications and regulatory standardization body. Entities such as government agencies, businesses, and academia rely on ITU-R developed recommendations to plan, study and design radio communication system. ITS has a long history of representing technical propagation issues that are important to U.S. interests to the ITU-R.

*ITS's Paul McKenna (center), International Chair of ITU-R Working Party 3K (Point-to-area propagation), convenes the opening plenary at the ITU headquarters in Geneva, Switzerland, in April 2015. Photo by Tim Riley.*

Within the ITU-R, Working Parties draft recommendations, reports, and handbooks that are reviewed and ultimately proposed for adoption by Study Groups. Once approved, these form the technical bases for decisions made at the World Radio Conference (WRC). ITU-R Study Group 3 (SG 3) is responsible for technical documentation on propagation issues, identifying relevant propagation effects and mechanisms and providing propagation prediction methods and models. ITS propagation work underlies a plurality of the propagation (P) series Recommendations, which guide the design and operation of radiocommunication systems and services worldwide and inform assessments of spectrum sharing.

In preparation for ITU-R SG 3 meetings, ITS leads a team of U.S. propagation experts who draft and review the U.S. technical input for the submission by the State Department. ITS provided leadership to two of the four Working Parties at April 2015 meetings and authored six of the eleven technical contributions on various engineering issues and subject areas submitted by the U.S. during the 2015 ITU-R Study Group 3 meetings in May. ITS also led correspondence groups on building penetration loss and earth-to-air-to-space.

## Earth-to-Air-to-Space Propagation Models

Different propagation models have been developed and standardized for the unique characteristics of different RF bands and electromagnetic environments, including various service applications and deployment scenarios. For example, to accurately model transmission links for Earth-to-air, Earth-to-space, and air-to-space, the special conditions required to predict the transmission losses and interference levels must be included in the model. Unfortunately, only a few propagation models are appropriate for modeling propagation above 1000 m—such as for aeronautical and satellite links. Recommendation ITU-R P.528, "Propagation curves for aeronautical mobile and radionavigation services using the VHF, UHF, and SHF band," which was developed from the ITS model IF-77, is of particular interest because of its high altitude component. This high altitude component is critical for spectrum sharing studies among satellite services and between those services and terrestrial broadband services. A recent example in the U.S. is the set of engineering studies leading up to the AWS-3 auction in the U.S. As a result of this auction, terrestrial services will be seeking access to the 1695 MHz band, which has both national and international allocations for space-to-earth satellite transmissions. ITU-R models provide a critical tool to determine interference potential and asset protection strategies for incumbent satellite ground stations.

Related Publication:

*T. Rusyn, P. McKenna, C.Behm ITU-R Report P.2345-0 :Defining Propagation Model for Recommendation ITU-R P.528-3, http://www.itu.int/pub/R-REP-P.2345*

Six ITS staff traveled to Geneva, Switzerland, to participate in ITU-R SG 3 meetings April 18–May 2. Paul McKenna led the meetings of Working Party 3K as International Chair; Tim Riley participated as acting U.S. Co-chair of Working Party 3J; Chris Behm participated as U.S. Chair of Study Group 3; and Teresa Rusyn participated as Rapporteur of ITU-R Correspondence Group 3K3M-9. This ITS-led correspondence group for the revision of Recommendation P.528 has been developing and verifying a computational method for this Recommendation. In FY 2015, SG 3 approved a report on "Defining Propagation Model for Recommendation ITU-R P.528-3" jointly authored by Teresa Rusyn, Paul McKenna, and Chris Behm of ITS. This report provides a comprehensive description of the ITS propagation model IF-77, which predicts propagation for frequencies from 125 to 20,000 MHz for aeronautical and satellite services. The IF-77 model can be used in interference studies for frequency sharing involving aeronautical and satellite services to produce reliable predictions of interference levels with other systems and separation distances between Earth-based stations.

ITU correspondence groups and meetings provide venues to exercise new methods and models in a peer review forum so that they can confidently be proposed and approved for standardization. Two ITS engineers sought peer review of new propagation model implementations developed at ITS at the 2015 Study Group 3 Working Party meetings: Billy Kozma for an improved implementation of the LF/MF model and George Engelbrecht for the HF model developed for the Propagation Modeling Website (PMW).

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## ITU-T and Related Standards Activities

### Objectives

- *Promote QoS/QoE standards through leadership roles in ITU-T Study Group 9 and the Video Quality Experts Group*
- *Develop and present technical contributions with U.S. standards proposals and ITS research results*
- *Work within the ITU-T to improve working methods by helping to revise key Recommendations and Resolutions*

### Overview

The Institute's long-term goal in ITU-T and its North American partners, ATIS and the Society of Cable Telecommunications Engineers (SCTE), is to motivate the standardization of user-oriented, technology-independent measures of telecommunication service quality (QoS/QoE), and to relate those measures to the technology-specific performance metrics and mechanisms providers use to provision and operate networks. This work promotes fair competition and technology innovation in the telecommunications industry, facilitates inter-working among independently-operated networks and dissimilar technologies, and helps users define their telecommunication needs and select products and services to best meet them. This facilitates the optimization and efficient use of spectrum and bandwidth resources.


*ITS's Arthur Webster has chaired ITU-T SG 9 for several years.*

## ITU-T Study Group 9

ITU-T SG 9 (Broadband cable and TV) studies the use of telecommunication systems to broadcast television and sound programs and of cable television networks to provide interactive video services, telephone, and data services, including Internet access. Recommendations standardized by ITU-T SG 9 define video and multimedia quality assessment and support emergency telecommunications over broadband cable networks. SG 9 also develops Recommendations on digital transmission systems, digital rights management, and program insertion specifications, all for cable television systems. In FY 2015, ITS researchers presented four U.S. technical contributions based on ITS research at the SG 9 meeting. ITS staff served as International Chair of SG 9, Head of the U.S. Delegation to SG 9, and Co-chair of the Intersector Rapporteur Group on Audiovisual Quality Assessment (IRG-AVQA), as well as SG 9 representative for Audiovisual Media Accessibility (AVA), Associate Rapporteur for Questions 2/9 (Measurement and control of the end-to-end quality of service (QoS) for advanced television technologies) and 12/9 (Objective and subjective methods for evaluating perceptual audiovisual quality in multimedia services within the terms of Study Group 9), and SG 9 contact for Electronic Working Methods.

## VQEG

The Video Quality Experts Group (VQEG) enables video experts from many countries to collaborate in developing and evaluating video quality metrics (VQM). The group's reports strongly impact the standardization of VQMs in both ITU-T and ITU-R. VQEG works largely via several e-mail reflectors, publicly accessible at http://www.VQEG.org. In FY 2015, over 500 participants were subscribed to the main reflector. VQEG produces independent validation data, which the U.S. considers to be a key prerequisite for standardizing a VQM. Thus, VQEG acts as a cooperative technical advisory committee that facilitates standardization efforts in ITU-T SG 9, SG 12 (Performance and Quality of Service (QoS)), and ITU-R WP 6C (Broadcasting Services—Programme Production and Quality Assessment) to develop objective, computer implementable, perception-based video and multimedia quality metrics that emulate the human visual system. An ITS staff member co-founded VQEG and has co-chaired it since 1997. ITS is spearheading new ITU-T work on audiovisual quality assessment and Internet video quality assessment through its leadership in VQEG and ITU-T SG 9, and staff provide key leadership and technical contributions to VQEG. Arthur Webster and Margaret Pinson are VQEG co-chairs and Arthur chaired the two FY 2015 meetings. Margaret also co-chairs two working groups: audiovisual high-definition television (AVHD) and the Independent Laboratory Group (ILG).

## IRG-AVQA

In related work, ITS leads the ITU-T's Intersector Rapporteur Group on Audiovisual Quality Assessment (IRG-AVQA). This group supersedes the Joint Rapporteur Group on Multimedia Quality Assessment and is a cross-cutting ITU standards body that unites the video quality expertise of SG 9 and SG 12 in the ITU-T with the quality experts in the ITU-R SG 6 in an effort to develop objective, perception-based metrics for combined audio and video signals in mobile, broadcast, cable, and PC environments. In FY 2015, the IRG-AVQA held meetings concurrently with VQEG, ITU-T SG 12, and the ITU-R WP 6C. The IRG-AVQA provides an official mechanism for coordinating VQEG activities with ITU-T SG 9, ITU-T SG 12, and ITU-R SG 6.

## Preparation for U.S. Participation in ITU World Conferences

In addition to direct participation in the technical committees, an ITS engineer participated in the State Department's U.S. preparatory process for the Telecommunication Standardization Advisory Group (TSAG). Arthur Webster attended TSAG and the ITU-T Review Committee (REVCOM) on the U.S. Delegation and presented reports, as Chairman, on SG 9.

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# ITS Resources

## Audio Visual Laboratories

### Subjective Testing Facilities

Subjective testing means gathering opinions from a group of users. This is the most accurate way to measure the perceived quality of a phone conversation or video stream.

Designing a subjective test can be tricky. The way one asks a test subject's opinion can influence the answer the person will give. Experts create ITU Recommendations that list "best practices." These attempt to minimize unwanted influences on a subject's answer. When subjective tests are designed with care, they can be highly repeatable; that is, results are the same regardless of where or when the test takes place.

A controlled test environment can enhance repeatability. A person's attention is focused on the task at hand since the lighting and background noise are controlled and there are no visual distractions. A controlled room also frees the experimenter from considering environmental variables when analyzing the test results. ITS has three such rooms: two are identically constructed sound isolation chambers; one is a secluded, quiet room.

The two identical sound isolation chambers can be connected to allow two persons to converse using audio, video, or both. This type of testing can reveal problems that are not apparent when people only listen to audio recordings or view recorded video. Key examples are delays in live audio and video—if either delay is too great, communication can be impaired.

The third subjective test room is a larger, quiet room with a window. This room provides flexibility, but a little less control. Currently, the third test room looks like a living room. This sets a different context for questions about audio and video quality. With these facilities ITS can perform testing in highly controlled environments or in more relaxed and realistic conditions. The choice is just one of many choices made by ITS experts when designing a subjective test.

*Audio Visual Laboratory facilities at ITS. Top: The video workstation includes a broadcast quality television, studio quality speakers, and uncompressed capture of HDTV. Acoustical foam reduces background noise, so that subtle audio impairments can be heard. Middle: Subjective test room set up as a real world living room. Bottom: Sound isolation booth set up for an audiovisual subjective test, with a broadcast quality television and studio quality speakers. Photos by Andrew Catellier.*

### Unique Capabilities

Because subjective testing is so time intensive and requires such expensive resources, only a few organizations in the United States perform them. Significant expenses are:

- Subjective test facility construction and operation
- Accurate audio and video play back
- Experiment design and implementation
- Production of audio and video recordings that match the test purpose
- Simulation of audio and video systems

ITS has proven expertise in designing and conducting subjective experiments. Over the past decades, ITS has answered dozens of key questions related to the perception of video and audio quality and the effects of distortions and has published the results in the refereed literature and in NTIA reports.

One surprisingly difficult problem is audio and video playback. Many audio and video players cannot guarantee that every person will see and hear exactly the same audio or video. ITS uses studio-quality hardware and special purpose software tools to ensure reliable playback. These playback systems often push cutting-edge computer hardware to its limit.

Simulating modern audio and video distribution is expensive because there are many methods in use in the telecommunication industry. The ITS audiovisual lab has a variety of hardware and software tools that encode, transmit, or play audio and video, and simulate how people use audio and video today. These tools span a wide range of audio and video services:

- Broadcast quality audio and video
- Satellite and cable TV
- Video on demand
- Streaming Internet video
- Video teleconferencing
- Cell phone audio and video
- VoIP

The ITS audiovisual lab supports standard definition (SD) television, high definition television (HDTV), three-dimensional television (3DTV), and monophonic, stereophonic, and 5.1 channel audio streams. Available equipment includes:

- Studio quality analog and digital video recorders with 2 to 8 audio channels
- Digital audio recorders
- Analog audio mixing, filtering, and equalization
- Studio quality video monitors, monitor loudspeakers, and headphones
- Telephone handsets
- Subjective test chambers compliant with ITU-T Rec. P.800, ITU-R Rec. BT.500, and ITU-T Rec. P.900
- Various hardware and software encoders and decoders
- Internet protocol network error simulator compliant with ITU-T Rec. G.1050

### Supporting Public Safety Communications

These long-standing ITS facilities and expertise areas have engendered additional facilities more specifically targeted to audio and video testing in the context of public safety communications. One of the most challenging aspects of public safety speech communication is the harsh noise environment in which public safety practitioners must effectively establish and conduct communications. ITS often tests systems to determine speech intelligibility levels under these conditions. This work is enabled by two smaller acoustically isolated booths, and two head-and-torso simulators (HATS) with acoustically accurate artificial ears and mouths. The HATS systems are defined by the ITU in Recommendations P.58 (Head and torso simulator for telephonometry), P.57 (Artificial ears), and P.51 (Artificial mouth). These recommendations specify the physical characteristics and acoustical/electrical interface characteristics that enable a consistent simulation of the speaking and hearing frequency responses of the "average" human.

*An ITU-Standard head and torso simulator (HATS) set up in a sound-isolated booth for testing public safety communications. Photo by Andrew Catellier.*

The HATS enable consistent acoustic input to communications equipment under test and provide a "willing subject" that will not suffer hearing loss when exposed to harsh noise environments for extended periods. These unique systems are supported by a foundation of digital audio mixing and distribution equipment. All audio mixing, distribution, storage, and filtering are conducted in the digital realm with 48 kHz sampled audio. This provides a high-quality, distortion-free distribution system that is not impacted by other equipment in the laboratory. The digital capabilities include: digital mixing, 24 track digital recording, 8 channel digital input and output to Windows-based computers, digital audio tape (DAT), and 1/3 octave digital filters.

These tools provide reproducible signal paths that enable emulation of the harsh noise environments encountered by public safety practitioners. The recorded output from the system can be used in a number of ways. For example, the recordings might be analyzed by an objective measurement technique such as ITU Recommendation P.862 Perceptual evaluation of speech quality (PESQ) or an objective intelligibility estimator such as ABC-MRT (developed by ITS experts to support public safety communications). Alternatively, the recordings might be incorporated into a subjective test where listeners determine the intelligibility or the quality of the recorded signals.

Parallel work in video is supported by additional cameras, video capture systems, video coding and decoding systems, network simulators, video editing stations, and props. Video scenes containing selected elements unique to or typical of public safety responder uses are created and filmed on high-definition cameras. These scenes include simulations of surveillance cameras (indoor and outdoor), in-car police cameras, and search and rescue robot cameras. The video is then captured and edited on video workstations. Selected scenes are processed through controlled versions of the video transmission and storage systems that are typical of what a jurisdiction might consider purchasing. The communication systems processing includes compression schemes and simulated wired and wireless networks.

To determine if a system is adequate for use in specified applications, first responders view the video and attempt to perform certain tasks such as identifying an object or reading a license plate. The results of these tests provide crucial data regarding suitability of video systems for specific applications in the burgeoning world of first responder video applications.


*Video sequences used in public safety video quality research represent public safety responder use cases. Top: In a sequence filmed during a simulated accident training exercise, emergency medical technicians respond to a burn patient inside an ambulance. A doctor in a remote hospital location uses visual and audio cues provided by the audiovisual transmission to asses the patient's condition. Bottom: The responder's ability to identify the license plate number in this surveillance camera sequence is tested. Stills courtesy of www.cdvl.org.*

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## Radio Frequency Measurement Capabilities

ITS designs, develops, and maintains a number of mobile and static radio frequency (RF) measurement systems that address a very broad range of wireless scenarios in frequencies from 10 MHz to 300 GHz.

- The RSMS system allows mobile or stationary RF measurements from 10 MHz to 40 GHz, both in laboratory settings and at field sites, attended or unattended (i.e., manually operated or automated).
- A fixed ultrawideband propagation measurement system covers a frequency range of 20 MHz to 18 GHz at distances of 2–300 meters for high precision measurements used in model validation.
- Another mobile propagation measurement system covers a frequency range of 20 MHz to 30 GHz and operates at ranges up to several kilometers in rural, suburban, and urban environments.
- A recently developed microwave frequency propagation measurement system operates between two vehicles outdoors and can be adapted to operate outdoors-to-indoors by removing one of the systems from a vehicle and placing it indoors as a suitcase system; it currently operates at distances of up to tens of kilometers and at frequencies up to 5 GHz, but can be adapted to work at higher frequencies.
- An automated wideband noise measurement system captures an entire noise signal in up to 36 MHz of bandwidth with I and Q samples, allowing complete reconstruction of the noise for later analyses.

- Spectrum compatibility test and measurement sets generate selectable types of interference for testing and measurement of receiver responses.

All measurement systems are modular and easily configurable for specific measurement purposes. For example, in FY 2013, ITS designed and configured a unique measurement system optimized to detect specific signal types for 3.6 GHz maritime radar band occupancy measurements. In addition, an extremely high frequency (EHF) measurement system for frequencies from 30 to 300 GHz is currently under development as part of the Millimeter Wave Research program described on page 48.

### Radio Spectrum Measurement System

The RSMS measurement system includes a comprehensive suite of test equipment, custom-built hardware and software, specialized measurement and analysis techniques, and the extensive expertise of engineers with years of radio frequency (RF) research experience. The program's objective is to ensure that the Institute has access to the most advanced software and hardware so that it can perform accurate and complete RF measurements of all types of radio systems between 10 MHz and 40 GHz. The RSMS system and related ITS engineering expertise are available for use by industry and other government agencies on a cost-reimbursable basis under CRADAs and IAs, respectively.

#### *RSMS Hardware*

While not defined by any single hardware configuration, the RSMS system uses state-of-the-art spectrum analyzers, digital oscilloscopes, vector signal analyzers, vector signal generators, and signal intercept and collection systems. This equipment is often fused with RF preselectors, custom built by ITS engineers using state-of-the-art microwave components, to allow measurement of high-dynamic-range signals such as those from radars and communication systems. Overall measurement dynamic range of up 130 dB can be achieved by RSMS systems, extending the nominal 70 dB instantaneous dynamic range of most off-the-shelf precision test equipment. The modular design of the RSMS measurement platforms allows mobile or stationary measurements, in laboratory settings or at field sites. Deployments can use the fourth generation (RSMS-4) mobile laboratory or be constructed at field sites from individually-shipped modules.

#### *RSMS-4 Mobile Laboratory*

An integral part of the system is a measurement vehicle, now in its $4^{th}$ generation. The vehicle has a highly-shielded enclosure (60 dB isolation from the ambient environment) with three full-size equipment racks, three 10 meter telescoping masts, and a 20 kW diesel generator with power conditioning, as well as Internet connections and a climate control system. The RSMS-4 mobile laboratory can be deployed to remote field sites where many operational systems are located and can operate independently from systems under test.

RSMS-4 mobile measurement lab.

#### *RSMS-5G Software*

The RSMS software package is now in its $5^{th}$ generation (RSMS-5G) of development. It is dynamic and flexible, incorporating automated, semi-automated, and manual techniques for radio emission measurement and analysis. ITS used the latest software tools to develop this version, simplifying the design and implementation of new measurement algorithms. The resulting package decreased dependency on third party software. Compatibility with multiple operating systems has extended the application life-cycle, reduced overall costs, and provided flexibility to continue to keep pace with rapid advances in RF technology.

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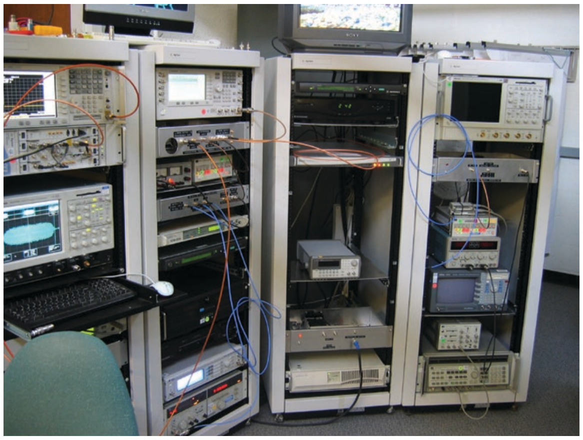
### Ultrawideband Propagation Measurement System



*Ultrawideband propagation measurement system.*

Over the past five years, a new ultrawideband propagation measurement system has come on line. It consists of a commercial-off-the-shelf vector network analyzer (VNA), transmit and receive antennas, and an analog optical link. The VNA is configured to perform two-port S-parameter transmission measurements between fixed transmit and receive antennas. The system covers a frequency range of 20 MHz to 18 GHz and is used to measure time- and frequency-domain propagation phenomena at distances of up to 300 meters. It is configured in a stepped-frequency mode, and $S_{21}$ data (amplitude and phase) are acquired and stored. The resulting frequency-domain data are post-processed, inverse Fourier transformed, and time gated to yield propagation parameters such as delay spread and basic path loss.

This system has high accuracy and is ideal for precision propagation measurements and model development/validation. The frequency- and time-domain signal processing yield high-dynamic range and excellent immunity to RF interference. The system transmits very low power levels (typically +5 dBm) and has low interference potential to existing wireless services. It has been used extensively for near-Earth propagation measurements at Table Mountain with excellent path loss and channel impulse response data obtained. Indoor and building penetration measurements are also performed using this system. This system also has excellent range resolution capabilities that permit the isolation and evaluation of selected propagation events.

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### Mobile Propagation Measurement System for Frequencies from 20 MHz to 30 GHz

The mobile propagation measurement system developed in FY 2012 for improved outdoor noise measurement has two operational modes: (1) narrowband channel probe and (2) broadband channel probe. The narrowband mode has high accuracy, dynamic range, and sensitivity, and excellent immunity to interference. A continuous wave (CW) signal is transmitted and received using a spectrum analyzer, vector signal analyzer, or sound card/communications receiver combination. The received data contain path loss, a slow-fading profile, and fast-fading information. The system is operated as a broadband channel probe by applying binary phase shift keying (BPSK) modulation to the transmitted signal using a pseudorandom number code with a user-selectable number of bits. Post-processing yields a channel impulse response from which useful parameters (e.g. delay spread, basic path loss) can be extracted. It is capable of measuring fast- and slow-fading phenomena and path loss.

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### Microwave Frequency Propagation Measurement System

*Mobile measurement van.*
*The weather cover at right protects the telescoping mast during travel. A 3.5 GHz omnidirectional antenna is racked for travel and will be mounted on the fully extended mast during measurements.*

The system consists of a mobile receiver in a modified utility van which receives signals from a transmitter in the RSMS-4 Mobile Laboratory parked at a fixed located. The transmitter sends a highly stable (rubidium-standard referenced) carrier wave into space. The receiver, which carries its own, matched rubidium oscillator on-board, processes the received signal as the mobile van moves through various locations. The on-board receiver uses a high-speed digital system to record the complex (I-Q) waveform of the propagation signal as a function of environment. The resulting data show the Doppler characteristics and attenuation of the transmitted signal for long mobile-van runs through urban, suburban and rural areas. For outdoor-to-indoor measurements, the receiver system in the van is removed as a suitcase system that is carried into buildings where data are to be acquired.

After a series of runs in field areas (typically lasting about a week per trip), the recorded data are returned to the ITS Boulder lab. There, they are analyzed to produce graphs that show propagation characteristics as a function of location through all of the runs in the target areas. These graphs are compared to the predictions generated with existing ITS propagation models. Differences are used to modify and improve the models, so that the model outputs more closely approximate those of the real world.

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### Automated Wideband Noise Measurement System

The ITS automated wideband noise measurement system consists of an antenna, ITS custom-built preselector, vector signal analyzer (VSA), and personal computer. The cornerstone of the system is the VSA that permits wideband noise measurements in up to 36 MHz of bandwidth and the recording of digitized in-phase/quadrature (I/Q) samples of the entire noise signal.

The ability of this system to record actual I and Q signal data in a wide bandwidth provides many options for processing and further use of the data. The preselector contains a fixed bandpass filter tuned to the measurement frequency, a low pass filter, and a low-noise amplifier (LNA). The filters can be easily exchanged to conduct noise measurements at different frequencies. This configuration provides for a very sensitive measurement system with a noise figure of approximately 3 dB. The system uses a quarter-wave monopole antenna, tuned to the desired measurement frequency and mounted on a ground plane.

A personal computer runs software developed by ITS to control the noise measurement system. This software allows the user to set the measurement frequency, bandwidth (span), number of data points, and other parameters. Once the measurement is started, the software will automatically collect data at user-defined time intervals for a user-specified duration. The software also performs and displays results of noise diode calibrations, spectrum captures, and single manual noise measurement data captures. To provide a high degree of RF shielding between the measurement equipment and the antenna, as well as AC power, temperature control, and shelter, the noise measurement system is operated in the RSMS-4 mobile laboratory.

The system limitations on dynamic range, analog sampling rate, limited anti-aliasing filtering, an internal-only intermediate frequency (IF) filter, and a restriction on center frequency agility. A new, two-channel measurement system design will address these limitations. It consists of one very sensitive RF channel and another less sensitive RF channel. Measurements are taken on both channels simultaneously with processing used to extract the composite data.

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### Spectrum Compatibility Test and Measurement Sets

The introduction of new radio technologies in close physical and frequency proximity to older ones can result in electromagnetic compatibility (EMC) problems. Although theoretical models and simulations provide useful information in guiding design decisions, the complexity of modern systems and the existing spectral environment often require real-world measurements of a proposed system's effects within its operating environment to determine its impact on other spectrum users.

Another problem is to adequately produce controlled interfering signals with known characteristics in environments where suspected interferers may be unavailable for tests and measurements. This includes laboratory investigations of possible interference from ship- or aircraft-mounted radars or terrestrial or space-based communications systems. In these situations, a system is needed that simulates the spectral emissions of other devices with high fidelity. An example of these needs is the requirement to determine thresholds at which interference from communication transmitters becomes observable in radar receivers.

Another example would be to determine the source(s) of interference from terrestrial services to space-based communication links.

To meet these needs, ITS engineers have developed capabilities to generate interference signals. These signals can be coupled directly into a system under test or they can be transmitted through space into a target system's receiver to more accurately gauge its response to a real interference situation.

ITS engineers generate interference by first using high-speed digitizers (vector signal analyzers (VSA)) to record interference waveforms in bandwidths up to 160 MHz. They subsequently radiate or hardline couple those signals into victim receivers using vector signal generators (VSG). Alternatively, VSGs may be pre-programmed with the requisite mathematical information to create particular waveform modulations, such as quadrature phase shift keyed (QPSK) signals.

The ITS interference signals can be transmitted with high-power amplifiers to generate high-power interference at frequencies up to 26 GHz. The advantages of using VSGs to generate interference include simplicity of operation and use, plus the ability to replicate very complex interference waveforms with complete confidence in the fidelity of the simulated signal to the characteristics of the original signal from which it was derived.

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## Public Safety Broadband Demonstration Network and Laboratory

The Public Safety Broadband Demonstration Network (PSBDN) supports research under the Public Safety Communications Research (PSCR) program. The PSBDN is hosted by NIST and co-operated and co-managed by NIST and ITS, using shared IT equipment. It not only supports lab connectivity for research efforts, but also provides a full LTE network for over-the-air (OTA) testing, using both Government-furnished equipment and equipment provided by industry partners under CRADA, including prototypes of new equipment under development. The PSBDN operates in the public safety broadband spectrum (LTE band class 14) allocated to FirstNet and allows end-to-end testing of LTE systems and configurations in a multi-vendor environment so that interested public safety agencies can observe these systems and execute specific test cases that are unique to their operational environment. LTE load testers, walk/drive test equipment and vehicles, digital and analog LMR radio test equipment, RF faders, signal generators, signal analyzers, spectrum analyzers, and other test equipment support a wide variety of tests and measurements of LTE, P25, and many other Radio Access Network (RAN) systems. Comprehensive test can be conducted on individual components in isolation or on the network or communications system as a whole, as well as internetwork and intersystem testing. A variety of packet capture systems support back end network testing for LTE and LMR systems for real-time network monitoring and diagnostics. A multi-server blade system and five virtual hosts provide high-performance computing capacity for hosting network applications and core network services, and for processing test data.

*ITS engineer Anton Nguyen-Vu adjusts the network configuration in preparation for a test of LTE priority mechanisms in the Public Safety Broadband Demonstration Laboratory. Photo by Jaydee Griffith.*

During FY 2015, changes and upgrades focused on streamlining network configuration and management, including connection to NIST's eNIST network. An architecture overhaul implemented network compartmentalization and increased network security between segments. The PSBDN is made available through CRADAs for manufacturers and carriers. It serves as an educational site for by allowing

### LTE Capabilities

The network currently supports both band class 14 Public Safety LTE systems and Band 13 Commercial LTE systems across a variety

*Two cell-on-wheels (COW) units can extend the reach of the fixed nodes on the Public Safety Broadband Demonstration Network. Photo by Jaydee Griffith.*

of vendors. The RAN includes both in-lab "toy" cells and active remote sites. Core network equipment in the lab consists of a Government-owned packet core as well as other packet cores provided under CRADA. CRADAs protect manufacturer proprietary information while making the equipment available for intensive testing under both laboratory and OTA conditions. This has allowed the introduction of a very broad variety of user equipment (UE) in various form factors (smartphones, tablets, USB "dongles," and in-vehicle modems) and multiple bands into the test environment for realistic interoperability assessment.

P25 Land Mobile Radio (LMR) Capabilities

The PSBDN lab has four P25 trunked LMR systems from two vendors, providing a range of features as well as VHF and UHF capabilities. These systems have been used in LMR-LTE integration projects using both the P25 native ISSI interface as well as baseband audio over SIP to provide audio and control integration over the LTE networks.

Over-The-Air (OTA) Coverage and Backhaul Connectivity

PSBDN coverage is provided by three fixed eNodeB sites, one in the laboratory and two at field sites. The Green Mountain Mesa site sits west of the main DoC campus in Boulder, providing local area band class 14 coverage for the DoC campus and vicinity. The Table Mountain field site is about 14 kilometers north of the DOC campus and provides coverage to the Table Mountain field site testing areas as well as North Boulder. The network also supports two cell-on-wheels (COW) units to provide portable network extension to specific geographic locations for additional testing. On an as-needed basis, researchers can access dark fiber on the Boulder Research and Administrative Network (BRAN), a secure fiber optical network shared by the city of Boulder, the University of Colorado at Boulder, the National Center for Atmospheric Research (NCAR), and the Boulder Department of Commerce Laboratories for high-speed backhaul (1 GB/s) connectivity.

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## Green Mountain Mesa Field Site

The Green Mountain Mesa Field Site is located on the main Department of Commerce Boulder Laboratories campus. The site is used year round for outdoor wireless network research and was extensively refurbished in FY 2010. Improvements included installation of a portable building situated on a concrete pad to securely house the fiber and power distribution. A new 16.8 meter (55 foot) tower was also constructed and raised to support research and evaluation of LTE 4$^{th}$ generation wireless technology. The site is connected to the ITS laboratories via fiber optic link, and to the Table Mountain Field Site via microwave link. The fiber optic link provides access to the ITS local area network (LAN) . The site can provide six independent duplex fiber channels to the ITS lab.

A 24 meter (80 foot) tower provides a structure on which to mount transmitting antennas to perform propagation measurements or other radio frequency experiments. The site's unique location, several hundred feet above the main Department of Commerce campus, allows for the provisioning of wireless test links over large portions of eastern Boulder County.

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*Antenna towers at the Table Mountain Field Site support one of three fixed nodes on the Public Safety Broadband Demonstration Network. The white cylinders on the tower on the left are an array of 700 MHz LTE antennas; below that a microwave antenna connects one field site to the other. Other antennas support different communication systems for OTA testing. Photo by Jaydee Griffith.*

## Table Mountain Field Site and Radio Quiet Zone

The Table Mountain Field Site and Radio Quiet Zone is located north of Boulder and extends about 4 kilometers (2.5 miles) north-south by 2.4 kilometers (1.5 miles) east-west, an area of approximately 1,800 acres. The site is designated as a Radio Quiet Zone where the magnitude of external signals is restricted by state law and federal regulation to minimize radio frequency interference to sensitive research projects. Site power distribution is by means of buried line to avoid interference. Partnerships and cooperative research activities with other entities are encouraged at the site—see the articles on CRADAs for the Use of Table Mountain on page 7 and Interagency Agreements for the Use of Table Mountain on page 10.

Facilities at the site include:

- Spectrum Research Laboratory—A state-of-the-art facility for research into radio spectrum usage and occupancy. Radio Quiet restrictions ensure that no signal incident on the mesa overpowers any other.
- Open Field Radio Test Site—As a flat-topped butte with uniform 2% slope, Table Mountain is uniquely suited for radio experiments. Lack of perimeter obstructions and relatively homogeneous ground facilitates studying outdoor radiation patterns from bare antennas or antennas mounted on structures.
- Mobile Test Vehicles—There are several mobile test equipment platforms available at the site, ranging from four-wheel drive trucks to full-featured mobile laboratories.
- Large Turntable—A 10.4 meter (34 foot) diameter rotatable steel table is mounted flush with the ground. Laboratory space underneath houses test instrumentation and control equipment, and motors to rotate the turntable. The facility can be operated remotely by computer.
- Two 18.3 Meter (60 Foot) Parabolic Dish Antennas—These two antennas are steerable in both azimuth and elevation and have been used at frequencies from 400 MHz to 6 GHz.
- A 3.7 Meter (12 foot) Dish Antenna—This computer controlled antenna is capable of tracking low earth orbiting satellites
- Radar Test Range—A large open space just south of the Spectrum Research Laboratory is available for testing radar systems.

Learn more online at: http://www.its.bldrdoc.gov/resources/table_mountain.

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## Radio System Software Simulator

Spectrum sharing is based on interference protection criteria (IPC) such as the allowable interference power to noise power ratio (INR). The allowable INR ensures that performance of federal radio services is not degraded to the point where the service can no longer satisfy its mission.

Allowable INR is usually determined with radio system field measurements. In these measurements, engineers measure radio system performance as they vary interference power. Typically, a vector signal generator is used to inject the interfering signal into the receiver. For a communication system, performance degradation might be measured with bit or packet error rates. For a radar system, the performance degradation is measured by probability of detection.

Field measurements have several disadvantages including

- Having to travel to the radio system location
- Having to remove the radio system from service while tests are performed
- Limited access to error rate or probability of detection performance metrics

A radio system software simulator on a computer in the laboratory can potentially overcome these difficulties. Simulations proceed in the same manner as field measurements, i.e., the interfering signal is injected into the receiver and performance is measured. However, the simulator can be used at any time in the engineer's office without having to take the system out of service. Performance metrics are readily accessible.

Another advantage of software simulation is unlimited access to intermediate signal processing signals. Access to these signals enables the engineer to identify subsystems that are most sensitive to the interfering signal and recommend ways to "harden" the victim receiver to the interference.

The off-the-shelf radio system software simulator used by ITS can emulate and interoperate with cellular equipment conforming to LTE Release 8/9 and LTE-Advanced Release 10 broadband radio services (BRS) standards, and with wireless local area networks conforming to IEEE 802.11 a, ac, ad, b, g, and n standards. The simulator is also capable of modeling non-coherent and coherent radar systems as well as non-linear effects such as amplifier gain compression. Finally, it can use the same vector signal generator interference waveform files used in field measurements to inject interference.

## Boulder Labs Frequency Manager

An ITS staff person acts as the Boulder Labs Frequency Manager, chairing the Boulder Labs Interference Committee. This committee protects the Department of Commerce Boulder Laboratories campus and the Table Mountain Radio Quiet Zone facilities from harmful radio frequency interference by evaluating new transmitters before they begin operating. Propagation analyses using various propagation prediction models or field measurements may be required to resolve potential electromagnetic interference problems.

The Committee has jurisdiction over all Government and private industry users seeking permission for frequency usage at the Table Mountain Radio Quiet Zone, and over stations in the area that meet the following conditions of effective radiated power (ERP) and radial distance:

- All stations within 2.4 km.
- Stations with 50 W or more ERP within 4.8 km.
- Stations with 1 kW or more ERP within 16 km.
- Stations with 25 kW or more ERP within 80 km.

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# ITS Activities in FY 2015

## Publications and Presentations in FY 2015

### NTIA Publications

**Frank H. Sanders, John E. Carroll, Geoffrey A. Sanders, Lawrence S. Cohen, "Measurements of Selected Naval Radar Emissions for Electromagnetic Compatibility Analyses," NTIA Technical Report TR-15-510, October 2014. http://www.its.bldrdoc.gov/publications/2781.aspx**

In response to proposals to introduce new Long Term Evolution (LTE) radio systems into the 3550–3650 MHz (called 3.5 GHz) portion of radio spectrum in the United States, a joint team of National Telecommunications and Information Administration (NTIA) and U.S. Navy electronics engineers performed measurements on the emissions of radars identified as Shipborne Radars 1 and 3 in the NTIA Fast Track Report. These radar types are deployed on many Navy surface vessels. Radar 1 operates in the band of interest; Radar 3 operates in adjacent spectrum. Although intentional Radar 3 emissions are not transmitted in the band of interest, it produces measurable out-of-band (OOB) and spurious emissions in the 3.5 GHz band. In this report, the authors present measured broadband Radar 1 and 3 emission spectra and time domain characteristics. These data encapsulate the OOB and spurious-region signal characteristics that possible future coastal broadband wireless base station receivers may see from these radars' operations in littoral waters. As such, these data may be used in electromagnetic compatibility analyses for future 3.5 GHz spectrum sharing.

*"An open exchange of scientific ideas, information, and research achieves the Department's vision for an informed society that uses objective and factual information to make the best decisions."* [1]

**William Kozma Jr., Joel Dumke, Brent Johnson, "An Algorithmic Approach to Optimizing Network Resources for Public Safety LTE Networks," NTIA Technical Report TR-15-511, December 2014. http://www.its.bldrdoc.gov/publications/2783.aspx**

This report examines the problem of how to allocate limited network resources in a public safety LTE network for the purpose of disseminating video streams to end users. We develop a mathematical model of the network environment, including the definition of a new metric called usefulness. We then apply known optimization techniques and algorithms to our model and analyze the results. We incorporate the concept of local control for public safety practitioners into our model through the use of a priority function and simulate its performance.

| *FY 2015 ITS Publication Downloads: Top 5* | |
|---|---|
| Edward F. Drocella Jr., James C. Richards, Robert L. Sole, Fred Najmy, April Lundy, and Paul M. McKenna, "3.5 GHz Exclusion Zone Analyses and Methodology," NTIA Technical Report TR-15-517, June 2015 | 495 |
| Frank H. Sanders, "Derivations of Relationships among Field Strength, Power in Transmitter–Receiver Circuits and Radiation Hazard Limits," NTIA Technical Memorandum TM-10-469, June 2010 | 384 |
| Stephen Wolf, "Color correction matrix for digital still and video imaging systems," NTIA Technical Memorandum TM-04-406, December 2003 | 375 |
| Geoffrey Sanders, John E. Carroll, Frank H. Sanders, and Robert L. Sole, "Effects of Radar Interference on LTE (FDD) eNodeB and UE Receiver Performance in the 3.5 GHz Band," NTIA Technical Report TR-14-506, July 2014 | 323 |
| George A. Hufford, Anita G. Longley, and William A. Kissick, "A Guide to the Use of the ITS Irregular Terrain Model in the Area Prediction Mode," NTIA Technical Report TR-82-100, April 1982 | 318 |

1. Department of Commerce Administrative Order DAO 219-1, Public Communications

**Geoffrey A. Sanders, John E. Carroll, Frank H. Sanders, Robert L. Sole, Robert J. Achatz, Emission Spectrum Measurements of a 3.5 GHz LTE Hotspot, NTIA Technical Report TR-15-512, February 2015.** http://www.its.bldrdoc.gov/publications/2790.aspx

In response to proposals to introduce new Long Term Evolution (LTE) radio systems into the 3550–3650 MHz (called 3.5 GHz) portion of radio spectrum in the United States, a joint team of National Telecommunications and Information Administration (NTIA) and U.S. Navy electronics engineers performed emission spectrum measurements on a 3.5 GHz (LTE Band 42) wireless access point (WAP), or hotspot. The hotspot was packaged for indoor use but similar systems could be deployed outdoors. The authors measured the hotspot emission spectrum with 110 dB of dynamic range across 1.5 GHz of spectrum (from 2.7 to 4.2 GHz). Other data outputs include: spectra measured with the device tuned to its lowest, highest, and middle available operational frequencies; comparative peak-to-average spectra; and spectra measured when the hotspot was operated with 10, 15, and 50 resource blocks. The emission spectrum is plotted against proposed in band, out-of-band (OOB) and spurious emission limits; the spectrum meets those limits by at least 10 dB at all points. The results presented here may be used in electromagnetic compatibility analyses for future 3.5 GHz spectrum sharing between LTE-based transmitters and incumbent systems such as radar receivers.

**Robert J. Achatz, Paul M. McKenna, Roger A. Dalke, Nicholas DeMinco, Frank H. Sanders, John E. Carroll, Effect of Broadband Radio Service Reallocation on 2900–3100 MHz band Marine Radars: Background, NTIA Technical Report TR-15-513, April 2015.** http://www.its.bldrdoc.gov/publications/2795.aspx

Spectrum reallocations may place broadband radio services (BRS) near spectrum used by 2900–3100 MHz band marine radars. Interference effects from these reallocations include unwanted emissions in the radar detection bandwidth and front-end overload. This report provides background information for subsequent reports that analyze these effects. Interference protection criteria (IPC) are identified, an interference scenario is described, and models for the radar system, BRS system, radar target, and radio wave propagation are presented. The BRS signal is shown to be reasonably emulated by Gaussian noise. A method for determining the aggregate power distribution using a realistic propagation model and Monte Carlo analysis is described. The aggregate power from the base stations was found to be as much as 6 dB more than power from a single base station. Finally a method for incorporating a variable SNR, caused by variable radar to target path loss, into interference analysis is shown.

**Robert J. Achatz, Paul M. McKenna, Roger A. Dalke, Frank H. Sanders, John E. Carroll, Effect of Broadband Radio Service Reallocation on 2900–3100 MHz band Marine Radars: Base Station Unwanted Emissions, NTIA Technical Report TR-15-514, April 2015.** http://www.its.bldrdoc.gov/publications/2796.aspx

Spectrum reallocations may place broadband radio services (BRS) near spectrum used by 2900–3100 MHz band marine radars. Signals from the BRS base stations can potentially introduce unwanted emissions in the radar detection bandwidth and cause interference. Interference protection criteria (IPC) are needed to mitigate this effect. The primary IPC of concern are the interference to noise power ratio (INR) and the reliability of the radar link at a specified radar signal to noise power ratio (SNR). Reliability is determined by radio wave propagation path loss variability which increases with distance. Distance separation between base stations and radar for various spurious attenuations were calculated using reliability expressions for short radar to target ranges with constant SNR and for longer radar to target ranges with variable SNR. For a magnetron radar under clutter free conditions, 90 dB of spurious attenuation is needed to obtain 90% radar operational reliability at1.2 km when the INR is -6 dB and the SNR is constant. Reducing the INR to -9 and -12 dB increased the separation distance to 1.7 and 2.7 km, respectively. At longer base station to radar separation distances, variable SNR required less spurious attenuation than constant SNR. Consequently, constant SNR analysis can be considered worst case. Distance and frequency separation were calculated using frequency dependent rejection (FDR). These calculations showed that for constant SNR 92.8 MHz of frequency separation is required to meet the 90% reliability IPC at 1.2 km separation distance when the INR is -6 dB. Only 54.6 MHz frequency separation is needed when the separation distance is increased to 32.8 km.

**Robert J. Achatz, Mark A. McFarland, Roger A. Dalke, Geoffrey A. Sanders, Paul M. McKenna, Frank H. Sanders, Robert T. Johnk, Effect of Broadband Radio Service Reallocation on 2900–3100 MHz Band Marine Radars: Front-end Overload, NTIA Technical Report TR-15-515, April 2015.** http://www.its.bldrdoc.gov/publications/2798.aspx

Spectrum reallocations may place broadband radio services (BRS) near spectrum used by 2900–3100 MHz band marine radars. Signals from the BRS base stations can potentially cause the radar front-end to overload and cause interference. This report provides a method that can be used to estimate front-end filter attenuation required at various radar to base station separation distances. The attenuation is the difference between the interfering power at the radar low-noise front-end (LNFE) and the allowable interference power. The BRS signal was emulated with 10 MHz bandwidth Gaussian noise. The allowable interference power IPC is determined from probability of detection measurements with a custom test fixture. Two front-ends were tested. One was an off-the shelf magnetron radar front-end assembly consisting of a circulator, limiter, and low-noise front-end. The other, referred to as the reference front-end, was constructed of discrete components. The reference front-end was tested without the frequency selectivity of the circulator and limiter. Results showed that the allowable interference power is -11.5 and -9 dBm for the reference front-end and magnetron front-end assembly, respectively. Additional front-end filtering is not required for either front-end at distances as close as 400 meters. Distances less than 400 meters were not analyzed due to near-field effects. Gain compression and noise enhancement metrics, which are simpler to measure than performance degradation, were also evaluated to determine if they could reliably predict allowable interference power. Only the noise enhancement metric could reliably predict the performance degradation. This result is important since many front-end overload studies are based on the gain compression point metrics.

**Christopher J. Behm, Nicholas DeMinco, Timothy J. Riley, Linh P. Vu, A Spectrum Sharing Case Study Leading to the Development of a Method for Identifying Interference Potential, NTIA Technical Report TR-15-516, April 2015.** http://www.its.bldrdoc.gov/publications/2804.aspx

This report details a method that was developed to identify all potential forms of interference that could occur with a proposed collocation of three federal systems in the 1675–1695 MHz frequency band. The incumbents are the National Oceanographic and Atmospheric Administration's (NOAA) Geostationary Operational Environmental Satellites (GOES) and receivers and radiosonde systems. The entrant is the Department of Homeland Security's (DHS) Video Surveillance System (VSS). The primary objective is that the quality of the mission-critical communications for each service is maintained.

A detailed electromagnetic compatibility (EMC) analysis is used to identify both the highest potential interference scenarios and those scenarios that have little to no effect. Two primary interference mitigation techniques can be implemented to achieve electromagnetic compatibility: frequency offset ($\Delta f$) and separation distance. Based on the frequency dependent rejection (FDR) between the interference source and the victim receiver, the $\Delta f$ and separation distance necessary for a desired level of interference rejection can be calculated. For all potential interference interactions, the $\Delta f$ and the separation distance can be adjusted to arrive at a solution for operation on a non-interference basis. It is not the intent of this report to make pronouncements on how to achieve coexistence within a shared band. The intent is to examine and illuminate the engineering questions that need to be answered so that those who are responsible for federal services in a band may negotiate and cooperate with their colleagues who are responsible for other federal services in the same band.

**Edward F. Drocella Jr., James C. Richards, Robert L. Sole, Fred Najmy, April Lundy, Paul M. McKenna, 3.5 GHz Exclusion Zone Analyses and Methodology, NTIA Technical Report TR-15-517, June 2015.** http://www.its.bldrdoc.gov/publications/2805.aspx

This report describes the 3.5 GHz Study. It explains the assumptions, methods, analyses, and system characteristics used to generate the revised exclusion zones for small-cell commercial broadband systems to protect federal radar operations (ship and land based) from aggregate interference in the band 3550–3650 MHz. The 3.5 GHz Study's exclusion zones are compared with the exclusion zones that were generated in the Fast Track Report, which considered macro-cell operations.

**Robert T. Johnk, Mitchell Powell, Jaydee L. Griffith, Mark A. McFarland, Kenneth R. Baker, Prachee Daithanker, Saman Samdian, Lavanya Gopal, Sai Gavva, In-Building LTE Testing at the University of Colorado , NTIA Technical Report TR-15-518, July 2015.** http://www.its.bldrdoc.gov/publications/2807.aspx

This report describes a comprehensive series of tests that were conducted by engineers and researchers from the U.S. Department of Commerce's Public Safety Communications Research (PSCR) program and the University of Colorado during the period of July 2013–May 2014. The report presents results obtained at two buildings located on the campus of the University of Colorado at Boulder. Indoor coverage was measured using the PSCR band class 14 LTE outdoor macro network. We also explored methods for improving in-building coverage using a cell-on-wheels and small cell feeding either discrete antennas or a distributed antenna system. The results indicate that the PSCR macro network by itself does not provide complete coverage inside these buildings and that coverage needs to be supplemented with combinations of a small cell deployed indoors and a cell-on-wheels (COW). The results indicate that significant system in-building performance improvements can be realized using small cells and a COW.

**Jeffery A. Wepman, Brent L. Bedford, Heather E. Ottke, Michael G. Cotton, RF Sensors for Spectrum Monitoring Applications: Fundamentals and RF Performance Test Plan, NTIA Technical Report TR-15-519, August 2015.** http://www.its.bldrdoc.gov/publications/2808.aspx

Great emphasis is seen on the networking and data management aspects of spectrum monitoring, but far less attention is given to the radio frequency (RF) sensor systems used to collect the spectrum data. This report focuses on these sensor systems and, in particular, the commercial-off-the-shelf (COTS) RF sensors used in the sensor systems. A test plan for evaluating the RF performance of COTS sensors is outlined. Evaluation of COTS sensors is an ongoing task of the Center for Advanced Communications (CAC) Spectrum Monitoring Program. The intent is to build a comprehensive cost/capability/performance matrix to help guide the selection of the appropriate COTS sensor for a given monitoring scenario. The test plan strives to standardize the tests and metrics, so that results can be compared from sensor to sensor.

**Stephen D. Voran, Andrew A. Catellier, Speech Codec Intelligibility Testing in Support of Mission-Critical Voice Applications for LTE, NTIA Technical Report TR-15-520, September 2015.** http://www.its.bldrdoc.gov/publications/2811.aspx

We describe a major effort to quantify the speech intelligibility associated with a range of narrowband, wideband, and fullband digital audio coding algorithms in various acoustic noise environments. The work emphasizes the relationship between these intelligibility results and analogous ones for an analog FM land-mobile radio reference. The initial phase of this project includes 54 noise environments and 83 audio codec modes. We use an objective intelligibility estimator to narrow the scope and then design a practically sized modified rhyme test (MRT) covering 6 challenging yet relevant noise environments and 28 codec modes for a total of 168 conditions. The MRT used 36 subjects to produce 432 trials for each condition. Results show that intelligibility depends strongly on noise environment, data rate, and audio bandwidth. For each noise environment we identify codec modes that produce MRT intelligibility values that meet or exceed those of analog FM. We expect that these results can inform some of the design and provisioning decisions required in the development of mission-critical voice applications for LTE.

## Outside Publications

**Margaret H. Pinson; Lark Kwon Choi; Alan Conrad Bovik, "Temporal Video Quality Model Accounting for Variable Frame Delay Distortions,"** ***IEEE Transactions on Broadcasting*****, vol. 60, no. 4, pp. 637-649, Dec. 2014.** http://www.its.bldrdoc.gov/publications/2816.aspx

We announce a new Video Quality Model (VQM) that accounts for the perceptual impact of variable frame delays (VFD) in videos with demonstrated top performance on the Laboratory for Image & Video Engineering (LIVE) Mobile Video Quality Assessment (VQA) database. This model, called VQM_VFD, uses perceptual features extracted from spatial-temporal blocks spanning fixed angular extents and a long edge detection filter. VQM_VFD predicts video quality by measuring multiple frame delays using perception based parameters to track subjective quality over time. In the performance analysis of VQM_VFD, we evaluated its efficacy at predicting human opinions of visual quality. A detailed correlation analysis and statistical hypothesis testing show that VQM_VFD accurately predicts human subjective judgments and substantially outperforms top-performing Image Quality Assessment (IQA) and VQA models previously tested on the LIVE Mobile VQA database. VQM_VFD achieved the best performance on the mobile and tablet studies of the LIVE Mobile VQA database for simulated compression, wireless packet-loss, and rate adaptation, but not for temporal dynamics. These results validate the new model and warrant a hard release of the VQM_VFD algorithm. It is freely available for any purpose, commercial, or noncommercial at http://www.its.bldrdoc.gov/vqm/.

**Margaret H. Pinson; Arthur A. Webster, "T1A1 Validation Test Database,"** ***VQEG eLetter,*** **Volume 1, Issue 2, December 2014, pp. 41-45.** http://www.its.bldrdoc.gov/publications/2822.aspx

During 1993-1994, the T1A1 subcommittee of the American National Standards Association (ANSI) accredited Alliance for Telecommunications Industry Solutions (ATIS) conducted an objective video quality metric validation test focused on video teleconferencing applications. (T1A1 is now known as PTSC QoSR—Packet Technologies and Systems Committee, Quality of Service and Reliability.) This article summarizes the T1A1 video quality subjective test, with a focus on information that a current researcher needs to effectively use this dataset. The T1A1 video sequences and differential mean opinion scores (DMOS) are available on the Consumer Digital Video Library (CDVL, www.cdvl.org).

**Margaret H. Pinson, Lucjan Janowski, "A New Subjective Audiovisual & Video Quality Testing Recommendation,"** ***VQEG eLetter*****, Volume 1, Issue 2, December 2014, pp. 51-60.** http://www.its.bldrdoc.gov/publications/2823.aspx

This paper introduces ITU-T Recommendation P.913, a new subjective video quality testing standard approved in January 2014. This Recommendation focuses on the evaluation of flat screens, laptops, and mobile devices. P.913 emphasizes flexibility of environment, rating scale, display technology, and stimulus modality (video, audio, or audiovisual). To balance this flexibility, P.913 includes mandatory reporting requirements.

**Margaret H. Pinson, Lucjan Janowski, and Zdzisław Papir, "Video Quality Assessment: Subjective testing of entertainment scenes,"** ***IEEE Signal Processing Magazine*****, vol. 32, no. 1, pp. 101-114, January 2015.** http://www.its.bldrdoc.gov/publications/2821.aspx

This article describes how to perform a video quality subjective test. For companies, these tests can greatly facilitate video product development; for universities, removing perceived barriers to conducting such tests allows expanded research opportunities. This tutorial assumes no prior knowledge and focuses on proven techniques.

Margaret H. Pinson, "A missing factor in objective video quality models: A study of color," *Ninth International Workshop on Video Processing and Quality Metrics for Consumer Electronics - VPQM 2015,* Chandler, AZ, February 5-6, 2015. http://www.its.bldrdoc.gov/publications/2786.aspx

This paper examines color from multiple perspectives. A theory is proposed that the current color spaces are poorly designed for video quality and video coding purposes. The implication is that objective video quality metrics could be improved by the development of a field-specific color edge detection algorithm or color distance measurement. A prototype subjective database is provided that could be used to train such an algorithm.

Nicolas Staelens, Margaret H. Pinson, Phillip Corriveau, Filip De Turck, Piet Demeester, "Measuring Video Quality in the Network: From Quality of Service to User Experience," *Proceedings of the Ninth International Workshop on Video Processing and Quality Metrics for Consumer Electronics (VPQM 2015),* Chandler, AZ, February 5-6, 2015. http://www.its.bldrdoc.gov/publications/2819.aspx

Consumers demand video delivery to a wide variety of multimedia capable playback devices in dissimilar contexts. Monitoring the quality of the network provides a preliminary indication of the video quality end-users can expect. However, more advanced measurements are needed to reliably predict perceived quality. In this paper, we provide information on how to measure video quality, from leveraging fundamental and pure network measurements all the way to modeling and measuring perceived video quality. Currently, video quality research is migrating towards measuring Quality of Experience and User Experience, which is known to be highly subjective and dynamic. Therefore, we also present and discuss the research challenges resulting from this change in focus in more detail.

Michael G. Cotton, Michael M. Souryal, Jeffery A. Wepman, Mudumbai Ranganathan, Julie E. Kub, Steve R. Engelking, Yeh Lo, Heather E. Ottke, Raian F. Kaiser, Douglas J. Anderson, "An overview of the NTIA/NIST spectrum monitoring pilot program," *International Workshop on Smart Spectrum at IEEE WCNC 2015,* New Orleans, LA, March 9-12, 2015. http://www.its.bldrdoc.gov/publications/2794.aspx

This paper provides an overview of a Spectrum Monitoring Pilot Program within the U.S. Department of Commerce. It provides background, motivation, goals, accomplishments, and plans for future work. We describe the development of a federated Measured Spectrum Occupancy Database (MSOD) architecture that allows organizations to host MSOD instances and contribute data to the overall program. We also describe progress in RF sensor R&D and deployment.

Quan Huynh-Thu, Arthur A. Webster, Kjell Brunnström, Margaret H. Pinson, "VQEG: Shaping Standards on Video Quality," *1st International Conference on Advanced Imaging,* Tokyo, Japan, June 17-19, 2015. http://www.its.bldrdoc.gov/publications/2806.aspx

The Video Quality Experts Group (VQEG) is an international and independent organisation of technical experts in perceptual video quality assessment from industry, academia, and government organisations. The main goals of VQEG are to advance the field of perceptual video quality assessment, establish best practices for subjective experiments, conduct large-scale subjective experiments, and evaluate new objective video quality assessment models. VQEG pursues several objectives and one of them is to support standardisation work. Based on results produced by VQEG, more than twenty-five international Recommendations on video quality have been approved by the International Telecommunication Union (ITU). This paper provides an overview of VQEG activities and how VQEG plays a major role in research and the development of standards on video quality.

Kristen Davis, "GIS plays critical role in US telecommunications planning & security," *Directions Magazine,* July 1, 2015. http://www.its.bldrdoc.gov/publications/2824.aspx

This article describes the architecture of ITS-developed Propagation Modeling Website (PMW) tools that use commercial geographic information systems to both acquire geographic data and display geographic coverage areas. The PMW integrates commercial, off-the-shelf GIS, database and web-development products in a fully customizable analysis environment that can be tailored to meet individual customer needs. The solution was designed to be cost efficient, modular and scalable.

**Michele A. Saad; Margaret H. Pinson; David G Nicholas; Niels Van Kets; Glenn Van Wallendael; Ralston Da Silva; Phillip Corriveau; Ramesh V Jaladi, "Impact of Camera Pixel Count and Monitor Resolution Perceptual Image Quality,"** ***Colour and Visual Computing Symposium (CVCS), 2015,*** **Gjovik, Norway, 25-26 August 2015, pp. 1-6.** http://www.its.bldrdoc.gov/publications/2820.aspx

Traditional 35 mm film cameras are no longer the main devices today's consumers use to capture images. Though the dominant technology has shifted to digital cameras and displays that differ widely in pixel count and resolution, our understanding of the quality impact of these variables lags. This paper explores the quality impact of resolution within this new paradigm. Images were collected from 23 cameras, ranging from a 1 megapixel (MP) mobile phone to a 20 MP digital single-lens reflex camera (DSLR). Subjective ratings from three labs were used to explore the relationship between the camera's pixel count, the display resolution, and the overall perceived quality. This dataset and subjective ratings will be made available on the Consumer Digital Video Library (CDVL, www.cdvl.org) when this paper is published. These images can be used royalty free for research and development purposes.

## Presentations

- Keith Gremban, "Future Mobile Networks – Propagation Modeling and Spectrum Sharing," CTIA Super Mobility 2015, Las Vegas, NV, on September 10, 2015.
- Frank Sanders "Best Practices for Spectrum Sharing Studies: A Proposed Approach," Briefing to the Spectrum and Receiver Performance Working Group of the FCC's Technological Advisory Council, August 6, 2016.
- Andrew Thiessen, "Public Safety Broadband Efforts in the United States," 19th Global Standards Collaboration meeting (GSC-19), Geneva, Switzerland, July 15, 2015.
- Chris Redding, with Camillo Gentile of NIST, "Extended Range Communications Testing—Pushing the Limits of LTE Coverage," 2015 Public Safety Broadband Stakeholder Meeting, San Diego, CA, June 4, 2015.
- Andrew Thiessen, International Standards Panel—Lessons Learned From Around the World, 2015 Public Safety Broadband Stakeholder Meeting, San Diego, CA, June 4, 2015.
- Andrew Catellier, "Public Safety Audio Quality Research—Assessing Broadband Codecs in Loud Noise Environments," 2015 Public Safety Broadband Stakeholder Meeting, San Diego, CA, June 4, 2015.
- Frank Sanders, "NTIA 3.5 GHz Spectrum Sharing Studies: Results to Date," International Symposium on Advanced Radio Technologies (ISART 2015), Boulder, CO, May 13, 2015.
- Chriss Hammerschmidt and Robert Johnk, "Clutter Measurement Research at 3500 MHz," International Symposium on Advanced Radio Technologies (ISART 2015), Boulder, CO, May 13, 2015.
- Jeff Wepman, "A Status on the NTIA/NIST Spectrum Monitoring Pilot Program," International Symposium on Advanced Radio Technologies (ISART 2015), Boulder, CO, May 13, 2015.
- Frank Sanders, "Spectrum Measurements and Monitoring," NTIA Federal Spectrum Management Training Course, U.S. Department of Commerce Washington, DC., May 8, 2015.
- Andy Thiessen, "LTE Global Standards/3GPP Update," National Public Safety Telecommunications Council (NPSTC) Meeting, Washington, D.C., May 6, 2015.
- Michael Cotton, "The CAC Spectrum Monitoring Pilot Program," University of Colorado GNU Radio Meet-Up Group, Boulder, CO, April 1, 2015.

- Andy Thiessen (Panel Moderator), "Mission-Critical Voice over LTE: Status Update," International Wireless Communications Expo (IWCE), Las Vegas, NV, March 18, 2015.
- Andy Thiessen, "Update on the Project 25 Compliance Assessment Program," International Wireless Communications Expo (IWCE), Las Vegas, NV, March 19, 2015.
- Andrew Catellier, "Noise, Interference and Audio Quality," International Wireless Communications Expo (IWCE), Las Vegas, NV, March 19, 2015.
- Mike Cotton, "An Overview of the NTIA/NIST Spectrum Monitoring Pilot Program," International Workshop on Smart Spectrum (IWSS) at the IEEE Wireless Communications and Networking Conference (WCNC 2015), New orlens, LA, International Workshop on Smart Spectrum, March 9, 2015.
- Margaret Pinson, Invited Paper: "A missing factor in objective video quality models: A study of color," Ninth International Workshop on Video Processing and Quality Metrics for Consumer Electronics (VPQM), Chandler, AZ February 5, 2015.
- Margaret Pinson, Invited Talk: "Four approaches used to measure video quality" Forschungszentrum Telekommunikation Wien (FTW), Vienna, Austria, December 3, 2014.
- Arthur Webster and Margaret Pinson, Invited Webinar: "Recent Advances in Video Quality Research and Standardization," Cisco Systems, November 20, 2014.

# ITS Standards Leadership Roles in FY 2015

ITS provides technical contributions to standards development organizations (SDO), standards related organizations (SRO), and other organizations that informally contribute to standardization. For over half a century, ITS has held technical leadership roles and provided research-based technical contributions to support U.S. Administration positions in formal national and international SDOs. These include:

- International Telecommunication Union Radiocommunication Sector (ITU-R)
- International Telecommunication Union ITU Telecommunication Standardization Sector (ITU-T)
- Alliance for Telecommunications Industry Solutions (ATIS)
- 3rd Generation Partnership Project (3GPP)
- Telecommunications Industry Association (TIA)

In recent decades, the scope of this technology transfer effort has expanded to support the technical working groups of organizations such as the National Public Safety Telecommunications Council (NPSTC) and the Video Quality Experts Group (VQEG). Reports produced by these bodies inform the deliberations of SDOs and are important precursors to technical standardization. They also inform the policy deliberations of regulatory bodies such as NTIA, FirstNet, and the FCC. ITS provides technical leadership and expertise to these groups through formal and informal contributions.

## Standards Leadership Positions Held by ITS Staff in FY 2014

- **Christopher J. Behm:** U.S. Chair of International Telecommunication Union Radiocommunication Sector (ITU-R) Study Group 3 (SG 3, Radiowave Propagation). U.S. Chair and International Vice-Chair of SG 3 Working Party (WP) 3L, Ionospheric Propagation.
- **Randall S. Bloomfield:** U.S. Department of Commerce Delegate to 3GPP SA (Service and System Aspects) Working Group 2 (Architecture) and Rapporteur for Mission Critical Push To Talk over LTE (MCPTT) Services.
- **John E. Carroll:** Delegate to ITU-R Study Group 1 (SG 1, Spectrum Management) WP 1A (Spectrum engineering techniques) and Study Group 5 (SG 5, Terrestrial Services) WP 5B (Maritime mobile service including the Global Maritime Distress and Safety System (GMDSS)); the aeronautical mobile service and the radiodetermination service).
- **Paul M. McKenna:** International Chair and U.S. Chair of ITU-R SG 3 WP 3K (Point-To-Area Propagation).

- **Margaret H. Pinson:** U.S. Chair of ITU-T SG 9 (Broadband Cable and TV). Co-Chair of ITU-T SG 9 Intersector Rapporteur Group Audiovisual Media Accessibility (IRG-AVA). U.S. Representative to ITU-T Questions 2/9 (Measurement and control of the end-to-end quality of service (QoS) for advanced television technologies) and 12/9 (Objective and subjective methods for evaluating perceptual audiovisual quality in multimedia services within the terms of Study Group 9) in SG 9. Co-chair of the Video Quality Experts Group (VQEG) and of VQEG's Independent Lab Group (ILG) and Audiovisual HD Quality (AVHD) group.

> *“Federal agencies and departments shall consult with voluntary, private sector, consensus standards bodies and shall, when such participation is in the public interest and is compatible with agency and departmental missions, authorities, priorities, and budget resources, participate with such bodies in the development of technical standards.”*
> *(15 U.S.C. §272 Note: Utilization of Consensus Technical Standards by Federal Agencies)*

- **Patricia J. Raush:** U.S. Co-chair and Head of Delegation of ITU-R SG 3 WP 3J (Propagation Fundamentals).
- **Teresa Rusyn:** U.S. Representative to ITU-R SG 3 Correspondence Group 3K3 (Aeronautical and Satellite Link Propagation Method).
- **Frank H. Sanders:** Delegate to ITU-R SG 5 WP 5B and Chair of WP 5B Radar Correspondence Group (RCG, Radar Technical Spectrum Issues). Delegate to ITU-R SG 1 (Spectrum Management) WP 1A (Spectrum engineering techniques).
- **Andrew P. Thiessen:** U.S. Department of Commerce Delegate to 3GPP Technical Specifications Group Radio Access Network (TSG RAN), Technical Specifications Group Service and System Aspects (TSG SA), and Working Groups SA1 (Services). Member of the ATIS Wireless Technologies and Systems Committee (WTSC) Systems and Networks Subcommittee (SN). Vice-Chair of the Technology and Broadband Committee and Chair of the Broadband Working Group, National Public Safety Telecommunications Council. Member, on behalf of PSCR, of the Global System for Mobile Communications Association (GSMA) Operators Group.


*ITS engineer Andrew Thiessen (seated third from right) briefed participants in the 19th Global Standards Collaboration meeting (GSC-19) on the progress of public safety broadband in the U.S. and the work of the Public Safety Communications Research (PSCR) program at ITU headquarters in July 2015. Photo courtesy ITU.*

- **Bruce R. Ward:** Member, 3rd Generation Partnership Project (3GPP) Technical Specification Group for Service and System Aspects Working Group 1 (TSG SA WG1, Services)
- **Arthur A. Webster:** International Chair of ITU-T SG 9. SG 9 representative for Telecommunications for Disaster Relief and to several ITU-T Joint Coordination Activities such as those on the Internet of Things (JCA-IoT) and Child Online Protection (JCA-COP). SG 9 contact for Electronic Working Methods. Co-chair of VQEG. Member of the U.S. Delegations to the ITU World Telecommunication Standardization Assembly (WTSA), Review Committee (REVCOM), Telecommunication Standardization Advisory Group (TSAG), ITU-R SG 6 WP 6C (Programme production and quality assessment), and Coordination Committee for Vocabulary (CCV). U.S. Department of Commerce voting member for ATIS Packet Technologies and Systems Committee (PTSC). NTIA voting member for the Society of Cable Telecommunications Engineers (SCTE) Data Standards Subcommittee (DSS). Observer for ITU-T SG 12 (Performance, QOS and QOE) and Standards Committee for Vocabulary (SCV).

# ITS Projects in FY 2015

## Cooperative Research and Development Agreements

### Public Safety 700 MHz Broadband Demonstration Agreements

Operate various elements of an LTE network in a laboratory test bed and over-the-air (OTA) network to test interoperability of public safety communications equipment under simulated field conditions. Forty-nine equipment manufacturers/resellers and wireless carriers who intend to supply 700 MHz LTE equipment and service to public safety organizations had CRADAs in place under this program in FY 2015.

### CRADAs for the Use of Table Mountain

*Areté Associates*

Use the Table Mountain Field Site as a field location to safely test and demonstrate LADAR technologies under development in atmospheric conditions and at distances relevant to potential applications.

*Project Leader: J. Wayde Allen, (303) 497 5871, wallen@its.bldrdoc.gov*

*FIRST RF Corporation*

Use the Table Mountain Field Site as a field location to fully test the functionality of new antenna designs during product development.

*Project Leader: J. Wayde Allen, (303) 497 5871, wallen@its.bldrdoc.gov*

*Lockheed Martin Coherent Technologies*

Use the Table Mountain Field Site for field-testing and characterization of components, subsystems, and systems for eyesafe coherent laser radar

*Project Leader: J. Wayde Allen, (303) 497 5871, wallen@its.bldrdoc.gov*

*Nutronics, Inc.*

Use the Table Mountain Field Site as a field location to safely and accurately test the Adaptive Tactical Laser System (ATLAS) compensated beacon adaptive optics (CBAO) system under development.

*Project Leader: J. Wayde Allen, (303) 497 5871, wallen@its.bldrdoc.gov*

*University of Colorado Research and Education Center for Unmanned Vehicles*

Use the Table Mountain Field Site as a field location to safely and accurately test collective and autonomous sensing and communication technologies for small unmanned aircraft.

*Project Leader: J. Wayde Allen, (303) 497 5871, wallen@its.bldrdoc.gov*

### CRADAs for Video Quality Research

*Intel*

Conduct subjective testing to model the impact of image resolution, display size, and display resolution on user perception of photos captured by mobile devices. As one of the related tools, create a set of test images and make them available royalty-free to other researchers and developers for similar investigations.

*Project Leader: Margaret H. Pinson (303) 497-3579, mpinson@its.bldrdoc.gov*

## Government Projects

### NTIA Science and Engineering Projects

*Audio Quality Research*

Develop and evaluate new techniques for encoding, decoding, and analyzing speech signals. Provide algorithms, software, and technical expertise to other ITS programs. Provide technical presentations and laboratory demonstrations as requested.

*Project Leader: Stephen D. Voran, (303) 497-3839, svoran@its.bldrdoc.gov*

*Broadband Wireless Standards*

Building on previous ITS radio propagation program, develop models and conduct comparisons using measured data for each propagation prediction model. Analyze and document results and contribute them to appropriate international standards bodies for validation and standardization.

*Project Leader: Paul M. McKenna, (303) 497 3474, pmckenna@its.bldrdoc.gov*

*Center for Advanced Communications: Clutter Measurement Collaboration*

Quantify clutter attenuation metrics through a complete measurement and analysis effort by a joint team of ITS and NIST personnel.

*Chriss Hammerschmidt, (303) 497 5958, chammerschmidt@its.bldrdoc.gov*

*Center for Advanced Communications: Spectrum Monitoring Capability*

Design and deploy a prototype nationwide spectrum monitoring network anchored by a federated Measured Spectrum Occupancy Database (MSOD) that collects spectrum data remote sensors and allows authorized users to view usage data.

*Project Leader: Michael G. Cotton, (303) 497 7346, mcotton@its.bldrdoc.gov*

*Center for Advanced Communications: Spectrum Sharing System Simulation Development*

Develop a system simulation capability to support spectrum engineering studies by evaluating new system compatibility scenarios. Evaluate commercially available simulation software and assess its accuracy using previously conducted measurements as a benchmark.

*Project Leader: Robert J. Achatz, (303) 497 3498, rachatz@its.bldrdoc.gov*

*Effects of the Channel on Radio Systems*

Develop analytic and discrete models that accurately characterize the radio link and receiver performance metrics that can be correlated to these characteristics. Publish descriptions of research results in a journal article, conference paper, or NTIA report

*Project Leader: Robert J. Achatz, (303) 497 3498, rachatz@its.bldrdoc.gov*

*International Standards Support*

Provide objective, expert leadership and key technical contributions in ITU-T and related U.S. industry committees responsible for developing broadband network performance, Quality of Service/Quality of Experience (QoS/QoE), and resource management standards.

*Project Leader: Arthur A. Webster, (303) 497 3567, awebster@its.bldrdoc.gov*

*RSMS Development*

Provide new and innovative measurement hardware and software tools for current and future RSMS capabilities. Project future needs and develop long-term strategies for building the necessary tools.

*Project Leader: Geoffrey A. Sanders, (303) 497 6736, gsanders@its.bldrdoc.gov*

*RSMS Enhancements*

Support RSMS operations through the development and maintenance of software, hardware, systems, and equipment.

*Project Leader: John E. Carroll, (303) 497 3367, jcarroll@its.bldrdoc.gov*

*RSMS Operations*

Provide NTIA with critical measurement support to determine radio spectrum usage across the U.S.; resolve interference problems involving Government radio systems; and determine the emission characteristics of radio transmitter systems that may affect Government operations.

*Project Leader: John E. Carroll, (303) 497 3367, jcarroll@its.bldrdoc.gov*

*Table Mountain Modernization*

Maintain and upgrade the Table Mountain Field Site infrastructure, ensure a safe working environment there, and provide logistical support for research activities at the field site.

*Project Leader: J. Wayde Allen, (303) 497 5871, wallen@its.bldrdoc.gov*

*Video Quality Research*

Develop technology to assess the performance of digital video transmission systems, promote standards that identify proven technologies, and actively transfer this technology to other government agencies, end users, standards bodies, and the telecommunications industry.

*Project Leader: Margaret H. Pinson, (303) 497 3579, mpinson@its.bldrdoc.gov*

## NTIA/OSM Projects

*5 GHz Dynamic Frequency Selection (DFS) Expansion*

Collect 5 GHz propagation data indoors, outdoors and indoors-to-outdoors. Develop simulations of 5 GHz operations for expanded 5 GHz spectrum use.

*Project Leader: Frank H. Sanders, (303) 497-7600, fsanders@its.bldrdoc.gov*

*Advanced Spectrum Sharing*

Build and deploy a demonstration monitoring system to collect baseline spectrum occupancy data in the 1695-1710 MHz band and serve as a prototype for monitoring systems to protect NWS Earth station sites from ducted, co-channel radio signals that have previously caused interference from a terrestrial radio system.

*Project Leader: John E. Carroll, (303) 497 3367, jcarroll@its.bldrdoc.gov*

*Digital Receiver Compatibility with Radar Signals*

Develop data and publish reports on all aspects of digital signal (e.g., LTE) compatibility with radar signals. Collect data on radar emissions, LTE emissions, and interference effects between radars and LTE.

*Project Leader: Frank H. Sanders, (303) 497-7600, fsanders@its.bldrdoc.gov*

*Interference to Noise Criteria for Radars*

Use existing database information on FAA, NWS and DoD radars operating in the band 2700-2900 MHz to determine empirically the closest distance-frequency separations that are tolerated for these systems. Use those data to determine the extent to which band re-packing down to just 100 MHz (e.g., 2700-2800 MHz) may be feasible based on current minimum-allowed separations for radars in the band.

*Project Leader: John E. Carroll, (303) 497 3367, jcarroll@its.bldrdoc.gov*

*Propagation Engineering Support*

Provide propagation-modeling technical support to NTIA/OSM within the 3.5 GHz Joint Working Group (3.5 JWG) and in response to propagation questions and inputs from the FCC, other federal agencies, and the private sector. Use existing models to predict propagation between new (e.g., LTE-based) and incumbent (e.g., Navy radar) systems in the 3.5 GHz band. Develop the Longley Urban/Suburban factor using the Basic Median Attenuation curves from Okumura et al. to account for isolated ridges and tropospheric scattering along 3.5 GHz propagation paths.

*Project Leader: Paul M. McKenna, (303) 497-3474, pmckenna@its.bldrdoc.gov*

*Radar Engineering Support*

Provide engineering support to OSM for revisions to RSEC emission criteria, resolution of problems involving interference to federal radars, and representation of Administration positions with respect to radar spectrum bands in ITU-R and other forums.

*Project Leader: Frank H. Sanders, (303) 497-7600, fsanders@its.bldrdoc.gov*

*Spectrum Coordination Portal*

Prepare the information technology infrastructure for, and develop and deploy the Radio Frequency Coordination Portal (RFCP) to coordinate the use of the 1695-1710 MHz band between federal and non-federal users.

*Project Leader: Patricia J. Raush, (303) 497 3568, praush@its.bldrdoc.gov*

*Spectrum Sharing Test Bed Support*

Evaluate equipment that uses Dynamic Spectrum Access (DSA) technology in the 410-420 MHz and 470-512 MHz bands to assess and address potential interference to incumbent spectrum users.

*Project Leader: Eric D. Nelson, (303) 497 7410, enelson@its.bldrdoc.gov*

## Other Agency Projects

### Department of Commerce / NIST / Communications Technology Laboratory

*Development of Millimeter Wave Radio Channel Probe*

Perform research to provide industry and standards bodies with the information and technology needed for development of next generation mobile communication systems in the extremely high frequency (EHF) band (30–300 GHz). Assemble and test a Ka band tranceiver and waveguide antenna assembly and multiplexer.

*Project Leader: Peter Papazian, (303) 497-5369, ppazian@its.bldrdoc.gov*

## Department of Commerce / NOAA / National Weather Service

### *National Weather Services Propagation Modeling Website (NWS PMW)*

Develop and enhance a web-based multipurpose GIS propagation modeling tool to predict NOAA Weather Radio coverage and integrate Census data to verify that NWR "All Hazards" radio transmissions reach 95% of the population of the U.S. as mandated by law.

*Project Leader: Teresa Rusyn, (303) 497-3411, trusyn@its.bldrdoc.gov*

### *NOAA Weather Radio Receiver Tests*

Test the responses of selected commercial NOAA Weather Radio (NWR) receivers to various simulated NWR transmissions using a series of repeatable measurement methods. Compile and report on the characteristics and responses of the tested receivers As applicable, determine whether the receivers comply with the standards set down in CEA 2009.

*Project Leader: Raian F. Kaiser (303) 497 5491, rkaiser@its.bldrdoc.gov*

## Department of Defense (DoD)

### *Propagation Modeling Website (PMW) HF 2.0 Functionality*

Expand the current PMW software product by enhancing the current capability, adding in new features, and incorporating new cutting-edge ITS propagation models.

*Project Leader: Julie Kub, (303) 497-4607, jkub@its.bldrdoc.gov*

## DoD / Defense Information Systems Agency (DISA) / Defense Spectrum Organization (DSO)

### *Clutter Measurements in the 1755-1780 MHz Band, Phase I*

Measure clutter loss values in various dense urban, urban, and suburban environments to collect data for use in refining and validating propagation models applicable to spectrum sharing in the 1755-1780 MHz band.

*Chriss Hammerschmidt, (303) 497 5958, chammerschmidt@its.bldrdoc.gov*

## DoD / U.S. Army

### *Propagation Modeling Web site (PMW) VHF Enhancements—GIS Server Map*

Provide the ability to view PMW analyses on an open-source GIS mapping program, incorporating the GIS software directly into the PMW VHF installation so that additional software is not required and the user receives immediate feedback to ensure that they entered the input parameters correctly, before exporting the data. Configure the PMW VHF software to display background imagery such as countries, cities, states, roads, etc. behind the analysis plots. Users will be able to zoom in or out of specific map regions, select which analyses they would like to display on the web map, and use the resulting web map for reporting and analyses.

*Project Leader: Kristen Davis, (303) 497-4619, kdavis@its.bldrdoc.gov*

## Department of Homeland Security (DHS) / Office for Interoperability and Compatibility

### *Public Safety Communications Research*

Provide applied science and engineering expertise to the Department of Homeland Security (DHS) and Project SAFECOM. Solve telecommunications interoperability and information sharing problems among local, state, federal, tribal, and international Justice, Public Safety, Homeland Security agencies by addressing voice, data, image, video, and multimedia information transfers.

*Project Leader: Andrew P. Thiessen, (303) 497-4427, athiessen@its.bldrdoc.gov*

### *Public Safety Communications Equipment Test and Evaluation*

Conduct scientific analyses, laboratory and field measurements, and test and evaluation activities to evaluate emerging public safety communications technologies, including extended cells, deployables, and P25 CAP and CBP support on LMR to LTE integration.

*Project Leader: Andrew P. Thiessen, (303) 497-4427, athiessen@its.bldrdoc.gov*

## DHS / Office of Emergency Communications

### *Coordination Support for the Office of Emergency Communications*

Provide support for public safety stakeholder involvement with the PSCR Public Safety Broadband Demonstration Network and the development of public safety broadband requirements and standards in applicable broadband committees and meetings.

*Project Leader: Andrew P. Thiessen, (303) 497-4427, athiessen@its.bldrdoc.gov*

*Priority Services*

Perform research on extending existing Wireless Priority Services (WPS) by enabling Next Generation Network Priority Services (NGN-PS) over commercial LTE networks in support of National Security and Emergency Preparedness (NS/EP).

*Project Leader: Andrew P. Thiessen, (303) 497-4427, athiessen@its.bldrdoc.gov*

## Department of Transportation / Federal Railroad Administration

*Railroad Telecommunications Study*

Provide engineering services and products to the Federal Railroad Administration Office of Research and Development, including testing VNB digital radios' audio quality in a railroad environment, evaluating the efficacy of the VHF channel plan, evaluating propagation models as applied to railroad environments, and verifying RF performance metrics of very narrowband digital radios. Prepare technical contribution pertaining to railroad telecommunications for the Association of American Railroads' Wireless Communications Committee.

*Project Leader: John M. Vanderau (303) 497-3506, jvanderau@its.bldrdoc.gov*

## DOT/ Federal Highway Administration

*Evaluation of 802.11ac/DSRC Modeling*

Perform electromagnetic compatibility (EMC) analysis for the Dedicated Short-Range Communication System (DSRC), as it relates to sharing spectrum with unlicensed devices operating in and adjacent to the 5850 to 5925 MHz band. Identify interference scenarios and determine the parameters required for an EMC analysis of both the DSRC and other systems and the appropriate analysis models. Identify all the variables that might cause reduced system performance, determine their potential impact and select the worst case set. Evaluate the resulting 802.11ac/DSRC modeling using live test data.

*Project Leader: Nicholas DeMinco, (303) 497-3660, ndeminco@its.bldrdoc.gov*

## First Responder Network Authority (FirstNet)

*FirstNet Priority, QoS, and Pre-emption*

Provide engineering support for the development and deployment of the Public Safety Bandclass 14 demonstration network to test priority, quality of service, and pre-emption capabilities on Release 9 and 10 LTE equipment in preparation for implementation of the nationwide interoperable public safety broadband network.

*Project Leader: Andrew P. Thiessen, (303) 497-4427, athiessen@its.bldrdoc.gov*

*FirstNet Test Bed*

Provide engineering support, scientific analysis, technical liaison, and test design and implementation to allow the identification, development, and validation of interoperability standards for the Justice, Public Safety, Homeland Security community, and other communication system products and services supporting wireless telecommunications and information technology needs. Perform technical assessments and evaluations of existing and emerging commercial products and services that may provide interim solutions for various interoperability scenarios.

*Project Leader: Andrew P. Thiessen, (303) 497-4427, athiessen@its.bldrdoc.gov*

*Public Safety Broadband Standards*

Provide engineering support, scientific analysis, technical liaison, and standards body participation to advance the development of standards for public safety communication system products and services intended to operate over the nationwide first responder broadband network under development.

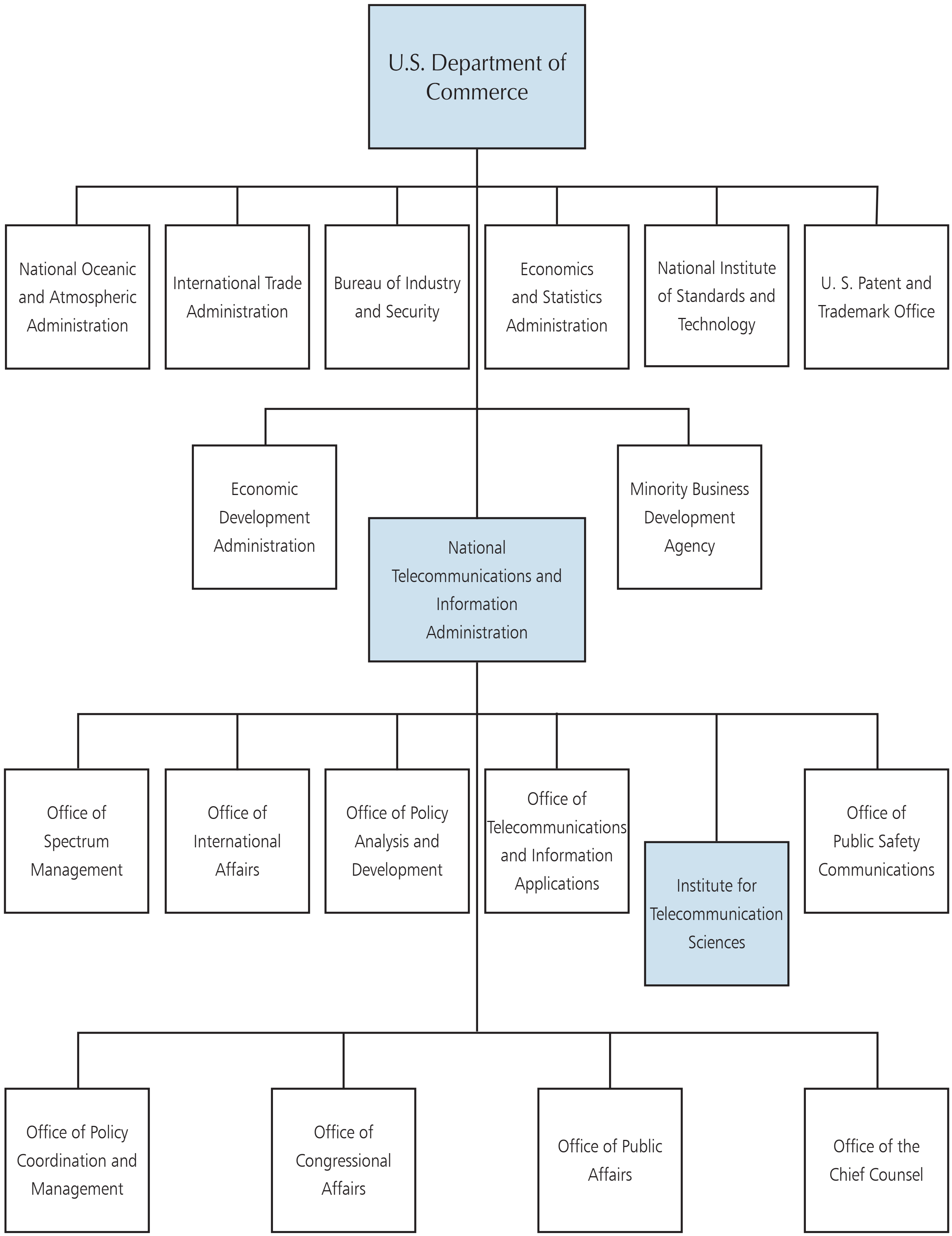
*Project Leader: Andrew P. Thiessen, (303) 497-4427, athiessen@its.bldrdoc.gov*

# Abbreviations/Acronyms

| | |
|---|---|
| 3DTV | three-dimensional television |
| 3G | third generation cellular wireless |
| 4G | fourth generation cellular wireless |
| 5G | fifth generation cellular wireless |
| 3GPP | 3rd Generation Partnership Project |
| ABC-MRT | Articulation-Index Band Correlation MRT |
| AC | alternating current |
| ANSI | American National Standards Institute |
| ATIS | Alliance for Telecommunications Industry Solutions |
| AUGNet | Ad Hoc UAV Ground Network |
| AVA | audiovisual media accessibility |
| AVHD | audiovisual high-definition television |
| BPSK | binary phase shift keying |
| BRS | broadband radio service |
| CAC | Center for Advanced Communications |
| CDAS | Command and Data Acquisition Station |
| CDVL | Consumer Digital Video Library |
| CEA | Consumer Electronics Association |
| CDF | cumulative distribution function |
| CTL | Communications Technology Laboratory |
| COTS | commercial-off-the-shelf |
| COW | cell-on-wheels |
| CRADA | cooperative research and development agreement |
| CSMAC | Commerce Spectrum Management Advisory Committee |
| CW | continuous wave |
| DAT | digital audio tape |
| dB | decibel |
| DFS | dynamic frequency selection |
| DHS | Department of Homeland Security |
| DoC | Department of Commerce |
| DoD | Department of Defense |
| DSRC | dedicated short range communication system |
| EHF | extremely high frequency |
| EMC | electromagnetic compatibility |
| eNB | eNodeB |
| EPC | Evolved Packet Core |
| EPS | Evolved Packet System |
| ERB | Editorial Review Board |
| ERP | effective radiated power |
| FAA | Federal Aviation Administration |
| FCC | Federal Communications Commission |
| FHWA | Federal Highway Administration |
| FirstNet | First Responder Network Authority |
| FLC | Federal Laboratory Consortium |
| FM | frequency modulation |
| FTTA | Federal Technology Transfer Act |
| FY | fiscal year |
| GETS | Government Emergency Telecommunications Service |
| GHz | gigahertz |
| GIS | geographic information system |
| GLOBE | Global Land One-km Base Elevation |
| GPS | global positioning system |
| GSM | Global System for Mobile Communications |
| GSMA | GSM Association |
| HATS | head and torso simulator |
| HD | high definition |
| HDTV | high definition television |
| HF | high frequency |
| HRTe | high-resolution terrain elevation |
| IA | interagency agreement |
| IEEE | Institute of Electrical and Electronics Engineers |
| IF | intermediate frequency |
| IF-77 | ITS-FAA 1977 propagation model |
| IFSAR | interferometric synthetic aperture radar |
| ILG | Independent Lab Group |
| IP | Internet protocol |
| IPC | interference protection criteria |
| IRG-AVQA | Intersector Rapporteur Group on Audiovisual Quality Assessment |
| I/Q | in-phase/quadrature |
| ISART | International Symposium on Advanced Radio Technologies |
| ITM | Irregular Terrain Model |
| ITS | Institute for Telecommunication Sciences |
| ITU | International Telecommunication Union |
| ITU-R | ITU Radiocommunication Sector |
| ITU-T | ITU Telecommunication Standardization Sector |
| kHz | kilohertz |
| km | kilometer |
| kW | kilowatt |
| LADAR | laser detection and ranging |
| LAN | local area network |
| LF | low frequency |
| LF/MF | low frequency/medium frequency |
| LIDAR | light detection and ranging |
| LMR | land mobile radio |

| | |
|---|---|
| LNA | low-noise amplifier |
| LTE | Long Term Evolution |
| MF | medium frequency |
| MHz | megahertz |
| MOS | mean opinion score |
| MRT | Modified Rhyme Test |
| MSOD | Measured Spectrum Occupancy Database |
| NASCTN | National Advanced Spectrum and Communication Test Network |
| NIST | National Institute of Standards and Technology |
| NOAA | National Oceanic and Atmospheric Administration |
| NPSBN | Nationwide Public Safety Broadband Network |
| NPSTC | National Public Safety Telecommunications Council |
| NTIA | National Telecommunications and Information Administration |
| NWR | NOAA Weather Radio |
| NWS | National Weather Service |
| OEC | Office for Emergency Communications |
| OIC | Office of Interoperability and Compatibility |
| OSM | Office of Spectrum Management |
| OTA | over-the-air |
| P25 | Project 25 |
| PESQ | perceptual evaluation of speech quality |
| PMW | Propagation Modeling Website |
| PSCR | Public Safety Communications Research |
| PTSC | Packet Technologies and Systems Committee |
| QoE | quality of experience |
| QoS | quality of service |
| RAN | radio access networks |
| RF | radio frequency |
| RSEC | Radar Spectrum Engineering Criteria |
| RSMS | Radio Spectrum Measurement System |
| SCTE | Society of Cable Telecommunications Engineers |
| SD | standard definition |
| SDO | standards development organization |
| SG | Study Group |
| SHF | super high frequency |
| SNR | signal-to-noise ratio |
| TIA | Telecommunications Industry Association |
| TIREM | Terrain Integrated Rough Earth Model |
| TMFS | Table Mountain Field Site TR technical report |
| TSAG | Telecommunication Standardization Advisory Group |
| TSG | Technical Specification Group |
| TV | television |
| U.S. | United States |
| UAV | unmanned aerial vehicle |
| UE | user equipment |
| UHF | ultra high frequency |
| UN | United Nations |
| USGS | U.S. Geological Survey |
| VHF | very high frequency |
| VNA | vector network analyzer |
| VoIP | voice over Internet protocol |
| VoLTE | voice over Long Term Evolution |
| VQEG | Video Quality Experts Group |
| VQiPS | Video Quality in Public Safety |
| VQM | Video Quality Model |
| VSA | vector signal analyzer |
| VSG | vector signal generator |
| W | watt |
| WG | Working Group |
| WiMAX | Worldwide Interoperability for Microwave Access |
| WP | Working Party |
| WPS | Wireless Priority Service |
| WRC | World Radiocommunication Conference |
| WTSA | World Telecommunications Standardization Assembly |
| WTSC | Wireless Technologies and Systems Committee [ATIS] |

# DOC/NTIA Organization Chart



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# Boulder, Colorado


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NATIONAL TELECOMMUNICATIONS & INFORMATION ADMINISTRATION