2016

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 2016 Technical Progress Report

National Telecommunications and Information Administration
United States Department of Commerce

June 2017

"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.

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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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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.

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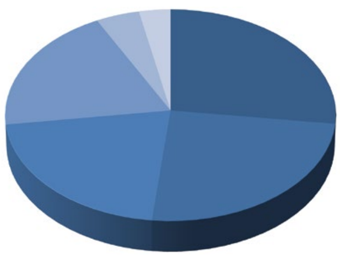
At a Glance ...

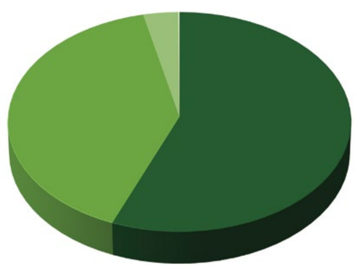
> *"ITS has extensive capabilities in public safety, radio-spectrum sensing, propagation modeling, and interference analysis. It is recognized by other government agencies (and, to some extent, private industry) for its objectivity, expertise, and physical resources; it is the historically trusted expert 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 2016



- Propagation Measurement and Modeling
- Spectrum Monitoring/Analysis/Enforcement
- Public Safety Communications
- EMC, IPC, and Systems Analysis
- User Experience
- Tech Transfer

Research Funding Sources in FY 2016



- Interagency Agreements
- Direct Appropriation
- Fees
- CRADAs

Tech Transfer in FY 2016

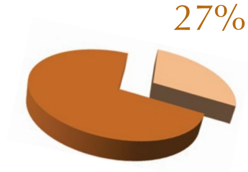
ITS participated in 62 CRADAs

ITS publications were downloaded 8,748 times

496 people downloaded the VQM software

Other software/data were downloaded 1,372 times

169 people downloaded 2,480 unique video clips from CDVL



27% 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. DOI: https://doi.org/10.17226/21867

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 performs the research and engineering necessary to inform spectrum policy and enable the growth and prosperity of the telecommunications sector of the U.S. economy.

ITS is recognized as one of the world's leading telecommunication research laboratories. Our research results are widely disseminated to advance innovation that improves telecommunications technologies and network performance. Our research, development, test, and evaluation (RDT&E) activities provide sound technical input to NTIA policy development and spectrum management, promoting a more agile and data-driven regulatory environment.

ITS performs cutting-edge telecommunications research and engineering with federal, state, local, and tribal government agencies as well as academic and industry partners.

ITS expertise is also applied to resolve specific telecommunications problems of other federal agencies and state and local governments. A primary objective is to support optimization of federal agencies' use of spectrum for communications, radars, and satellites in an increasingly crowded and shared spectrum. Electromagnetic compatibility (EMC) analysis is key to ensuring that offsets in time, frequency, and geography are sufficient to allow disparate services to operate simultaneously without interference—but also calculated to maximize access to spectrum for new wireless services.

Basic research and engineering efforts enhance scientific knowledge and provide new, expanded scientific understanding to support the applied research, testing, and evaluation that drives innovation and development of advanced communications technologies and services for public and private use, including improved public safety communications. 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 also 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).

Fiscal Year 2016 Research Directions

The proliferation of wireless devices in an increasingly connected society is one of the signature phenomena of the early 21st century. Some estimate that currently licensed mobile broadband spectrum has a direct economic value of close to $500 billion and generates $5–10 trillion in total social welfare.[1] This phenomenon presents enormous opportunities for economic growth and a better way of life, but also equivalent technical challenges. The most pressing challenges are tied to spectrum availability—how best to fully exploit available spectrum through both acquiring a better understanding of its current and potential future use and developing new, innovative technologies to use it more effectively. Since the turn of the century, ITS research has been largely directed at laying the scientific and technical groundwork to enable

1 Coleman Bazelon and Giulia McHenry, *Mobile Broadband Spectrum: A Vital Resource for the American Economy*, The Brattle Group, Inc., May 11, 2015. Accessed http://www.brattle.com/system/news/pdfs/000/000/839/original/Mobile_Broadband_Spectrum_-_A_Valuable_Resource_for_the_American_Economy_Bazelon_McHenry_051115.pdf?1431372245 May 25, 2017

reliable operation of radio services in an increasingly shared, crowded, and noisy spectrum environment. Anticipating and addressing those challenges will enable efficient and imaginative uses of spectrum that maintain and enhance America's global competitiveness, increase productivity, deliver better health care, enable efficient management of energy and infrastructure, and improve public safety.

The Federal Communications Commission's (FCC) 2010 National Broadband Plan[1] set the target of identifying 500 MHz of federal and non-federal spectrum to be repurposed for commercial broadband use. NTIA responded with a ten-year *Plan and Timetable to Make Available 500 MHz of Spectrum for Wireless Broadband*.[2] Working groups were formed to devise reliable ways of making more spectrum available for commercial use while assuring the protection of vital government operations. The traditional approach of clearing government-held spectrum of federal users to auction it off to the private sector for exclusive use was soon shown to be untenable. The low-hanging fruit has long been picked; incumbent operations that retain exclusive licenses are too costly, too time-consuming, and too mission-critical to move. Spectrum sharing is the new reality: sharing across time, geography, and other dimensions among government agencies, among commercial services, and between government agencies and commercial services.

Making spectrum sharing the new norm poses significant technical and regulatory challenges. The President's Council of Advisors on Science and Technology (PCAST) described some of those in 2012 and proposed dynamic spectrum sharing techniques to make optimal use of frequency, geography, time, and the physical properties of specific frequencies and radio systems. The PCAST recommendations were premised on the availability and functionality of nascent advanced technologies; it was acknowledged that achieving the full extent of the recommendations might take two or three decades. The recommendations included innovative licensing schemes to identify underutilized spectrum capacity for use or sharing, a framework of minimum technical standards for the coexistence of transmitters and receivers, and sophisticated metrics that reveal how effectively a particular spectrum band can accommodate a variety of complementary services within a given geographic area. As a prerequisite, PCAST said, "incumbent Federal spectrum users will need to have confidence that sharing of the spectrum they have been allocated will not cause harmful interference to the technologies that they operate, and commercial operators with new technologies will need to be made sure of the reliability of the spectrum access needed for their business models."[3]

This FY 2016 Technical Progress report describes research ITS performed to address the technical, engineering, and regulatory challenges outlined above. Highlights and notable achievements are briefly listed below. In the section on *Fiscal Year 2016 Research: Spectrum Sharing* on page 20, we describe the most important research efforts of the fiscal year in support of spectrum sharing. In *Fiscal Year 2016 Research: Quality of Experience* on page 44 we describe research to objectively define and characterize the tradeoff between economy of bandwidth and quality of received transmission. As in prior years, a number of research projects focused specifically on *Mission Critical Communications for Public Safety* (story begins on page 49). To ensure ITS research continues to remain relevant and useful, research teams continue to develop new and enhanced *Systems, Software, and Analyses for Spectrum Sharing* (story begins on page 57). A mission imperative is to ensure that not only research results but also validated tools and data sets are widely disseminated and openly available to all stakeholders through *Technology Transfer* (story begins on page 66). A full list of research projects funded in FY 2016 begins on page 88.

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1 Federal Communications Commission, *Connecting America: The National Broadband Plan*, March 17, 2010. Accessed https://transition.fcc.gov/national-broadband-plan/national-broadband-plan.pdf January 9, 2017.

2 U.S. Department of Commerce, National Telecommunications and Information Administration, Plan and Timetable to Make Available 500 MHz of Spectrum for Wireless Broadband, October 2010. Available https://www.ntia.doc.gov/files/ntia/publications/tenyearplan_11152010.pdf.

3 President's Council of Advisors on Science and Technology (PCAST), *Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth*, July 2012, p. iii. Accessed https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf February 9, 2017.

Fiscal Year 2016 Key Accomplishments

- In October 2015, an ITS team delivered the AWS-3 Radio Frequency Coordination Portal (RFCP) mandated by the FCC rulemaking that opened the 1695–1710 MHz spectrum band to sharing. The team received an NTIA Bronze Medal Award (see page 5) for this effort.
- ITS's work on behalf of FirstNet and the public safety community at large achieved a significant milestone in March 2016, when the 3rd Generation Partnership Project (3GPP) "froze" Release 13 of the international specification for LTE cellular equipment and included Mission-Critical Push-to-Talk Standards as well as many other ancillary features of interest to public safety. Story on page 74.
- Included in the ancillary features frozen in 3GPP Release 13 were specifications for voice codecs based in part on ITS work described in Technical Contribution S4-160020. Stephen D. Voran and Andrew Catellier of ITS were awarded a DoC Silver Medal (see story below) for this work, which was part of the FY 2016 research on *Speech Intelligibility Testing for Mission Critical Voice* described on page 51.
- In April 2016 ITS demonstrated a prototype low-cost (under $1000) sensor capable of detecting and measuring communications signals like LTE for interference mitigation and enforcement—critical enablers of spectrum monitoring. The principal developer received an NTIA Bronze Medal Award (see page 5).
- In May 2016, ITS delivered new software to NTIA's Office of Spectrum Management (OSM) that enables spectrum management and policy engineers to use the IF-77 air-to-ground propagation model to assist their analyses of potential interference. Story on page 27.
- In August 2016, a joint NTIA/NIST team released—and open-sourced the code for—a beta version of a federated Measured Spectrum Occupancy Database (MSOD), with a distributed MSOD architecture that allows many organizations to contribute data by hosting a peer MSOD or adding sensors to the MSOD network. This web-hosted database application provides graphical tools for recording and examining spectrum measurements taken by spectrum monitoring sensors. Story on page 20.
- In August 2016, the Audio Quality program completed the first crowdsourced speech intelligibly test and analysis showed the crowdsourced test results aligned closely with results of controlled laboratory testing. This is a breakthrough that offers the potential to rapidly and cost-effectively gather large amounts of high-quality speech intelligibility data as part of a more efficient overall test plan. Story on page 46.
- Throughout FY 2016, ITS both deepened and expanded its relationships with other research laboratories considering similar problems. A collaborative research project was undertaken with the nearby Colorado School of Mines, and a highly respected professor at the U.S. Naval Academy accepted a temporary duty assignment in the ITS Theory Division to provide expert assistance with a number of projects of interest to the Navy. This type of collaboration leverages ITS's limited resources to ensure that research results are both sound and widely promulgated, and made available as early in the regulatory process as possible.

Fiscal Year 2016 Awards

DoC Silver Medal Award

Stephen D. Voran and Andrew A. Catellier of ITS were honored with the Department of Commerce (DoC) Silver Medal Award for designing and executing a highly compressed speech intelligibility testing regime that produced internationally accepted authoritative results to inform international standards under development for next-generation wireless communications equipment. The Silver Medal is the second highest honor granted by the Secretary of Commerce for distinguished and exceptional performance.

The work was performed on behalf of the First Responder Network Authority (FirstNet) as part of the Public Safety Communications Research (PSCR) program, a joint effort of NTIA and NIST's Communications Technology Laboratory (CTL), and sponsored by the Department of Homeland Security (DHS), which leads an ongoing effort to enable interoperable emergency communications among 60,000 federal, state, and local public safety agencies. These agencies will benefit by being able to purchase standardized commercial off-the-shelf equipment to meet their mission critical communication needs. Dean Prochaska, Director of Standards for FirstNet emphasized, "The work that Stephen and Andrew performed provided the basis for 3GPP to select a voice codec that meets the needs of public safety for inclusion in the next release of international LTE communications standards, and manufacturers all over the world will include that codec in new equipment designs."

ITS Engineer Andrew Catellier accepted the U.S. Department of Commerce Silver Medal Honor Award on behalf of himself and Stephen D. Voran during ceremonies in Washington, DC. From left, Deputy Secretary of Commerce Bruce Andrews, Secretary of Commerce Penny Pritzker, Andrew Catellier, and Assistant Secretary for Communications and Information and NTIA Administrator Larry Strickling. Photo courtesy U.S. Department of Commerce.

FirstNet, an independent authority within NTIA, was tasked to develop and deploy a nationwide public safety broadband network (NPSBN). The public safety community chose LTE as the most promising technology for a robust and efficient NPSBN, and FirstNet committed to building the network to open standards to take advantage of increased vendor competition and economies of scale, driving down the cost to public safety users while opening the market of millions of public safety users to more vendors. Standards for commercial LTE equipment (such as smartphones), however, did not include many critical requirements to help meet public safety communication needs.

The National Public Safety Telecommunications Council (NPSTC), a federation of public safety organizations, identified audio quality as a critical requirement for mission critical voice communications over the NPSBN. Standardized algorithms for digital audio (codecs) compress speech for transmission over a network and decompress it for playback. When loud background noise is mixed with speech—a typical scenario in public safety communications—codecs with greater noise resistance are needed to provide acceptable speech intelligibility. Speech intelligibility testing is the primary means by which public safety evaluates a voice codec, and that testing was not included in standards bodies' deliberations on selection of a voice codec for the next LTE standard.

To remedy this, Voran and Catellier designed and executed a testing regime that accelerated speech intelligibility testing that normally would have taken 12 months into two months. Catellier was able to present test results that showed the intelligibility performance of different LTE speech codecs at meetings of the 3rd Generation Partnership Project (3GPP, the international standards organization for LTE commercial wireless broadband networks). Based on those results, representatives of the United States and five other countries took a strong and unified position on which voice codec is most suitable for the public safety user community, ensuring the next 3GPP release would contain a voice codec that meets the needs of public safety. Voran and Catellier's work directly informed the international technical standards that will ensure that public safety mission critical voice communications requirements will be met by next-generation commercial off-the-shelf equipment worldwide. The compressed testing regime devised by Voran and Catellier models a fast-response, targeted research effort that builds on long-standing expertise to produce reliable and trusted objective results to inform international standards. Including speech intelligibility testing in future evaluations of voice codecs at 3GPP ensures a single stream evolution for public safety and commercial communications technology. FirstNet and all subscribers will realize significant cost and time savings if internationally standardized commercial off-the-shelf equipment that meets public safety's needs is available to operate on the NPSBN when it is launched.

NTIA Bronze Medal Awards

Seventeen ITS staff members shared four DoC Bronze Medal Awards for work performed in FY 2016. The Bronze Medal is a Department of Commerce Honor Award granted by the head of an operating unit or Secretarial Officer for superior performance.

Kristen Davis, George Engelbrecht, William ("Billy") Kozma, Julie Kub, Abdalla Elmedani, Ken Tilley, William ("Bill") Ingram, Mike Chang, and Frank Sanders shared a group award with Gary Patrick and Christine Mattingly of the Office of Spectrum Management for development of the AWS-3 Radio Frequency Coordination Portal (RFCP) to coordinate spectrum sharing. The RFCP facilitates frequency coordination between federal incumbent agencies and commercial entrants in the 1695–1710 MHz spectrum band through process automation. The team developed and deployed the RFCP under punishing time and funding constraints—a beta version was deployed after only five months of requirements identification, development, and testing, including a two-week window for incumbent testing and feedback.

Douglas Anderson, an Intern in the Pathways program, received an individual award for leading a research team that developed a prototype software defined radio for inclusion in the Spectrum Monitoring Boulder

ITS Bronze Award recipients. From left, Mike Chang, Bill Ingram, Kristen Davis, Julie Kub, Ken Tilley, Billy Kozma, and George Engelbrecht shared a team award; Doug Anderson received an individual award; Gerry Saqueton and Anton Nguyen-Vu shared a team award; Brian Gomez, Robert Booth, Ted Mullen, and Gunnar Philipp shared a team award.

Test bed described on page 22—a key project milestone. While maintaining a challenging engineering course load, he rapidly gained expertise in software defined radio configuration and testing and developed and integrated the new system into the Spectrum Monitoring database.

Gerardo Saqueton and Anton Nguyen-Vu received an award for meeting aggressive deadlines for testing Wireless Priority Services (WPS) network protocols now under development for LTE commercial cellular networks. WPS prioritizes the calls of federal, state, local, tribal and territorial national security and emergency personnel (e.g., the President, Governors, Chiefs of Police) to ensure they can communicate during emergencies when cellular networks are overloaded. The test results allowed inclusion of clear, precise, and quantifiable capability requirements in Government service agreements for LTE WPS.

Robert Booth, Brian Gomez, Ted Mullen, Jacob Neal, and Gunnar Philipp of ITS shared an award with Bart Gibbon of the Office of Policy Analysis and Development for outstanding teamwork and innovative cross-location collaboration to successfully deploy and implement improved security and state-of-the-art technology on NTIA's systems infrastructure, laying the foundation for further improved accessibility and collaboration among ITS sponsors and federal agency partners.

ITS Outstanding Publications Awards

The ITS Outstanding Publications Awards are granted by a panel of peers for exceptional works published in the prior calendar year. In FY 2016, the awards went to Paul McKenna and Margaret Pinson.

McKenna was honored for his contribution to NTIA Technical Report TR-15-517, 3.5 GHz Exclusion Zone Analyses and Methodology, co-authored with five Office of Spectrum Management staff and published in June 2015. The report explains the assumptions, methods, analyses, and system characteristics used to generate revised exclusion zones to protect federal radar operations from aggregate interference from small-cell commercial broadband systems entering the 3550–3650 MHz band under new FCC spectrum sharing rules. This publication "addresses a topic of intense interest and potential impact on major decisions on future spectrum sharing. Despite the many complex equations, the report is very approachable. The executive summary in particular can be understood by a non-technical expert. This is rare and worthy of note. The report provides an excellent example of adhering strictly to a technical analysis of the situation without delving into opinions or commentary."

Paul M. McKenna (top) and Margaret H. Pinson accept the ITS Outstanding Publication Award from Director Keith Gremban. Photos by Lilli Segre.

Pinson was honored for co-authoring the tutorial article "Video Quality Assessment: Subjective testing of entertainment scenes" with two researchers from AGH University of Science and Technology in Cracow, Poland. It was published in *IEEE Signal Processing Magazine* in January 2015. The tutorial assumes no prior knowledge and aims to remove perceived barriers to conducting such tests, thus expanding research opportunities for industry and academic research and development. It "provides a very accessible distillation of over 20 years of subjective video quality testing experience. It guides readers simply and cleanly through video scene selection, video devices under test, test environments, test protocols and rating scales, and statistical analysis of test results. The article provides a wealth of information that can be used to great advantage by any reader seeking to enter the field. It could potentially save other organizations many thousands of dollars, untold person hours, and much frustration associated with learning these lessons one-by-one over the years."

ITS Operations and Resources

ITS Operations

ITS is located on the DoC Boulder Laboratories campus in Colorado, sharing advanced laboratory and test facilities with NOAA and NIST. ITS also maintains and operates the Table Mountain Field Site and Radio Quiet Zone, located a few miles north of Boulder and one of only two federally mandated radio quiet zones in the U.S. See *Table Mountain Field Site and Radio Quiet Zone* on page 18 for a full description of the Table Mountain Field Site.

Research Funding

ITS research is funded in four ways: by reimbursement from other agencies under interagency agreements (IAA), by reimbursement from industry and academia under cooperative research and development agreements (CRADA), from spectrum fees paid to NTIA's Office of Spectrum Management (OSM), and directly through congressionally appropriated funds. ITS is authorized to receive reimbursement from other agencies for the cost of performing research on their behalf, leveraging the unique expertise or specialized resources of ITS to benefit the Government. 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 other agencies can access through Interagency Agreements (IAA).

In any given year, up to 75% of ITS research programs are undertaken for and with other federal agencies; state, local, or tribal governments; private corporations or associations; or international organizations. This includes assisting the FCC and federal defense, public safety, and other agencies that use federal and non-federal spectrum, as well as supporting OSM, which is primarily responsible for managing federal use of the radio frequency spectrum.

The Federal Technology Transfer Act of 1986 (P.L. 99-502) authorized the use of CRADAs to allow one or more federal laboratories and one or more non-federal parties to enter into agreements to conduct specified research and development-related activities that are consistent with the laboratory's mission. In FY 2016, as in the past seven years, most of the CRADAs ITS entered into were no-cost CRADAs that contractually protect the intellectual property of vendors and manufacturers who provide equipment to populate various test beds. Nonetheless, some funding was received through reimbursement under a small number of CRADAs for the use of Table Mountain and for specific joint research efforts. FY 2016 CRADAs are described beginning on page 67.

OSM manages the Interdepartment Radio Advisory Committee (IRAC), whose members represent 20 federal departments or agencies and advise NTIA on federal frequency assignments and policies, programs, procedures, and technical criteria pertaining to the allocation, management, and use of spectrum. Since the Consolidated Appropriations Resolution of 2003, federal agencies have been required to reimburse NTIA for the cost of federal spectrum management. When OSM or the IRAC request that ITS undertake special studies to support their work, those are reimbursed from the spectrum allocation fees paid to OSM.

Direct funding by appropriation for research and development is essential to maintaining U.S. leadership in technology development. The private sector often does not have sufficient economic incentive to make the required investments in the early fundamental scientific investigation that ultimately drives the development and commercialization of new technologies. Direct-funded basic research also provides critical unbiased technical input to NTIA policy development and spectrum management, and is a key component in promoting a more agile and data-driven regulatory environment.

Organization and Expertise

ITS is organized into divisions that act as disciplinary communities of interest. Projects engage researchers from multiple divisions as required by the tasking. The Telecommunications Theory Division, for example, supports sophisticated mathematical analysis for propagation modeling, propagation measurement, spectrum monitoring, and other areas of applied research. The majority of the 75 researchers and technicians are electrical engineers, but the nature of the research also engages computer engineers and computer scientists, including world-renowned experts in propagation modeling and emission measurements, as well as a small core of applied mathematicians and physicists. Credentials range from PhDs to graduate students enrolled in the federal government's Pathways Internship program. Because ITS is small, there is opportunity for knowledge sharing and mentoring, promulgating a culture of best practices that has been a hallmark of the laboratory for 100 years. Proximity to the University of Colorado Boulder and colocation with NIST also provides a fertile climate for knowledge sharing to leverage the unique capabilities of all three organizations. Some examples of knowledge sharing and transfer in FY 2016:

- In November 2015, ITS hosted a four-day Course On Radiowave Propagation that drew about 50 attendees from ITS, OSM, and NIST/CTL. The course was presented by a team of three internationally renowned propagation experts, led by Les Barclay, the editor of *Propagation of Radiowaves*, 3rd Ed., The Institution of Engineering and Technology, London, UK, 2013, the essential text for professionals and researchers involved in the planning, design, and operation of radio systems.
- In January 2016, ITS's Dr. Robert Achatz presented to ITS and NIST/CTL leadership and technical staff on "Radar IPC Measurement Simulation," the subject of an NTIA Technical Report to be published in FY 2017. Interference Protection Criteria (IPC) simulation is of intense interest to ITS, CTL, and OSM. IPC are specified by both the FCC and NTIA to ensure that rulemaking adequately protects all users from harmful interference—the more rapidly and accurately IPC can be defined, the more rapidly rulemaking can open spectrum to new uses. Relative to measurement, simulation has produced results with less uncertainty and improved repeatability at lower cost. More details on IPC Estimation Methods on page 41.
- In February 2016 ITS hosted a presentation for ITS and NIST researchers by Dr. Pierre de Vries, Senior Fellow and Co-Director of the Spectrum Policy Initiative at the Silicon Flatirons Center for Law, Technology, and Entrepreneurship at the University of Colorado Boulder and a member of the FCC Technological Advisory Council (TAC), on "Risk-Informed Interference Assessment: A Case Study." The FCC TAC has recommended the use of probabilistic risk analysis in the assessment of radio interference, and proposed a method to do so. This form of analysis complements the traditional worst case analysis that aims to prevent any possibility of interference and yields useful insights for moving towards a new regulatory environment in which coexistence risks are assessed and managed. Both forms of analysis are needed to help regulators make better trade-offs between the interests of incumbents and new entrants.
- In March 2016, ITS hosted an invited presentation by Dr. Tod Martin of Science and Technology Associates, Inc. in Arlington, VA, on his PhD research at George Mason University on Probabilistic Reasoning for Dynamic Spectrum Access. Uncertainties regarding wireless propagation environments pose challenges to dynamic spectrum access (DSA) systems. Dr. Martin's proposed model uses risk-constrained access to regulate spectrum access behaviors, with greater situational uncertainty resulting in lower spectrum access performance while maintaining the requisite level of risk. The presentation stimulated lively, prolonged, and fruitful discussion between Dr. Martin and ITS subject matter experts.
- Over the summer of 2016, ITS Division Chief Mike Cotton and Dr. Ken Baker, Scholar in Residence, Interdisciplinary Telecom Program, University of Colorado Boulder, arranged to jointly sponsor a Senior CAPSTONE project at the University as part of the ITS Spectrum Monitoring and Boulder Test Bed initiatives (page 20). Under the year-long project, a team of six designed and prototyped an integrated sensor solution at the lowest level—e.g., capacitors, resisters, active components soldered on a printed circuit board, aiming to drive down sensor cost and size and enable more widespread and effective sensing.

National Context

In launching a $400 million Advanced Wireless Research Initiative in July 2016, the National Science Foundation (NSF) pointed out that efforts and investments to accelerate the growth and development of advanced wireless technology must be coordinated across federal agencies to maximize the impact of federal research investment and maintain U.S. leadership in the field. Along those lines, the NSF highlighted four complementary ITS research initiatives—the Boulder Test Bed, the Measured Spectrum Occupancy Database (MSOD) for Spectrum Monitoring data, urban and indoor propagation measurements (see pages 20 and 52), and the EMC analyses (page 34). In FY 2015, the National Academies of Sciences, Engineering, and Medicine, at the behest of Congress, 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."[1] The final report, released in early FY 2016, pointedly emphasized both the need for the research performed by ITS and the uniqueness of ITS capabilities.

> *"Measurement, testing, modeling, and analysis are essential to facilitate coexistence and spectrum sharing of technologies that use the radio frequency spectrum for applications such as wireless local area networks (LANs), mobile cellular, and radar. Although there are a few other laboratories, both within the Department of Defense (DOD) and in the private sector, that have the resources and knowledge to deploy staff and hardware to a particular site to test/verify interference between users, the combination of expertise, physical resources, and objectivity (i.e., their status as a trusted agent in performing and reporting on measurements and analysis) are exclusive to ITS. The value to the nation of ITS as a trusted neutral party is likely to grow as the need to arbitrate the various potential uses of spectrum continues to increase.*[2]"

ITS Resources

Audio Visual Laboratories

Subjective Testing Facilities

The perceived quality of a phone conversation or video stream strongly influences its commercial value. Subjective testing, that is, gathering opinions from a group of users, is the most accurate way to measure perceived quality. ITS is a leader in performing unbiased, scientifically rigorous subjective tests of audio, video, and audiovisual quality. The results are broadly disseminated through publication and contributions to standards bodies to advance technology-neutral standards for audio and video encoding that support open competition.

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 are highly repeatable; that is, results are the same regardless of where or when the test takes place.

A controlled test environment enhances repeatability. A person's attention is focused on the task at hand since the lighting and

Top: ITS subjective test room set up as a real world living room. Bottom: Sound isolation booth set up for an audiovisual subjective test. Photos by A. Catellier.

1 H. Rept. 112-463 - Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2013. Accessed https://www.congress.gov/congressional-report/112th-congress/house-report/463 March 1, 2017.

2 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, p. 2. DOI: https://doi.org/10.17226/21867

background noise are controlled and there are no visual distractions, and the experimenter is freed from considering environmental variables when analyzing test results.

ITS has three such controlled test environments: two identically constructed sound isolation chambers; one 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, it 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 made by ITS experts when designing a subjective test.

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 television
- Video on demand
- Streaming Internet video
- Video teleconferencing
- Mobile phone audio and video
- Voice over internet protocol (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.912
- Various hardware and software encoders and decoders
- Internet protocol network error simulator compliant with ITU-T Rec. G.1050

Supporting Public Safety Communications

Over 60,000 emergency response agencies nationwide face the challenge of purchasing communications equipment that meets their unique needs. Many do not have the capacity to perform the research required to define the technical specifications, test and compare candidate equipment, or advocate for the inclusion of needed features in equipment standards. With the addition of some facilities more specifically targeted to audio and video testing in the context of public safety communications, ITS has leveraged its audio visual testing facilities and expertise to perform these activities on behalf of public safety.

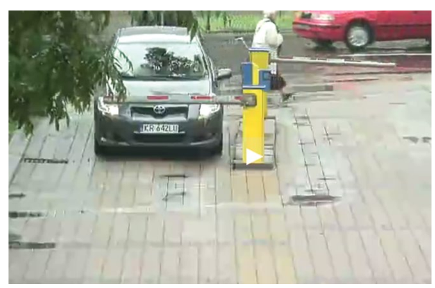
One of the most challenging aspects of public safety speech communication is the harsh noise environment in which public safety practitioners must effectively establish and conduct communications. ITS often tests systems to determine speech intelligibility levels under these conditions, and the results inform the development of audio quality standards and certification methodologies to verify that equipment marketed to public safety meets those standards of voice intelligibility.

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

This work is enabled by two small 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.

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.

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.



Video sequences that 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.

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.

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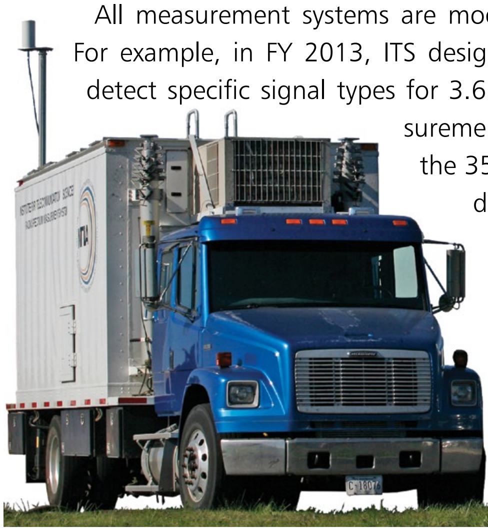
Radio Frequency Measurement Capabilities

In an increasingly crowded spectrum environment, detailed and accurate information about how spectrum is actually being used is critical to the development of sound regulation and more efficient ue of the this limited resource. Radio science is not a "perfected" science—though radio waves were first described in the late 19th century, the complexities of radio wave propagation are still not fully understood. So in addition to understanding actual current usage, in order to maximize our use of spectrum we need to increase our understanding of how radio waves propagate in different environments. This information, too, provides a foundation for sound regulation and efficient spectrum utilization.

Since the first radio frequency measurements taken by the Radio Section of the National Bureau of Standards in 1909, measurements taken by ITS and its predecessor have been trusted by regulators and industry alike. Today, the need for trusted ground truth measurements is greater than ever, as is the scope of measurements needed. ITS designs, develops, and maintains a number of mobile and static radio frequency (RF) measurement systems for taking both RF spectrum occupancy and RF propagation measurements under a very broad range of wireless scenarios in frequencies from 10 MHz to 40 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 10 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, and 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. These measurements informed spectrum sharing rulemaking that eventually opened the 3550–3650 MHz band (commonly called 3.5 GHz) to sharing. In addition, an extremely high frequency (EHF) measurement system for frequencies from 30 to 300 GHz is currently under development to support exploration of EHF allocations being considered for emerging next generation 5G wireless services that will operate in the FCC-named "Spectrum Frontiers."



RSMS-4 mobile measurement lab.

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 IAAs, 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

In many cases, measurements must be taken on site—for example, the systems whose emissions are being measured must continue to operate (e.g., radars), or spectrum occupancy measurements are needed for a specific location. An integral part of the RSMS system is a measurement vehicle, now in its 4th 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, a 20 kW diesel generator with power conditioning, 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. Deploying the RSMS-4 to different locations to take spectrum occupancy measurements ensures that the results are comparable and gives a true picture of geographic variations in spectrum occupancy.

RSMS-5 Software

The RSMS software package is now in its 5th generation (RSMS-5) 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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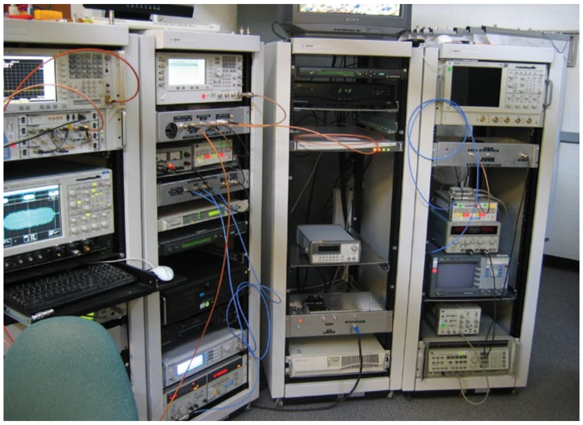
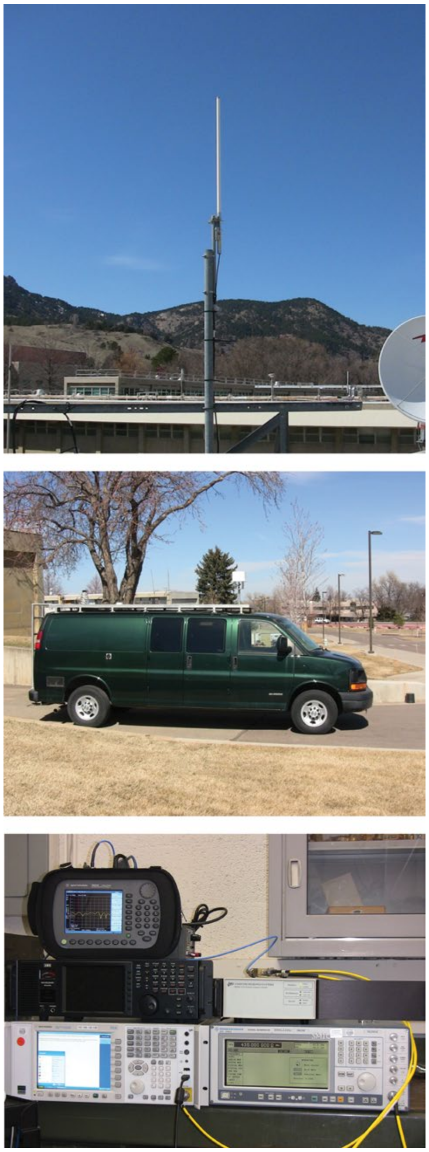
Ultrawideband Propagation Measurement System

Over the past five years, an extremely accurate new ultrawideband propagation measurement system has been developed for taking precision short-range propagation measurements. This system provides the highest resolution and precision, yielding measurements used to both develop and improve propagation models that can accurately inform rulemaking for spectrum sharing. It has high-dynamic range and excellent immunity to RF interference and transmits very low power levels (typically +5 dBm), and so has low interference potential to existing wireless services. This makes it an ideal system for indoor and building penetration measurements. This



Ultrawideband propagation measurement system.



Components of the mobile propagation measurement system. Top: transmitter antenna fixed on a rooftop; middle: the receiver van; bottom: measurement equipment includes a vector signal analyzer/spectrum analyzer combination and a rubidium clock. The vector signal generator in at lower right in the image was used to bench test the system. Photos by Bob Johnk.

system also has excellent range resolution capabilities that permit the isolation and evaluation of selected propagation events to answer specific questions about a particular radio propagation path under study. For example, it was used for near-Earth propagation measurements at Table Mountain with excellent path loss and channel impulse response data obtained. The data helped DoD develop better methods to protect warfighters against buried improvised explosive devices (IED) triggered by cell phone transmissions.

The system 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.

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Mobile Propagation Measurement System for Frequencies from 20 MHz to 10 GHz

For longer range propagation measurements, a new mobile propagation measurement system was developed in FY 2012 to collect measurements useful for developing channel models that have time-delay characteristics. A detailed understanding of these characteristics is critical for the development of more efficient wireless communication systems able to operate in crowded spectrum. The data collected includes path loss, a slow-fading profile, and fast-fading information. The system is operated as a channel sounder by applying a broadband binary phase shift modulation to the transmitted signal. Post-processing yields a channel impulse response from which useful parameters (e.g. delay spread, basic path loss) can be extracted. These parameters are used to develop more accurate longer range propagation models.

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High-Performance CW Mobile Channel Sounder

EMC studies to address increasingly complex spectrum sharing scenarios require more granular measurements. This system was developed in response to a need to rapidly deploy field measurement capabilities to address evolving policy decisions. This is a narrowband system for which temporary authority to transmit is much more easily obtained. This allows ITS to rapidly deploy the system in response to national spectrum needs. 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 location. The transmitter sends a highly stable carrier wave into the environment. The receiver captures and geolocates the signal as the mobile van moves along a selected drive route. 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.

The recorded data are used to analyze propagation characteristics as a function of location through all of the runs in the target areas. These high-precision measurements are compared with existing propagation model predictions, and the intercomparison used to modify and improve the models, leading to more accurate predictions that can be used for more efficient and robust system design and rulemaking that allows more expansive sharing.

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Radiated LTE Measurement System

As public demand for mobile wireless spectrum has increased, devices that use Long Term Evolution (LTE) wireless data communications technology have become predominant consumers of newly allocated spectrum. This spectrum is often shared with or adjacent to frequencies being used by federal systems. A greater understanding of the RF and network characteristics of LTE networks is needed to ensure that sharing occurs efficiently and that each system can complete its mission without interference. Radiated measurements from the ITS Radiated LTE Measurement System system allow ITS to develop this understanding without reference to the closely guarded proprietary protocols used by individual carriers. This information is used to facilitate the development of models and standards to assure efficient and effective spectrum planning and coordination between federal and commercial radio systems.

The ITS Radiated LTE Measurement System is composed of a commercial off-the-shelf test instrument that can receive the uplink and downlink transmissions from three different LTE base stations (eNBs) at the same time, along with the transmissions of their associated mobile phones (UEs). Sampling the radio spectrum at rates over 30 million samples per second, this instrument is able to decode the command and control information from the eNBs to their respective UEs in real-time as well as the replies from the mobile units. Subsequent analysis of this information, with correlated information from spectrum analysis traces also provided by the device, allows insight into the network and RF behavior of individual UEs as well as investigations into the aggregate effects of multiple devices operating simultaneously.

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Automated Wideband Noise Measurement System

Radio frequency noise—unwanted emissions that do not convey information—is always present in the environment to some degree. Some is naturally occurring (lightning and sun flares, e.g.) and some is man-made (aggregated unintended radiation from electrical or electronic equipment, power lines, or engine ignition, e.g.). System designers must understand the background levels of radio frequency noise to design communications systems that can transmit wanted signals without interruption or degradation. The last comprehensive survey of RF background noise was completed in the 1970s, when the RF environment was dramatically different. Today's much improved measurement tools can be used to take badly needed new baseline measurements that record more parameters with greater granularity, providing the useful details that system designers and regulators need about the RF noise environment in different geographic areas.

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 amplifier (LNA). The filters can be easily exchanged to conduct noise measurements at different frequencies. This configuration results in a very sensitive measurement system with a system 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 high 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.

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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 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. Interference is generated by first using high-speed digitizers (vector signal analyzers (VSA)) to record interference waveforms in bandwidths up to 160 MHz. Those signals are then radiated or hardline coupled 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

For first responders, a communications system's ability to perform as expected is a life or death matter. ITS, in conjunction with NIST through the Public Safety Communications Research (PSCR) program, operates a Public Safety Broadband Demonstration Network (PSBDN) to test new public safety communications technologies under development so that both practitioners and vendors can be assured that the equipment performs as required. The PSBDN 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. CRADAs with manufacturers and carriers protect the proprietary information of companies whose prototypes are being tested in this neutral environment. Interested public safety agencies can observe these systems and execute specific test cases that are unique to their operational environment, while vendors observe how their target end users actually use the equipment in the field to de-bug any problems before the equipment goes to market. The PSBDN has the capacity to rigorously exercise emerging public safety communication technologies under simulated field conditions to minimize the risk of potentially life-threatening failure after the product has been introduced. 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.

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

LTE Capabilities

The network currently supports both band class 14 Public Safety LTE systems and Band 13 Commercial LTE systems. 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 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, west of the main DoC campus in Boulder, provides local area band class 14 coverage for the DoC campus and vicinity. The Table Mountain field site, about 14 kilometers north of the DoC campus, 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.

Antenna tower at the Green Mountain Mesa Field Site. Photo by Rob Stafford.

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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 4th 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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Table Mountain Field Site and Radio Quiet Zone

Table Mountain Field Site and Radio Quiet Zone. Map data ©2017 Google Imagery ©2017 , DigitalGlobe, U.S. Geological Survey, USDA Farm Service Agency.

The Table Mountain Field Site and Radio Quiet Zone is protected from strong external signals by state law and federal regulation to minimize radio frequency interference to sensitive research projects. Located north of Boulder and extending 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 enables interference-free research and development activities by Government, industry, and academic researchers across the electromagnetic spectrum. ITS administers the CRADAs and IAAs through which cooperative research activities with other entities are enabled on this restricted access site. Of the two federally mandated radio quiet zones in the U.S., the Table Mountain site is the one most consistently available for collaborative research with industry. Small businesses in particular have benefitted from access to the site for field testing of new technologies under development, including classified DoD-funded programs (FY 2016 details on page 67). Other DoC laboratories on the Boulder campus also make use of the site's unique geophysical characteristics and radio quiet to collect data used by the government to improve GPS accuracy and by myriad industries to plan and manage operations (FY 2016 details on page 70). Facilities at the site include:

- Spectrum Research Laboratory—A fully equipped facility for research into radio spectrum usage and occupancy. Radio Quiet restrictions and power distribution by means of buried line 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.
- Radar Test Range—A large open space for testing federal and commercial radar systems.
- 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.
- 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.

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

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Radio System Software Simulator

Trust in spectrum sharing depends in part on trust that the interference protection criteria (IPC) defined by sharing rules adequately protect the performance of incumbent radio services so they can continue to satisfy their mission. Scientifically sound unbiased radio system field measurements performed by ITS provide data that regulators use to define IPC, but field measurements are expensive and time-consuming, and may require that mission-critical radio systems be removed from service while tests are performed.

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—an interfering signal is injected into a receiver and performance is measured. However, the simulator can be used at any time in the laboratory without having to take systems out of service or send equipment and researchers to remote field locations. Other advantages of simulation are readily accessible performance metrics and unlimited access to intermediate signal processing signals. This enables ITS engineers to identify subsystems that are most sensitive to the interfering signal and recommend ways to "harden" the victim receiver to the interference.

ITS has developed simulations that 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 ITS simulator uses commercial off-the-shelf hardware and software components and 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. Simulated results have been compared to measured results, and simulation has been shown to be a potentially viable alternative to field measurements for IPC definition when models and parameters appropriate to the sharing scenario under study are carefully selected and used.

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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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Fiscal Year 2016 Research: Spectrum Sharing

For spectrum sharing to work and assure the viability of all the services involved, regulators and operators need three things:

- Spectrum monitoring to accurately and continuously identify spectrum available for sharing
- Measurements and modeling that reliably describe the parameters of sharing
- Electromagnetic compatibility (EMC) analyses that quantitatively describe the interactions between disparate systems that share spectrum

Spectrum monitoring is an emerging application of radio science; doing it accurately and correctly demands deep expertise in those areas of radio science and engineering that ITS is widely regarded for—accurate RF measurements, propagation modeling, and advanced equipment design. Radio propagation measurement and modeling are critical and complementary research areas for spectrum sharing. Research to assess the accuracy of both modeling and measurement techniques continues to be a fundamental focus of ITS work. Research in this area is iterative, with measurements both providing the basis for modeling algorithms and the validation for computational implementations of those algorithms. Validated propagation models and best practices for propagation measurement are essential to inform national spectrum policy and product development. These tools are applied to performing EMC analyses and parametric studies of potential interference among different radio services—and EMC analyses ultimately provide the data all stakeholders need for risk-informed decision-making in an RF environment where sharing is the new normal. In this section we describe research performed in FY 2016 under these three research categories.

Spectrum Monitoring

Spectrum monitoring—long-term continuous measurement of the RF environment from multiple sensors—is widely seen as essential to enabling increased exploitation of spectrum. CTIA, the U.S. wireless communications industry association, estimates that every 10 MHz of spectrum opened to commercial use adds $3 billion to the U.S. GDP.[1] Monitoring is expected be the cornerstone to modern spectrum management that is proactive and automated instead of reactive and static, enabling dynamic spectrum sharing by billions of new connected devices while protecting the operations of incumbent critical radio services.

In contrast to traditional short-term, single-time, single-location measurements, spectrum monitoring provides real-time context awareness and observations of historical trends and events. This type of data is needed to support the four steps of spectrum enforcement—interference detection, location, identification/classification, and resolution or remediation. Effective monitoring and advanced data visualization will give spectrum managers and regulators a dashboard of information on a level previously unattainable: actual spectrum use compared to assignment and license information; occupancy statistics for different frequency bands; spectrum maps of white spaces and areas of strongest signal. Potential interference events can be identified with a specified level of confidence. Longitudinal studies would enable spectrum efficiency data that can be used to compare usage before and after rule changes. Man-made noise statistics can be identified and monitored at frequencies and locations currently free of intentional radio transmissions.

Characterizing the wireless environment is too big for any one data collection effort. Spurred by the availability of cheap and plentiful sensors, ubiquitous network access, and advances in data science that facilitate ingestion, analysis, and visualization of big data sets, organizations world wide are working to develop spectrum monitoring capabilities, which should enable economies of scale. But these disparate and largely independent efforts, each constrained to the finite scope of one organization's resources, cannot provide the sheer volume of data regulators need, and there has been limited effort to aggregate and curate

1 CTIA Wireless Quick Facts. Accessed https://www.ctia.org/industry-data/wireless-quick-facts May 25, 2017

data for the common good. Anticipating this gap, ITS has been working for several years to develop and prototype standardized architectures for collective monitoring to support advances in spectrum management and enforcement. In August 2016, and in collaboration with NIST/CTL, ITS released a beta version of a federated Measured Spectrum Occupancy Database (MSOD) that collects spectrum data from remote sensors and allows authorized users to view usage data (Figure 1).

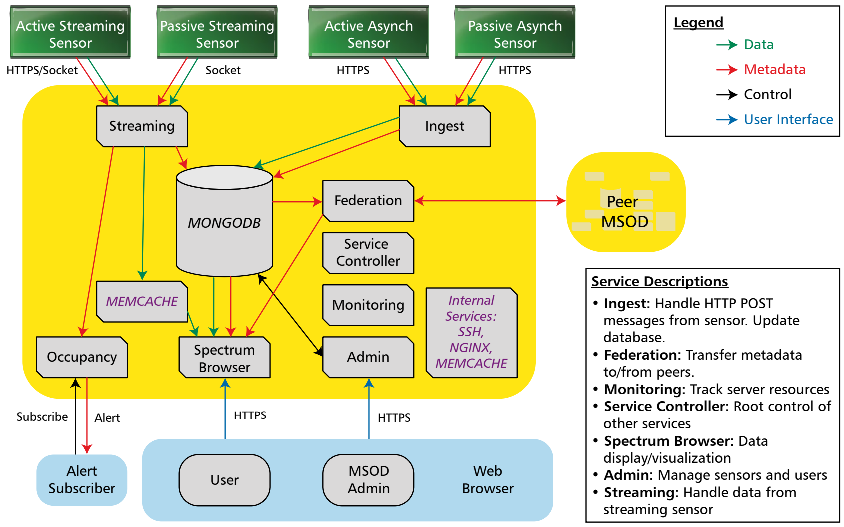


Figure 1. Block diagram showing conceptual architecture of the federated Measured Spectrum Occupancy Database (MSOD).

From this work, the need for a local test bed for both sensor and networking development became clear. Having identified faculty at the University of Colorado at Boulder (CU) with similar interests in spectrum monitoring and automated spectrum enforcement, ITS is entering into a no-cost Cooperative Research and Development Agreement (CRADA) with CU. This will enable ITS to place sensors and associated network infrastructure around the CU campus, which is larger and has a richer radio propagation environment than the Boulder DoC labs campus alone. Figure 2 shows the initial planned distribution of sensors on the CU and DoC labs campuses.

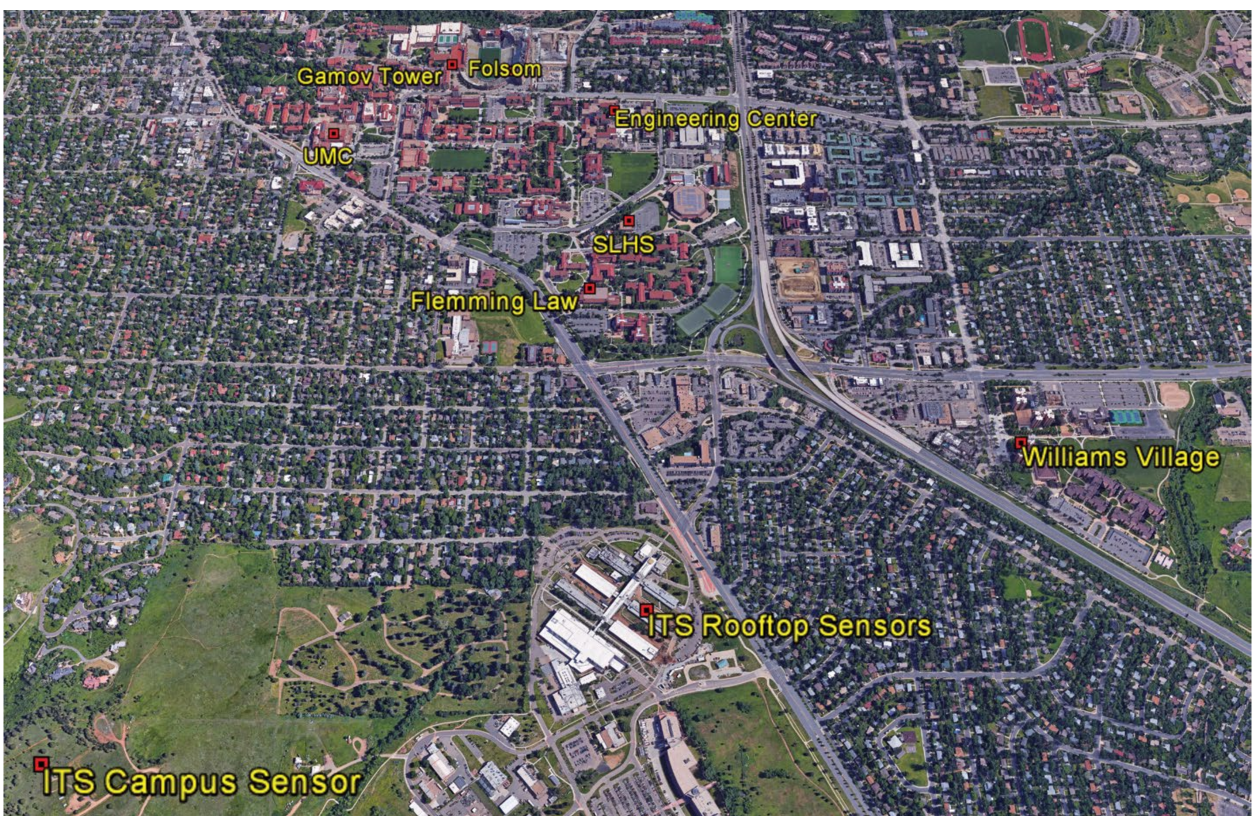


Figure 2. Boulder Test Bed sensor and infrastructure placement on the campuses of the University of Colorado Boulder and the Department of Commerce Boulder Labs. Google Earth™ map data ©2017 Google; image Landsat Copernicus.

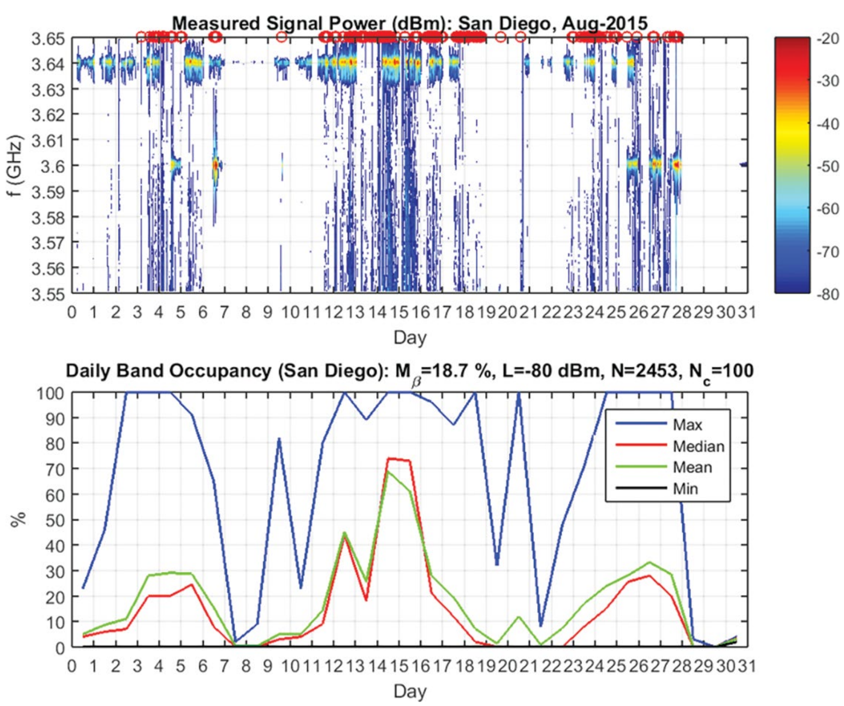
The Boulder Test Bed

The CRADA with CU will also lay the groundwork for a Boulder Test Bed that will eventually grow to city scale, encompassing the City of Boulder and perhaps surrounding communities. The benefits to government, academic, and industry researchers of access to this city-scale wireless facility are expected to be rapid and abundant. When it is completed, we expect this facility to be used not only to field test spectrum monitoring technology but also to offer wireless technology trial and development capabilities. The availability of a facility where the wireless industry can efficiently trial new technology over a city-scale area under real world conditions will benefit government, academia, and industry. The Boulder Test Bed will also provide a glimpse of what it will take to prototype and build a nationwide spectrum monitoring network.

For spectrum monitoring, developing the capability for data collection over a large area begins with developing and testing individual components, then exploring efficient and robust network connectivity between the various sub-systems. In preparation for local sensor deployment, in FY 2016 ITS began development of programmable sensors that will enable a wide range of investigation. These sensors will be band-specific devices based on commercial-off-the-shelf (COTS) software defined radio (SDR) technology.

These SDR based sensors will enable the rapid development and trial of sensing algorithms unique to the government spectrum sensing mission, which prioritizes monitoring for protection of mission-critical government systems. For example, in FY 2016, ITS began developing prototype SDR based sensors for LTE uplink and downlink characterization and for sensing radar emissions. These sensors will be deployed first on the ITS campus in Boulder for trial and further testing and then, in FY 2017, along the coast, where federal radars will shortly have to share spectrum with new commercial wireless systems expected to use LTE protocols. The mechanisms to protect both incumbents and entrants from interference—which will rely on sensor networks—are still under design. As the networking infrastructure is established, the ITS-designed sensors may also be deployed at the CU campus for additional burn-in and field testing.

Simultaneous with the development of sensors, the MSOD system will be moved to servers on-site at the ITS facilities in Boulder. This effort will enable secure collection of coastal radar data in FY 2017. At the same time, this transition will put the software into an environment in which further research and development can be better facilitated. As the larger Boulder Test Bed takes shape, the local MSOD will be the stepping stone to the development of a spectrum data collection and storage capability that enables the automated data analytics and visualization needed for a nationwide spectrum monitoring system.



Visualization of monthly band occupancy at 3.55-3.65 GHz as measured in San Diego, CA, in August 2015.

For modern spectrum monitoring, sensing hardware development and networking infrastructure go hand in hand with data analytics and data visualization. With data arriving from a set of spatially distributed sensors, it becomes possible to perform automated direction finding and/or emitter localization. This is an important capability for automated spectrum enforcement. For enforcement actions, it is not enough to simply detect an interferer. It is equally important to localize and accurately identify the source of interference. The Boulder wireless test bed, which includes the networking and analytics infrastructure, will serve as the development platform for the advanced emitter localization and identification techniques essential to effective spectrum monitoring.

To enable the development of a broader spectrum monitoring ecosystem, ITS personnel are leading a "spectrum monitoring as a service" standardization effort within the IEEE. This standards group is chartered under IEEE 802.22.3. The intent is to develop a public standard for the control of spectrum sensors and the collection of spectrum data from these sensors to a data storage facility. The scope of spectrum monitoring is large and the need is international. It will be of great benefit to enable industry to develop sensing capabilities that use a common communications standard so that multiple stakeholders can participate and industry can produce equipment that inter-operates. The architecture for this sensing network was defined in FY 2016 and we expect to have a first draft of the standard by late FY 2017 or early FY 2018. We will use the Boulder Test Bed as a development platform for this sensing standardization effort.

Radio Propagation Modeling and Measurements

After over a century of research, the behavior of radio waves is still not fully understood, and hence our ability to predict the effective coverage area of any transmitter is still imperfect. This is important because spectrum sharing scenarios are proposed and implemented in rulemaking based on the predicted ability of all the services that will share spectrum to operate effectively without causing interference to each other, or even to services in adjacent frequencies. Radio propagation models are used to make these predictions, and the models consider frequency, distance, and other parameters that may vary by frequency. The mathematical models that describe propagation at different frequencies are complex, and trust that a proposed sharing scenario will work depends on trust in the reliability of the models used to assess its feasibility. Today, as regulatory developments accelerate and spectrum rights transition, propagation prediction tools with improved accuracy and higher resolution are in high demand—and they are achievable via data-driven and site-specific prediction tools that use the increased storage and processing technologies now available.

Physicists have described the parameters that are important to predicting the propagation of signals of different wavelengths—for example, at which wavelength will a transmission be blocked by foliage and at which will it pass through. ITS has built a reputation as the premier source of radio wave propagation research based on its ability to analyze propagation questions from first principles and propose physics-based modeling solutions to provide unbiased results. ITS propagation experts hold technical leadership positions and/or make regular contributions at important spectrum regulatory and technology meetings such as the International Telecommunications Union (ITU), Commerce Spectrum Management Advisory Committee (CSMAC), and Wireless Innovation Forum (WInnForum)—all venues where stakeholders debate the reliability of different models. Primary examples of ITS propagation research results that have been incorporated into national or international standards for propagation modeling include general tools to predict effects due to: (1) diffraction and scattering over long terrestrial paths,[1] (2) ray curvature through a spherically symmetric atmosphere along air-to-ground paths,[2] and (3) atmospheric refractivity as a function of known meteorological variables at relatively high frequencies where molecular absorption dominates.[3]

1 Anita G. Longley and P. L. Rice, "Prediction of Tropospheric Radio Transmission Loss Over Irregular Terrain: A Computer Method - 1968," NTIA Technical Report ERL 79-ITS 67, July 1968. Available https://www.its.bldrdoc.gov/publications/2784.aspx.

2 M.E. Johnson and G.D. Gierhart, "The IF-77 Electromagnetic Wave Propagation Model," NTIA Sponsor Report FAA-ES-83/3, September 1983. Available https://www.its.bldrdoc.gov/publications/2524.aspx.

3 Hans J. Liebe, George A. Hufford, and Michael G. Cotton, "Propagation modeling of moist air and suspended water/ice particles at frequencies below 1000 GHz," *Proc. NATO/AGARD Wave Propagation Panel*, 52nd meeting, No. 3/1-10, Mallorca, Spain, 17 - 20 May, 1993. Available https://www.its.bldrdoc.gov/publications/2670.aspx.

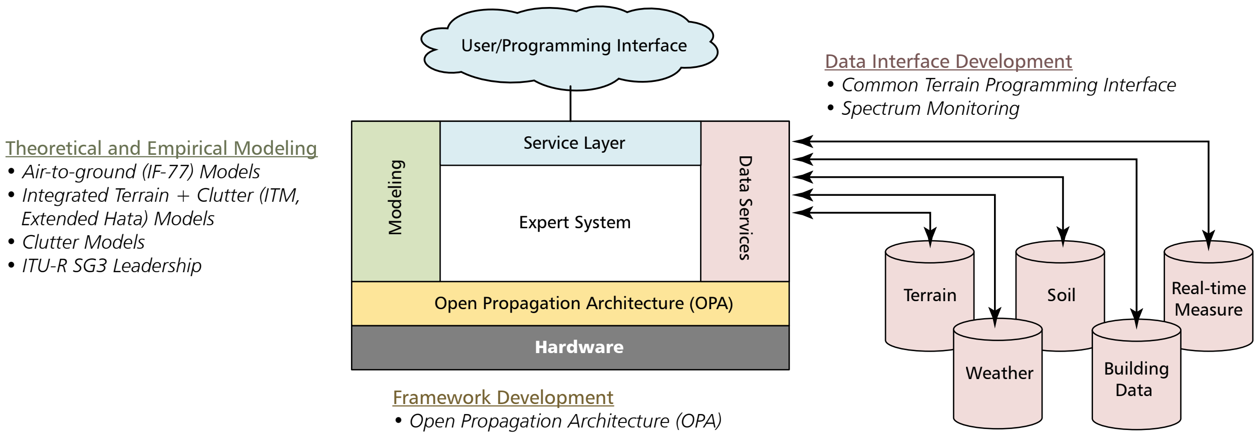


Figure 1. ITS propagation modeling framework to provide common and consistent model development, testing, and evaluation.

To assist in further improvement and evolution of these tools, ITS is working to establish a propagation modeling framework to provide common and consistent development, testing, and evaluation. The figure above schematically illustrates the proposed ITS propagation modeling framework being developed through a number of inter-related initiatives described elsewhere in this report. These include improvements to several different propagation prediction models, software elements using Open Propagation Architecture (OPA) principles, collaboration with international standards bodies, and model and measurement validation efforts. Once foundational elements of the framework are established ITS will begin work on collaboration and integration (i.e., Human Machine Interface, Service Layer, and Expert System).

Open Propagation Architecture Toolkit

Propagation models tend be uniquely devised to address specific scenarios and frequency bands. However, each model also uses a number of similar operations such as data extraction, terrain handling, unit conversion, and various intermediary results. A simple example is the calculation of free-space loss, implemented in multiple models. A more complicated example would be the extraction and sub/super-sampling of terrain data, which most models require. Because current models were developed over many decades, implemented in the software language that was most appropriate at the time, and designed to take advantage of then-available computational capacity, it may be difficult to add functionality to individual models. Often, for example, models that implement their own terrain extraction routines are tied explicitly to inflexible and archaic data formats and are not easily extended or adapted to more modern formats.

The Open Propagation Architecture (OPA) toolkit aims to alleviate these issues through an interface and programming framework that implements many of the building blocks of a propagation model as tested and extensible modules. This allows the propagation engineer to focus on composition of a model that more accurately predicts propagation, rather than on programming inputs and outputs, automation, and other trivial but error-prone tasks. As a proof of concept and source of inspiration, an existing model is used as a basis for a vertical slice implementation. The model is discretized and implemented with the OPA toolkit framework, then compared to the existing implementation for correctness and performance.

A primary goal of OPA is the melding of existing and new native language functions and libraries into a single set of common routines and abstractions. These should be easy to use and include verification tools that are cost-free to the user once the interface is properly specified. An example propagation library has been built that implements some fundamental propagation methods, most notably a two-ray model. An extendable build tool that is well supported, easy to use on multiple platforms, and has support of all the native languages targeted by OPA—C, C++, Java, Fortran—was chosen to build the shared libraries whose source code will be integrated into the OPA toolkit. The OPA toolkit can also use pre-compiled shared libraries for which the source code is unavailable.

Propagation Model Validation

The traditional approach has been to empirically derive radio propagation models from large sets of measurement data collected for the specific scenario. But with the proliferation of new, radically different communications technologies and protocols, models are often needed to predict the behavior of transmitters that have not yet been built. As mentioned at the beginning of this section, this leads to an iterative development process that validates theory by comparison to measurements and theoretically derives better models from new, more sophisticated measurement results. While work proceeds on modernization of propagation prediction tools to improve accuracy and resolution, ITS is also performing research to assess the accuracy of both modeling and measurement techniques.

It is essential that both NTIA and the U.S. telecommunications community have access to trusted tools such as validated propagation models and best practices for doing propagation measurements to inform national spectrum policy and product development. Through an integrated and iterative series of measurements, computation, and modeling, ITS is building a framework to assess both model and measurement accuracy. Researchers start with validating simple "ground-truth" configurations and gradually move on to examining increasingly complex propagation scenarios.

In the first half of FY 2016, ITS and NIST researchers formed a Propagation Modeling and Validation Working Group to discuss channel sounder measurement systems, large scale computing for propagation modeling, analytical and numerical propagation modeling, and statistical methods for quantifying the differences between channel measurements and models. The group identified several experiments whose results would contribute to advancing research in those areas:

- Intercomparisons of different channel sounder systems
- A series of short-range propagation measurements over a metal ground screen on an open-area test site (OATS)
- A mixed-path propagation study with one antenna located on the OATS and the other positioned off the OATS
- A series of scattering and diffraction measurements using canonical structures
- Intermediate-range propagation measurements above Earth ground in the more complex environment at the ITS Table Mountain Research Facility in conjunction with both modeling and computer simulations
- Measurements, modeling, and large-scale computations in more complex environments with a mix of static measurements and an extensive venue of mobile propagation measurements

ITS and NIST researchers performed a comprehensive intercomparison of four different channel sounder systems:

- The ITS-developed continuous wave (CW) mobile channel measurement system described on page 14
- A NIST-developed pseudo-noise (PN) channel system
- A NIST-developed oscilloscope channel sounder with a multi-sine pulse generator
- A NIST-calibrated vector network analyzer used as the reference standard

Figure 1 shows the conducted setup. It consists of a switch matrix network that successively

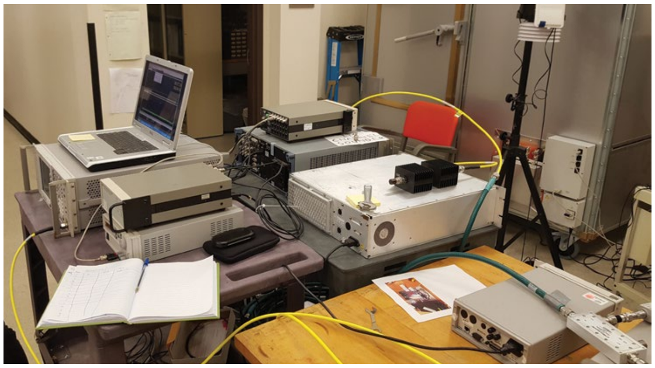


Figure 1. The ITS mobile channel measurement system deployed in the conducted channel sounder test setup. Photo by Bob Johnk.

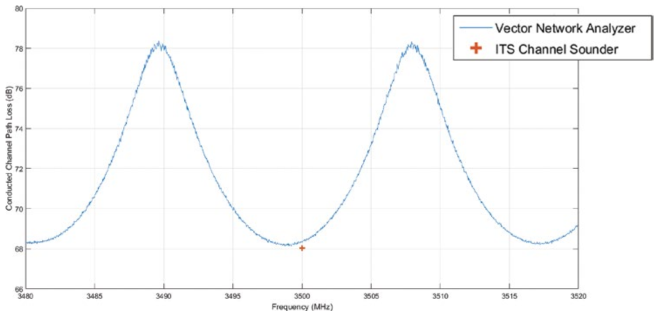


Figure 2. A direct comparison of results plotted by the ITS channel sounder and a NIST-measured, swept-frequency frequency VNA measurement.

Figure 3. ITS VNA/optical link system deployed on the NIST OATS for propagation measurements. Photo by Bob Johnk.

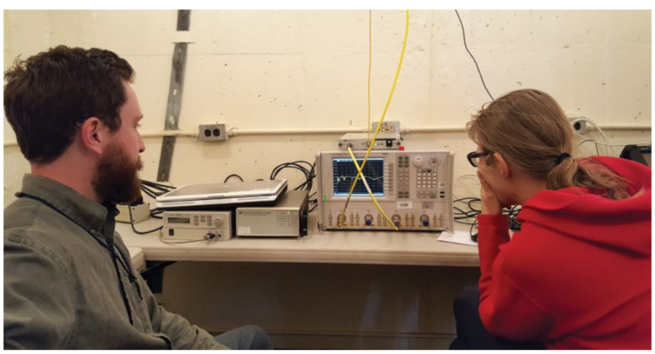


Figure 4. ITS engineers Erik Hill and Irena Stange observe the VNA during propagation measurements.

connects each of the channel sounders to an attenuator/delay line combination that simulates a short-range propagation scenario. The core of this measurement system is a precision vector network analyzer (VNA) that is used as a basis for intercomparisons with other channel sounder systems. Figure 2 shows a direct comparison of an ITS system measurement of conducted path loss at 3500 MHz with a swept-frequency VNA measurement. The results demonstrate the excellent accuracy of the ITS channel sounder and demonstrate the efficacy of ITS-developed propagation measurement procedures. These will be published as replicable best practices for this type of measurement.

ITS engineers also performed a series of short-range propagation measurements on the NIST OATS located on the campus of the Boulder Commerce Laboratories. Two different systems were tested: a cart mounted version of the ITS-developed CW mobile channel system, and a swept-frequency system consisting of a VNA and optical link. The VNA/optical link system was deployed on carts with omni-directional transmitting and receiving antennas. A series of path gain measurements at frequencies in the AWS-3 and 3.5 GHz bands were carried out over the ground plane at separations ranging from 2.5 meters to 43 meters. The cart deployment on the NIST OATS is shown in Figure 3. The VNA is in a control room located underneath the OATS (Figure 4).

The omni-directional antennas were modeled over a perfectly conducting ground plane of infinite extent using a high-performance Method-of-Moments (MoM) code. The antennas were modeled in considerable detail and the MoM code was used to compute path gain for some of

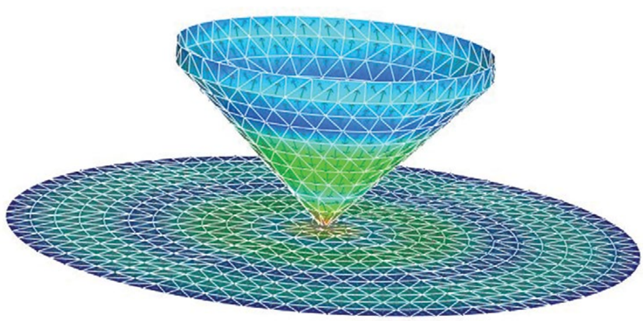


Figure 5. A MoM model of a discone omni-directional antenna. Arrows denote the direction and strengths of the computed current densities.

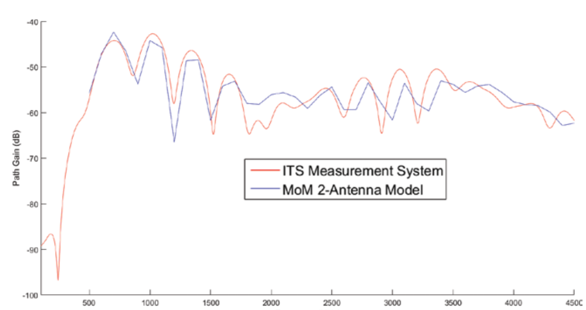


Figure 6. A comparison of path gains measured by the ITS VNA optical link system with computed results using the MoM technique.

the actual testing configurations. Figure 5 depicts the MoM model of the transmitting antenna and the computed current densities and Figure 6 shows a typical intercomparison for an antenna separation of 5 meters. Modeled and measured results were generally well-correlated, providing some initial "ground truth" data that will be published for use in developing coordination tools in the newly-shared AWS-3 and 3.5 GHz bands.

Integrated Terrain plus Clutter Propagation Modeling

When a radio wave encounters a rigid obstacle, a portion of the signal is not stopped but redirected. This phenomenon of wave behavior was first posited in the 17th century and has been extensively studied ever since. With respect to modeling attenuation due to urban clutter, perhaps the most difficult problem is generalizing the cumulative effect of multiple hard surfaces and sharp edges. This is called multiple knife-edge diffraction, and several mathematical models have been proposed to describe it.

In 2016, the NTIA's Office of Spectrum Management (OSM) funded initial work on an Integrated Terrain and Clutter Radio Propagation Model. A key feature of this model is the rigorous solution of the multiple knife-edge diffraction via one mathematical model that is then verified by comparisons to others. Additional comparisons to cluttered environment radio propagation solutions are in progress.

Several issues must be addressed to make the Integrated Terrain and Clutter model a more general purpose solution to this radio propagation problem. First, at ranges near the smooth Earth radio horizon distance, the model should blend smoothly with the smooth sphere diffraction solution. At greater ranges still, the most efficient radio propagation mechanism will shift to forward, or tropospheric, scatter. Finally, the variability of radio signal propagation in time, location, and situation should be included.

Air-to-Ground-Propagation Modeling

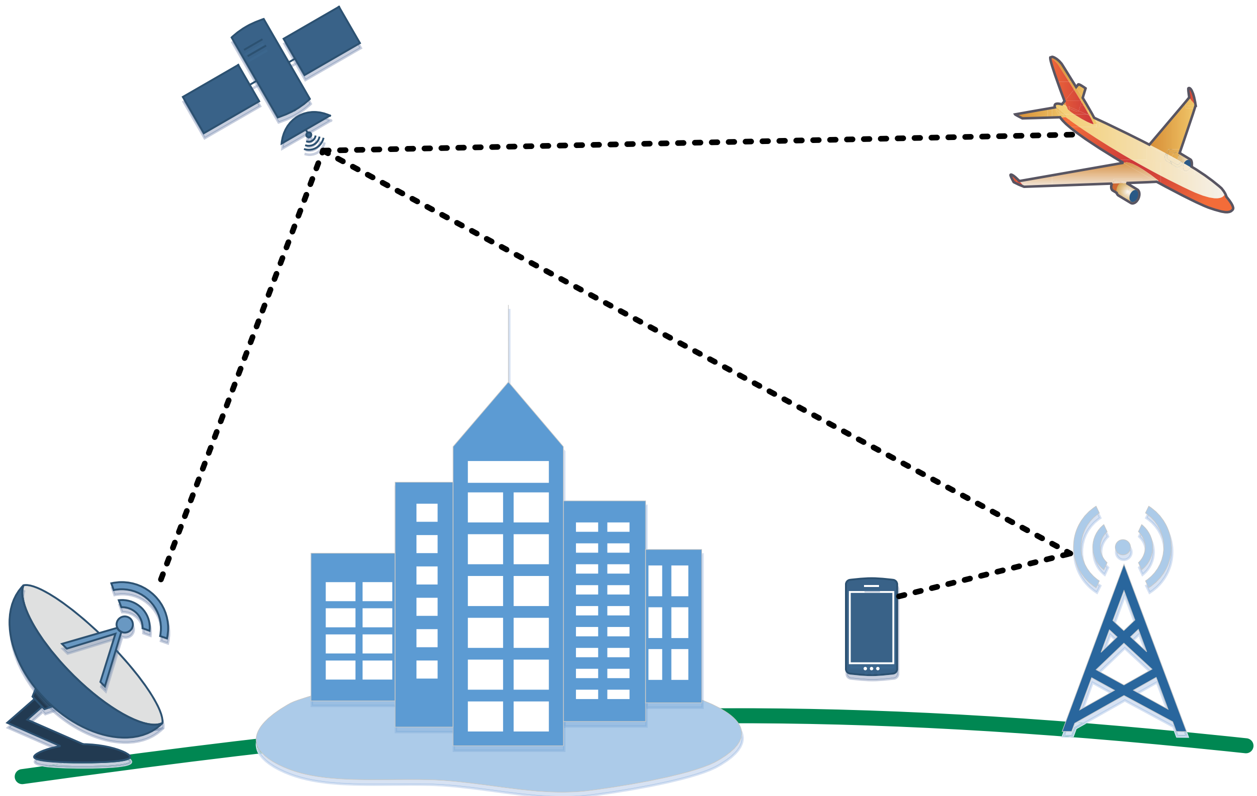
As spectrum sharing proposals reach into bands previously reserved exclusively for satellite uplinks and downlinks, demand for propagation modeling that can reliably predict radio propagation in and above the Earth's atmosphere has also increased. The demand is lent urgency because of concern that data streamed by, for example, a weather satellite, may be lost forever if the downlink is interrupted by interference. The ITS-FAA 1977 (IF-77) propagation model is an air-to-ground and air-to-air propagation model for systems between 0.1 and 20 GHz. The model takes into consideration irregular terrain, atmospheric absorption, and ray bending caused by the atmosphere, and also predicts propagation through space. Although developed decades ago, IF-77 is still one of the most used and trusted air-to-ground propagation models in existence.

However, IF-77 has some drawbacks. Since its development, advances in propagation modeling have occurred that, if incorporated into IF-77, would increase the accuracy of model subcomponents. Additionally, the software implementation of the model exists only as a Fortran-77 code base with its inputs still mapped to the original three-card IBM EBCDIC card format.

ITS has embarked on a three-phase effort to modernize and improve the propagation model and its software implementation so that it can be more widely and easily used. The work is staged so that an initial operating capability can be rapidly delivered to current simulation environments even as longer term, more extensive modeling improvements are made.

Phase 1: Encapsulate

The first phase of the effort had two goals, 1) deliver Initial Operating Capability (IOC) by exposing the propagation model through the creation of a standardized Application Programmable Interface (API), and 2) document the model's internal workings, including both the software design and any modeling approximations. The API allows external software applications to integrate the IF-77 air-to-ground propagation model into their current simulation environments in a straight-forward manner. This will meet



This schematic shows some of the propagation paths that could be modeled using the IF-77 air-to-ground and air-to-air propagation model.

the immediate demand for this type of modeling so that incumbent agencies can coordinate systems for both exclusion zones and spectrum sharing purposes. For example, in the 1755-1780 MHz band recently opened to sharing as a result of the AWS-3 auction, there are legacy government air assets that cannot be relocated. Coordination with new entrant ground transmitters and receivers will require modeling analysis.

Documenting the original design and modeling approximations increases our understanding of the accuracy and limitations of the model. This will support risk-informed uses of model results. It will also support prioritization of Phase 3 improvements.

Phase 2: Modernize

The theoretical underpinnings of the IF-77 propagation model are still valid, albeit dated in certain areas, but the software implementation predates standardized software engineering practices. Thus, while the software is functional and faithfully reproduces the model, the way it is written makes the code base unmanageable and unusable in most programming environments today. This limits the ability to incorporate new and improved modeling techniques. Phase 2 will focus on modernizing the software implementation of the propagation model to allow for future modeling improvements. Leveraging modular architecture constructs, the IF-77 software implementation will be re-architected with a focus on extensibility, maintainability, and compatibility.

Phase 3: Improve

A modernized software architecture will allow ITS to incorporate into IF-77 both previously developed improvements and new research. Models like the Millimeter-wave Propagation Model (MPM-93) can help push the upper frequency limit of IF-77 past the current 20 GHz and into millimeter wave frequency bands. Integrating new high fidelity datasets, such as collaborative work ITS is pursuing involving global surface refractivity, can improve accuracy through the inclusion of higher quality site-specific data. Likewise, inclusion of improved hydrometeor and weather data allows for a more accurate model of the atmosphere when specifying a time and place for propagation modeling. Lastly, parallel work at ITS focusing on clutter modeling will allow improved urban modeling. These and other improvements will allow spectrum planners to use the improved air-to-ground propagation model to both reduce exclusion zones for legacy air-to-ground systems and achieve improved spectrum sharing with reduced interference between systems.

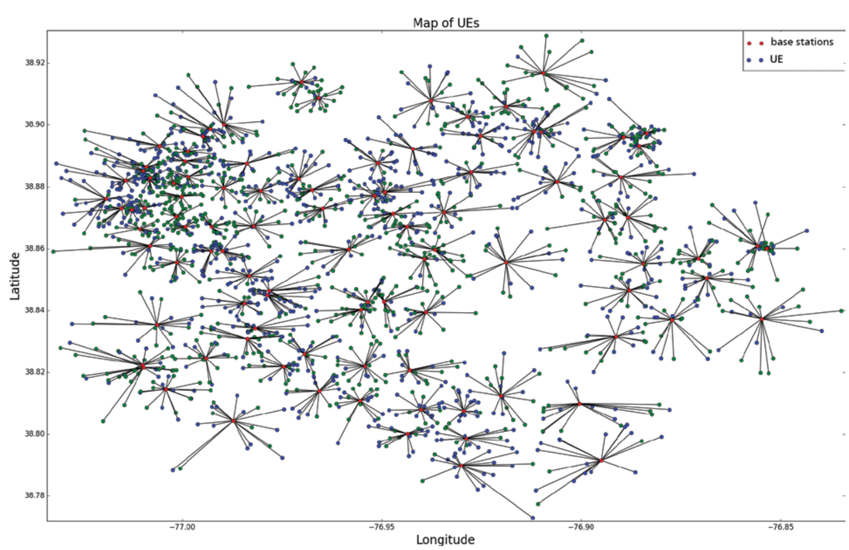
Aggregate Modeling

Imagine that you are trying to have a conversation with a friend sitting across a table from you in a restaurant. You may have difficulty hearing each other if a fire engine drives down the street with its siren blaring. This is an analogy for typical RF interference problems involving a single interferer. But you may also have a difficult time hearing each other if the restaurant is very crowded with many other people talking. No individual speaker is loud enough to disrupt your conversation on their own, but with enough people there can be a great deal of noise. This is an analogy for the aggregate interference problem. It’s an important problem because many interesting spectrum sharing arrangements involve technologies such as LTE where many devices spread over a large area are transmitting in the same radio band. In the domain of spectrum sharing, for example, an urgent question is determining the effect on the accuracy of a radar’s ability to detect its target when many cellphones begin transmitting on the same frequency as the radar.

The ITS Aggregate Emissions from LTE (AELTE) model is designed to predict the level of radio emissions coming from multiple interferers, specifically multiple pieces of LTE user equipment (UE) such as cellphones and hotspots. ITS’s aggregate model takes the general form of a Monte Carlo simulation, a method used to model the probability of different outcomes in complex systems with many random variables that produce a lot of uncertainty.

Using Monte Carlo simulation, we don’t merely generate one scenario that we believe represents the network we are studying. Instead we randomly generate a large number (typically thousands) of scenarios that represent plausible network configurations. The figure below shows a map of a typical scenario—the red dots represent fixed base stations and the other dots represent randomly placed UEs. The lines illustrate which base station provides service to each UE.

In this way, we get not only an idea of the most likely interference level, but also a good sense of the range of possible interference levels, which may range from minimal to tolerable to obstructive. This is a powerful tool for interference studies because it allows us to approach the problem from a risk management perspective. With precise knowledge of how rare a given aggregate power level is, we can frame our requirements in terms of how rare we want interference to be rather than the unrealistic demand that interference never happen.



Realistic UE pairing to base stations mapped by latitude and longitude.

Progress in FY 2016

The downside of a Monte Carlo approach is that it can take a long time to generate a large number of scenarios even on a modern computer. This is especially true when the simulation is modeling a large area with thousands of base stations and UEs. At the end of FY 2015, we had successfully described the algorithms necessary to perform our Monte Carlo analysis, but some interesting situations would require weeks or months of computation before we could produce results. This led us to produce a new implementation of our model in FY 2016. This implementation included new data structures and algorithms that dramatically increased the speed of our simulations. Now we are able to generate meaningful results without the time and computational expense typically associated with Monte Carlo analysis.

We also took a measurement-based approach to model development in FY 2016. This involved incorporating empirical propagation models such as Okumura-Hata as well as measurements of real LTE networks operating in various bands. We were able to extract from these measurements some basic statistics about the operation of various LTE schedulers. The scheduler is a critical component of modeling an LTE network because it determines when UEs are allowed to transmit and what frequencies they use. Schedulers control all the radio emissions in the network. Modeling them is difficult because their exact algorithms are considered highly proprietary. By using measurements of a real network, we can realistically simulate schedulers.

These real-world LTE measurements also gave us a preliminary idea of the power levels a typical UE uses when it transmits. This has been a critical question in many aggregate models that preceded ours. By performing a detailed comparison between these measurements and the internal results of our model, we were able to determine that UE power levels depended very strongly on their distance from their base station. This was not surprising, but it was important to discover that this is a much more critical factor than any interference from other UEs in the network. As we go forward, this insight will allow us to refine our model by focusing on the exactly placement of UEs on the map. We can generate much more realistic radio emissions by putting our UEs in more realistic locations.

Other measurements have been planned through ITS's spectrum monitoring project and others. These will yield actual aggregate power measurements of real LTE networks that will help us begin to validate the results of our simulation.

Immediate Applications for Spectrum Sharing Scenarios

47 U.S.C. §902 assigns NTIA the responsibility to perform "research and analysis in the general field of telecommunications sciences in support of assigned functions and in support of other Government agencies." Thus, one of the primary missions of ITS is to serve as a principal federal resource for addressing the telecommunications concerns of other agencies. AELTE is a good example of a tool developed in anticipation of requests for expert assistance from other agencies as a result of regulatory or technological changes.

ITS is working closely with NOAA on spectrum sharing issues in the 1695-1710 MHz band (see related story on page 61). LTE carriers want to use this band, recently opened to sharing by commercial users and currently used by NOAA for meteorological satellite downlinks. In order to ensure continued reliable operation of the weather satellites, we must accurately predict the interference to a given satellite Earth station that will be generated by a proposed LTE network. This is a perfect application for the ITS AELTE model, and many preliminary results were generated and shared with NOAA in FY 2016. Those results were used by NOAA in preparing the Draft Request for Proposals (RFP) for the design, development, testing, and deployment of Radio Frequency Interference Monitoring System (RFIMS) devices to protect meteorological satellite earth stations from LTE interference in the 1695–1710 MHz band.[1]

Part of this analysis involved developing new code to simultaneously consider multiple antenna orientations. Because these satellite Earth stations use large parabolic dish antennas with highly focused beam patterns, the orientation of the antenna can have a very significant impact on the level of interference. The interference levels can change by orders of magnitude when the antenna rotates by just a few degrees. To

1 The National Oceanic and Atmospheric Administration (NOAA) Acquisition & Grants Office issued the RFIMS_DRAFT_RFP on December 21, 2016. Details are available at FedBizOpps.gov (https://www.fbo.gov/index?s=opportunity&mode=form&id=e04ac18688e1a507ec8df90e751fc082&tab=core&_cview=1).

understand these issues, we have simultaneously generated separate results for hundreds of different antenna orientations. Each scenario generated in our simulation tells us something about all of the antenna orientations. This avoids the enormous computational costs of running hundreds of separate Monte Carlo simulations. With this approach, we were able to demonstrate that waiting to acquire a satellite signal until the dish is elevated 5° above the horizon would substantially reduce the potential for interference from an LTE network on the ground. This enables consideration of specific operational procedures NOAA might adopt to protect the integrity of the data downlinks.

Radio Channel Measurement

Many factors affect the radio channel. In urban environments tall buildings can largely obstruct signals and the various construction materials like glass, brick, reinforced concrete, and steel all influence propagation in substantially different ways. Street widths that range from broad avenues to narrow alleys—even street orientations with respect to a distant victim receiver—can impact radio waves. In rural areas, dense tree canopies can hedge out signals. Even the size of needles or leaves can result in markedly different amounts of signal loss for transmissions with different wavelengths. Since the Institute's inception, ITS radio engineers have performed many propagation measurements in these types of environments and have developed a host of models for various situations.

However, in July 2012 when the Commerce Spectrum Management Advisory Committee (CSMAC) stood up a number of working groups with federal agencies and commercial wireless operators to lay the groundwork for the AWS-3 auctions, it became clear that these legacy propagation models were not ideal for the new use cases being envisioned. Similar use cases under consideration for the 3.5 GHz rulemaking presented comparable modeling challenges. The old models work very well with tall transmitters and elevated receive antennas—for example, television broadcast applications. However, the new use cases involve transmissions from cell phones at street level, and even though there are new repositories of building height data now available, the models weren't designed to ingest and process the new data. Rather, legacy propagation models assume a "bare earth" devoid of buildings and foliage. It was clear that the models needed adjustments to treat "clutter" (i.e., foliage and man-made structures) and this would require extensive new measurements to permit further model refinements.

In response, ITS developed and deployed an updated propagation pathloss measurement system in FY 2013. Recognizing the need for greater confidence in measurement precision and repeatability, in FY 2014 ITS worked jointly with NIST to design and execute a battery of system validation tests. Those measurements yielded a number of important findings. First, they confirmed suspicions that clutter losses were being underestimated in dense urban environments, and thus revealed the need for a longer term program to collect more extensive measurement data. That work led to a clutter measurements research program in support of the Defense Information Systems Agency (DISA), under the auspices of its new Spectrum Sharing Test & Demonstration (SST&D) Program.

Second, the system validation tests exposed location errors up to 20 m due to poor GPS satellite reception. Since the small cells now being deployed in urban environments may have a radio footprint as small as 10 m, an error of this magnitude is unacceptable for predictive purposes. This spurred the design of a project to improve geolocation precision or location accuracy by merging inertial navigation and precision optical imaging. Improving geolocation accuracy will lead to predictive models with the accuracy and granularity required by modern cellular technologies. Finally, this work motivated the creation of a longer term research effort at ITS to validate specific propagation models by systematically coordinating propagation measurements with propagation model development and validation efforts so that predictive data for new sharing scenarios can be developed more rapidly.

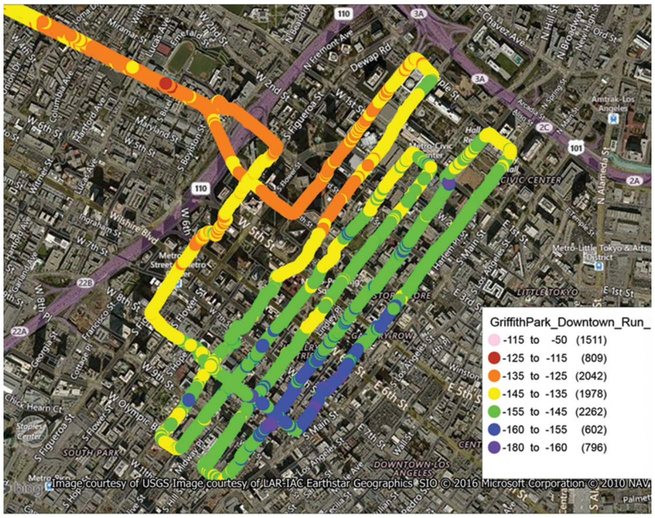


Figure 1. Basic transmission gain along streets in downtown Los Angeles with a transmitting antenna in Griffith Park. Violet dots represent greatest attenuation, pink least attenuation. Satellite imagery courtesy USGS, LAR-IAC Earthstar Geographics SIO © 2016 Microsoft Corporation © 2010 NAVTEQ.

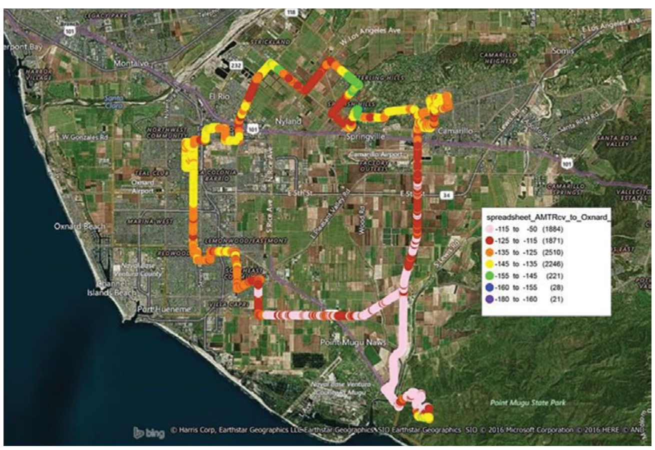


Figure 2. Basic transmission gain streets in the Oxnard area with a receiving antenna at the Point Mugu AMT receiver site. Violet dots represent greatest attenuation, pink represent least attenuation. Satellite imagery © Harris Corp., Earthstar Geographics LLC, Earthstar Geographics SIO © 2016 Microsoft Corporation © 2016 HERE.

SST&D Clutter Measurements, Phase II

Wireless carriers began submitting "early-entry" coordination requests to transmit in AWS-3 bands where DoD has operational services in November 2015. DISA asked ITS to make measurements to estimate clutter losses so that it could respond to the specific requests. These SST&D Phase I measurements used a technique that, while it produced rapid results, could not be generalized to a predictive model. It was clear that a longer term solution for integrating clutter losses into the propagation model was necessary, and in FY 2016 ITS initiated Phase II measurements to collect more data with the aim of developing a generalized predictive model of the impact of clutter on propagation.

In Phase I of the Clutter Measurements project, ITS performed targeted measurements to create location-specific estimates of the statistical distribution of clutter losses. The first three regions measured were Denver, CO; Washington, DC; and Los Angeles, CA. The results from these measurements, presented at the 2016 IEEE Military Communications Conference (MILCOM), were used to make end-point corrections to pathloss calculations. That is, adjustments based on local measurements of pathloss due to buildings and foliage were applied to the first estimates of signal attenuation generated by propagation models. While expedient, this technique was found to be too dependent on the characteristics of local environments: empirical measurements would be required in every location for which a coordination request was received to make the necessary end-point corrections, which is prohibitive both in terms of cost and schedule.

In response, the Clutter Measurements Phase II project team is now collecting propagation data in additional locations—especially where DoD's compatibility analysis with commercial systems is believed to be underestimating the potential for spectrum sharing. This approach serves a dual purpose of providing more local end-point correction datasets and an expanded repository of data for propagation model development. The first Phase II propagation measurements were carried out in Los Angeles, CA, at three transmitting locations. The locations were specified by the SST&D Propagation Working Group to address particular issues being considered by model developers. Figure 1 shows the basic transmission gain along streets in downtown Los Angeles with the transmitting antenna located in Griffith Park, which is approximately 9 km northwest of the city center. Colors toward the blue end of the color spectrum, which represent more negative gain (or loss), indicate greater attenuation due to building clutter.

Measurements were also made near Point Mugu near Oxnard, CA to better understand the basic transmission gain between the Oxnard area and the Aeronautical Mobile Telemetry (AMT) receiving antennas on Point Mugu. AMT systems track aircraft during flight testing and because of their high gain dish antenna are highly susceptible to interference from commercial user equipment (UE). In that instance, we reversed the transmitting and receiving antennas so as to prevent interference with sensitive military receivers at that location. An omnidirectional transmitting antenna was used to mimic UE antenna behavior and the receiving antenna was a high-gain omnidirectional antenna. The basic path transmission gain along our drive route is shown in Figure 2. The greatest distance between the transmitter and receiver was approximately 15 km. As the plots illustrate, there is much more signal attenuation in the urban core of Los Angeles.

ITS will be conducting further studies in both rural and urban-core areas throughout FY 2017.

Precision Geolocation

Global Positioning System (GPS) receivers have become widespread and are used for everything from navigation to obtaining location information during propagation measurements. Simpler consumer-grade receivers obtain their signals from a single antenna which is usually built into the device and may only receive from the U.S. GPS satellite constellation. Professional grade receivers use dual antennas and can receive signals from foreign global navigation satellite constellations as well. Even professional grade GPS receivers have difficulty obtaining accurate locations in urban canyons or other environments where satellites are hidden from view due to buildings or terrain features. Position errors can be as large as 40 to 50 m.

Recently, ITS has focused on making propagation measurements in cluttered environments—precisely where GPS receivers perform at their worst. However the path between transmitter and receiver must be precisely known so that the physical interactions between the radio wave and the environment can be understood well enough to develop accurate models. To address this problem, ITS procured a dual-frequency, multi-constellation GPS receiver (Figure 1), which improved location accuracy by 2 to 5 m in rural/suburban areas and 5 to 40 m in urban canyon areas. ITS is now augmenting this system with better antennas and adding cameras, inertial measurement units, and wheel encoders. The simultaneous localization and mapping (SLAM) method, normally applied to autonomous robotics and artificial intelligence (AI), was developed in response to the question, "If a mobile robot was placed in an unknown location in an unknown environment could it build an incremental map while simultaneously determining its location within the same map?"

SLAM promises to dramatically improve location accuracy for mobile drive testing, but the testing may also provide data to improve its application in robotics. ITS is initiating a CRADA with the University of Colorado's Autonomous Robotics and Perception Group in Boulder to jointly explore this application of SLAM. System specification and equipment procurements have been completed and in FY 2017 ITS will assemble instrumentation, calibrate the system, and field test it on the ITS measurement vehicle. First phase systems integration will fuse sensor data from the two cameras, an inertial measurement unit (IMU), and the GPS receiver (Figure 2). The wheel encoders will be added at a later stage. Figure 3 on the next page illustrates how the system might identify landmarks in a street scene (as indicated by the white circles). As the camera moves through the environment, the changing position and distance to the landmarks can be fused with the IMU data. The IMU tracks six degrees of freedom of motion—translational (x, y, z) and rotational (yaw, pitch, roll). With this new technology, ITS hopes to decrease positioning uncertainties to approximately 5 cm.

Figure 1. Dual-antenna, multi-constellation GPS receiving system.

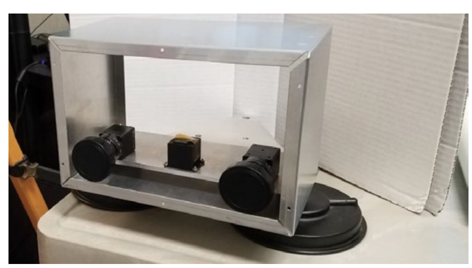


Figure 2. Cameras and IMU to be installed on the roof of the measurement van.

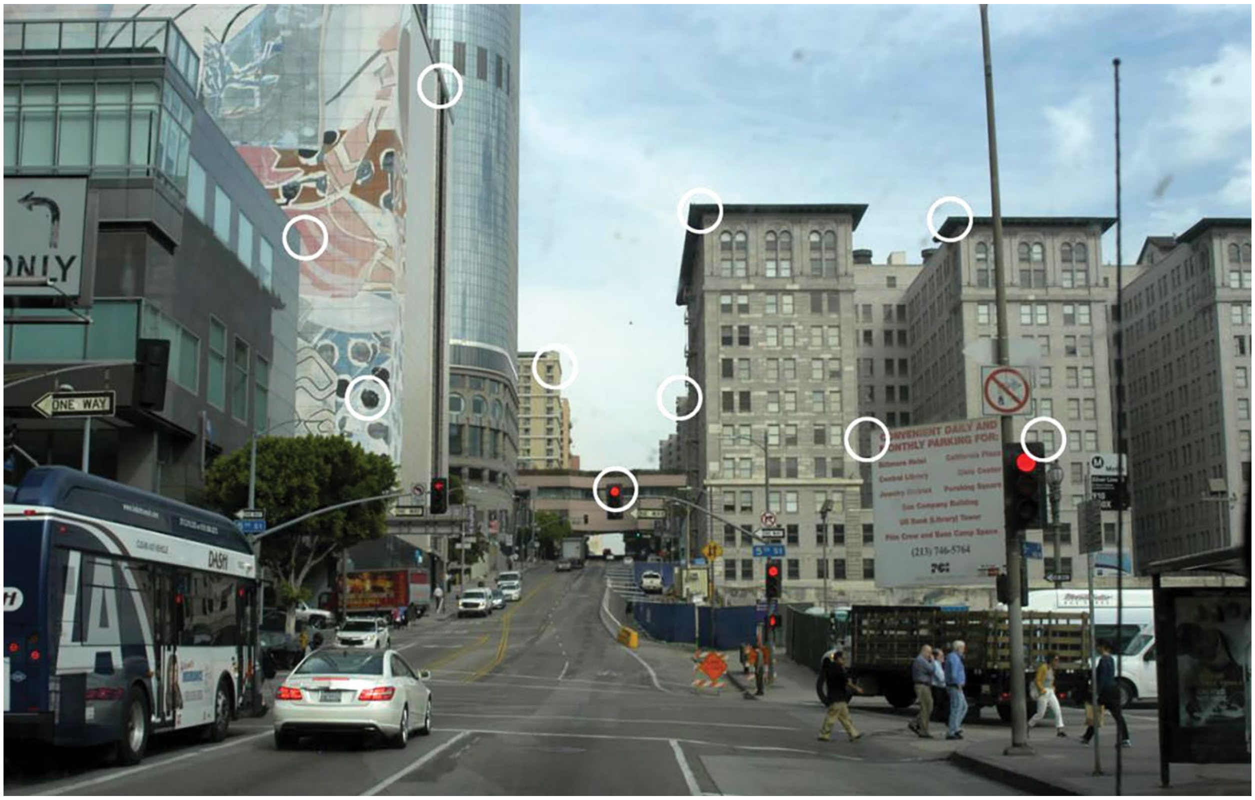


Figure 3. Tracking relevant features using simultaneous localization and mapping (SLAM) system.

Electromagnetic Compatibility (EMC) Analysis

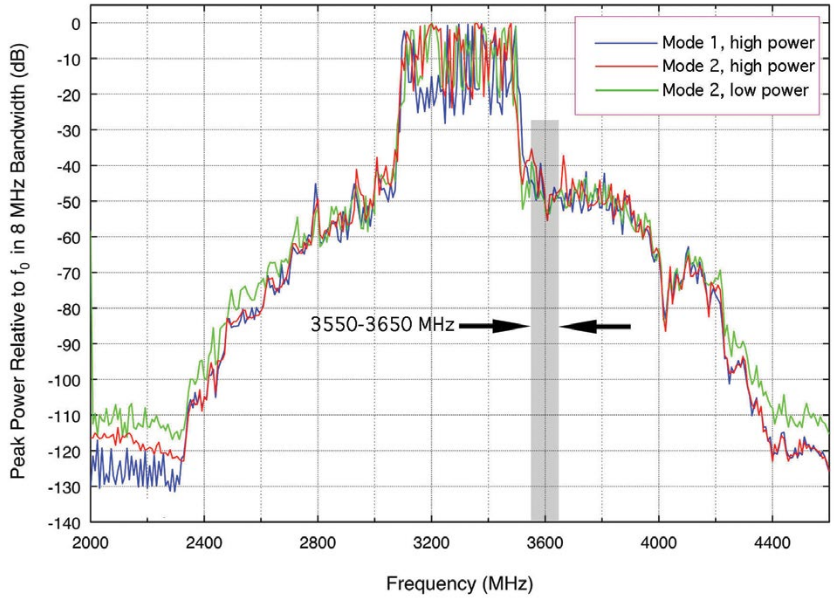
In the initial stages of an analysis, NTIA's Office of Spectrum Management conducts a preliminary "desktop" EMC study using known federal system characteristics and assumed behaviors of commercial systems. The preliminary study generates a number of scenarios or "use cases" for further studies that determine how separations in distance, frequency, direction, polarization, and coding can be exploited to prevent interference between systems.

While these studies are often sufficient to identify limiting use cases, they do not provide the level of detail needed to create well informed policy. For this, the more complex EMC measurement and analysis methods ITS uses are needed. In these more detailed measurements and analyses, ITS engineers consider each radio link component starting from the potentially interfering transmitter and ending with the victim receiver. The primary objective of the measurements is to characterize the interfering signal, radio propagation channel, and receiver so that they can be modeled and reduced to the parameters needed for EMC analysis.

The interfering signal characteristics include the signal amplitude probability distribution (APD) and power spectral density (PSD) statistical functions. The amplitude probability distribution is used to determine signal statistics such as the mean power or the percentage of time power exceeds critical victim receiver interference thresholds or interference protection criteria (IPC). The PSD is used to determine how much power gets through the victim receiver filters to degrade performance. In addition to these characteristics, interfering waveforms are digitized and later played back in interference tests.

The radio channel characteristics are probably the most difficult of all to determine. This is because radio channel propagation includes a number of random effects such as atmospheric conditions and building obstructions. However, they are also some of the more important characteristics because they determine propagation losses and the corresponding separation distances between the interfering signal transmitter and the victim receiver needed to keep the interfering signal below the IPC. Typically the interfering signal and victim receiver antenna patterns are considered a part of the radio channel and so must also be characterized.

Finally, receiver characteristics are needed to determine the victim receiver's response to the IPC. In the initial EMC analysis IPC are determined from estimates of how much interference power reaches the victim receiver detector. As mentioned earlier, this estimate is made from the receiver detection frequency response and the interfering signal PSD. Also during the initial EMC analysis, victim receiver non-linear effects thresholds are determined to ensure that the interfering signal will not cause reductions in receiver gain or sensitivity. Finally, the most definitive IPC is obtained by evaluating victim receiver performance degradation across a wide range of interfering signal powers.



The results of measurements to characterize the signals of incumbent transmitters for an EMC analysis for sharing. The graph shows measured emission spectra for three federal radars operating adjacent to a band proposed for sharing with commercial transmitters, identified by the gray shading. (Figure 7 from NTIA Technical Report TR-15-510.)

Additional aggregate interfering signal measurements and analyses are needed for systems that will share spectrum with commercial mobile data systems that support tens of thousands of transmitters. With these systems, each transmitter can dynamically adjust its modulation, frequency assignment, and transmit power. Also, since mobile devices are involved, each transmitted signal can travel over a unique propagation channel and reach the receive antenna from a different angle. Consequently these systems generate aggregate interfering signals that are random and must be statistically characterized.

Anecdotal analysis or measurement of a particular radio link component, such as the interfering signal, is often sufficient to update an existing analysis, and ITS's research portfolio contains a number of one-time studies of this sort. Broader research areas such as radio propagation and aggregate interference are common to many sharing studies. These correspond to major sources of uncertainty in our EMC analysis and if that uncertainty could be reduced, expanded spectrum sharing opportunities might become available. This research is pursued both as part of our core research mission and on behalf of other agencies who sponsor such research to address a specific question. Application-specific EMC analyses to address unique use case scenarios are typically funded through interagency agreements with impacted federal agencies. Two current application-specific EMC analyses underway are that for the NOAA Radio Frequency Interference Monitoring System (RFIMS) and that for the DoT Dedicated Short-Range Communications (DSRC) service.

For the RFIMS, ITS is tasked with specifying the parameters of a system that will someday monitor LTE user equipment signals that will share the 1695–1710 MHz meteorological satellite band with meteorological satellite ground stations operated by NOAA. The monitoring system will detect the presence of an interfering signal, verify that it is an LTE signal, and notify the federal agency operating the meteorological ground station so that operators may notify the LTE service provider to take steps to minimize this interference with the LTE service provider. The EMC measurements and analysis needed to specify these parameters draw on all three characterization areas—interfering signal characterization (story on page 38), radio wave propagation channel characterization, and receiver characterization (story on page 41).

During the course of our study, a number of interesting EMC analysis issues have come up that ITS is uniquely situated to address. The first issue is what type of antenna pattern the monitoring station should use. That is, should the monitoring system use the ground station antenna itself or perhaps can a better measurement be made with an omnidirectional antenna? As it turns out the ITS aggregate interference model that has been in development for a number of years (see page 29) is key to answering this question. Another issue is whether adjacent channel interference (ACI) power from the other signals transmitted by the meteorological satellite will influence the IPC. To determine this, we must know the interfering signal power spectral density, the receiver filter frequency response, and the amount of polarization discrimination. Once again, ITS measurement and analysis methods developed over a number of years are needed to answer this question.

EMC Analysis for the Dedicated Short-Range Communications Service

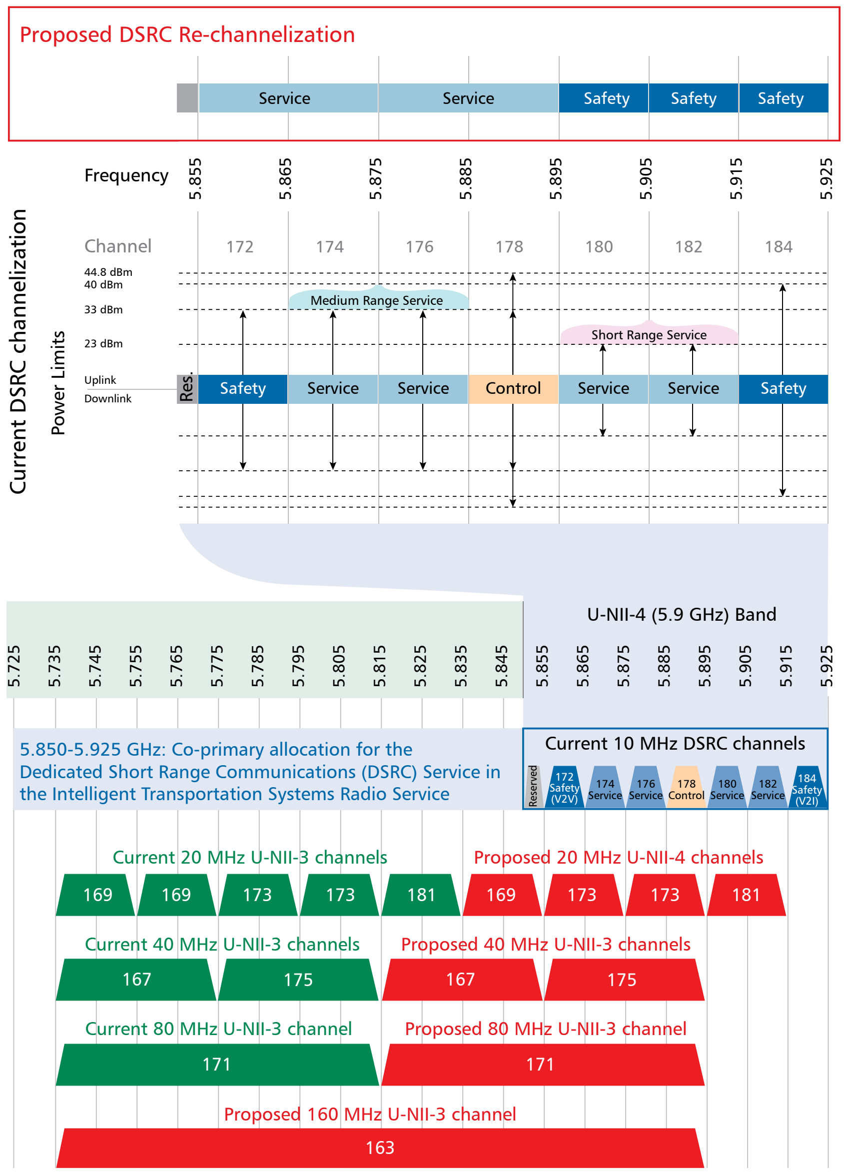
In 1999, the FCC allocated spectrum at 5850–5925 MHz (also known as the 5.9 GHz or U-NII-4 band) on a primary basis for the Dedicated Short-Range Communications (DSRC) service. DSRC is a short to medium range Intelligent Transportation System communication service intended to improve roadway safety for both public safety and private operations. It uses short-range wireless links to enable communication between appropriately-equipped vehicles (“vehicle to vehicle” or “V2V”) and between vehicles and roadside systems (“vehicle to infrastructure” or “V2I”). On-Board Units (OBUs) are mounted in vehicles and Roadside Units (RSUs) are units installed at fixed locations along infrastructure, streets, and roads. Wireless communications based safety applications using V2V could inform a driver of roadway hazards and dangerous situations that they can’t see, and mobility applications using V2I could help optimize transportation system performance by providing real-time information on traffic flow, speeds, and other vehicle conditions. In December 2016, the Department of Transportation (DoT) issued a proposed rulemaking that would require automakers to include V2V technologies in all new light-duty vehicles, predicting that, once fully deployed, the technology could prevent hundreds of thousands of crashes every year.

Recently, the 5850–5925 MHz band was identified as a prime candidate for sharing with Unlicensed National Information Infrastructure (U-NII) devices. U-NII devices provide short-range, high-speed unlicensed wireless connections in the 5 GHz band for, among other applications, Wi-Fi-enabled radio local networks, cordless telephones, and fixed outdoor broadband transceivers used by wireless internet providers. In addition to proposing to open the band to shared use with U-NII devices, the FCC has suggested a re-channelization to move the three most heavily used DSRC safety channels (Vehicle-to-Vehicle, Control, and High-Power Vehicle-to-Infrastructure) to the upper 30 MHz of the DSRC band. The Federal Highway Administration (FHWA) asked ITS to perform several EMC analyses of different scenarios under both the current and proposed band occupancy. The scenarios contain geometries representative of worst case situations that would occur in a real environment. First, the potential for interference from U-NII 802.11ac devices to the DSRC devices in both V2V and V2I scenarios was examined. Then the reverse situation—interference to U-NII devices from DSRC devices—was explored. Thirdly, an adjacent channel analysis of the potential U-NII to U-NII interference was performed, and finally a DSRC to DSRC adjacent channel interference analysis was also performed in response to the re-channelization proposal.

ITS conducted a survey of potential interference sources operating in and adjacent to the 5850–5925 MHz band. 802.11ac devices 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 parameters needed for analysis of the interference source 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 if the DSRC is being interfered with include the received signal strength indicator (RSSI) and the packet error rate (PER) outputs of the DSRC. Where sufficient information was not available, 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.

Specialized propagation models are needed to predict emissions for both DSRC and the U-NII devices in the roadway environment because both use very low height antennas and transmit over ultra-short distances. Antenna characteristics and separation distances between the transmitters and desired receivers and between the interference source and the desired receivers must be identified. The models must be able to predict indoor versus outdoor propagation through various building materials and foliage. In this case, three models were found to be suitable: the ITS-developed Undisturbed-Field Model, the ITS-developed Short Range (ITSSR) Model, and the model described in Recommendation ITU-R P.1411. All three had been previously verified and validated with measured data. ITS used these models to determine frequency dependent rejection, assess interference potential, and determine protection distances.

At each step, the results from the analysis models were compared to data from tests developed using scenarios determined by FHWA and ITS. This thorough communications and EMC analysis of the test data identifies whether it is necessary to modify the model input parameters of the systems or re-evaluate the initial assumptions; the analysis is rerun as necessary until the model output matches the live test data. This iterative process verifies the analysis procedure and gives confidence that the approach will provide realistic and reliable results. With this confidence, the analysis results can be applied to other scenarios that will not be verified with actual testing due to time and cost constraints, since testing all possible scenarios is prohibitively expensive. This approach allows researchers to extrapolate and assess many more potential interference interactions than would otherwise be possible.



Current and proposed DSRC and U-NII-3 and -4 allocation and channelization in the 5.9 GHz band.

Interfering Signal Characterization

Spectrum sharing studies require EMC analyses based on accurate and reliable measurements of transmitters and receivers. These measurements need to have the widest possible dynamic range to ensure that all possible sources of interference are observed. Receiver measurements show the extent to which unwanted energy is rejected. Transmitter measurements characterize the emission spectra. These two measurements are then used to determine required frequency and distance separations between transmitters in the same frequency band.

Since transmitters are supposed to meet emission limits (called emission masks), why do we need to perform measurements of transmitter emission spectra? Because transmitters' emissions almost never come even close to the mask limits set by regulators. They are usually substantially lower than the required limits, often by tens of decibels. EMC studies that assume that transmitter emissions are as high as emission mask limits therefore seriously overestimate the required frequency and distance separations needed for compatible operations between systems. They end up being overly conservative.

The only way to accurately ascertain the out of band and spurious emission levels of transmitters for EMC analyses is to actually measure those emissions, and not simply guess what they might be based on mask limits. The primary tools ITS uses for emission measurements are the RSMS platform and related measurement systems described beginning on page 12. The RSMS is constantly expanded and enhanced through procurement of state-of-the-art test equipment and construction of new custom ITS designed hardware. New measurement routines and data analysis techniques are incorporated into the software on a regular basis and features are added to existing automated measurement routines to make use of new hardware features as they become available.

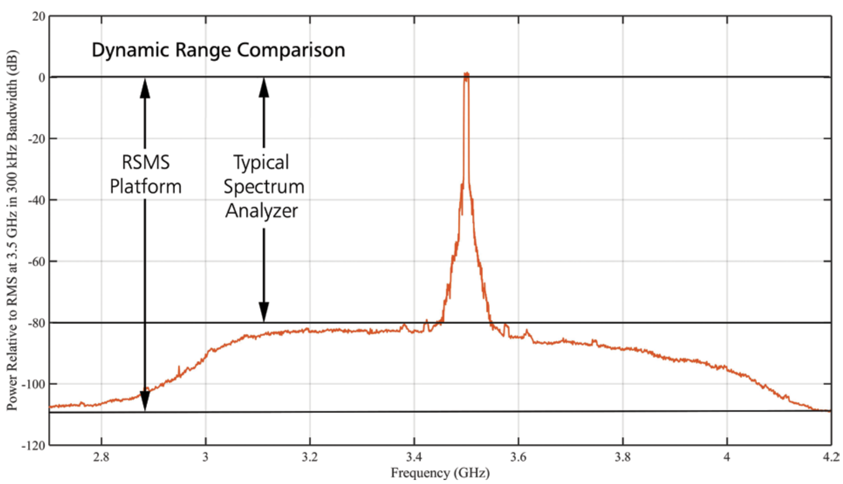


Figure 1. Plot showing the expanded measurement dynamic range of the RSMS measurement platform. Although the out of band emissions revealed by the RSMS system (below the solid black line) have low power, they may still cause a problem to an adjacent band receiver that cannot reject that unwanted energy.

LTE Hotspot Emission Measurements

A key feature of the RSMS system is the ability to make wide dynamic range measurements. Figure 1 shows the results of an emission measurement performed on an LTE hotspot operating at 3.5 GHz—a band identified for sharing. The figure shows that despite the instantaneous dynamic range of the spectrum analyzer that was used being only 80 dB, ITS was able to measure the emission spectrum with nearly 110 dB of dynamic range. This sort of dynamic range is required for thorough EMC studies and only ITS measurement systems achieve this kind of performance.

LTE User Equipment Emission Measurements

It is not enough to just measure transmitter emission spectra and receiver characteristics for EMC analyses. The time behavior of radio systems must also be measured to see how often and how long individual frequencies are used. An example of a difficult sort of transmitter to measure in time is LTE mobile phones

(UEs). UEs use sets of individual channels that are each 180 kHz wide, called resource blocks (RBs). They shift activity around these RBs every few milliseconds, and the shifts are unpredictable. As the histogram in Figure 2 shows, almost 70% of the time no resource blocks might be allocated for UE transmissions. On the average, about 7 out of 50 available RBs might be used at a time. Since RB occupancy is so short and sporadic and frequencies change rapidly, many traditional test instruments are not adequate for measuring them.

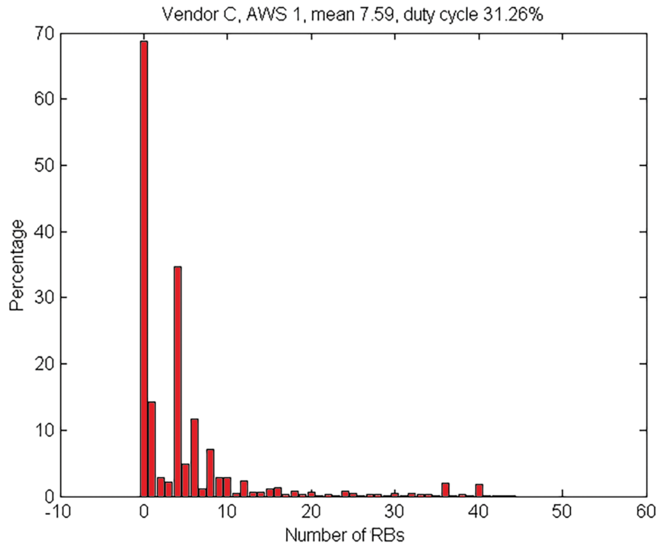


Figure 2. Histogram showing RB allocation for UEs operating in the AWS-1 band for a single wireless carrier.

ITS builds and uses systems that can measure the emissions of such transmitters, as shown by this example data set. To take these measurements, ITS used the *Radiated LTE Measurement System* described on page 15. This specialized test instrument decodes commands from the LTE base station to their associated mobiles to determine the behavior of those mobiles on a millisecond by millisecond basis. This work combines LTE signal protocol analysis with radio spectrum measurements, to provide a complete picture of how transmitters occupy both frequencies and time. This kind of multi-dimensional data set is crucial for good EMC analyses for spectrum sharing.

RSEC Measurements

ITS also conducts emission measurements to ensure that radio systems meet government regulations. Using methods described in NTIA Technical Report TR-05-420, ITS has done extensive work in measuring radar emissions, which must meet the NTIA Redbook[1] radar spectrum engineering criteria (RSEC) to be permitted to operate. RSEC measurements have been built into the RSMS. They are automated and allow ITS engineers to easily measure radar characteristics such as beam scanning rate, pulse width, pulse rise time, pulse fall time, and pulse repetition rate. Again, the wide dynamic range of the RSMS measurement platform is very important since in some cases the RSEC requires OOB emissions to be suppressed by more than 80 dB. This means that RSEC measurements must be able to see down 100 dB or more in the measured spectra. Figure 3 shows an example of an RSEC mask overlaid on a radar emission spectrum.

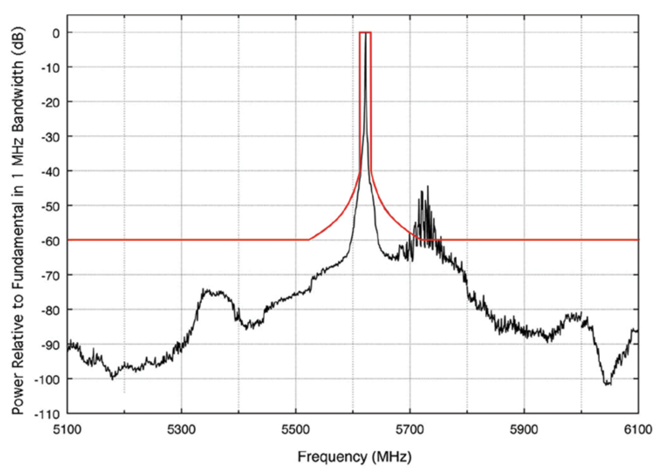


Figure 3. Example of a measured weather radar emission spectrum with the RSEC mask overlaid.

1 The [Manual of Regulations and Procedures for Federal Radio Frequency Management (Redbook)] is incorporated by reference into 47 U.S.C. §300.1(b). It is the compilation of policies and procedures that govern the use of the radio frequency spectrum by the U.S. Government and must be followed by federal government agencies who use spectrum. Section 5.5 of the Redbook specifies criteria for equipment characteristics to ensure an acceptable degree of electromagnetic compatibility among radar systems and between radars and other radio services sharing the frequency spectrum—the radar spectrum engineering criteria (RSEC). One of these is an emission mask that describes the limits on the amount of energy that a radar system can radiate in various parts of its RF emissions. The Redbook refers users to NTIA Report TR-05-420, "Measurement Procedures for the Radar Spectrum Engineering Criteria (RSEC)," of which ITS Senior Technical Fellow Frank Sanders is lead author, for information about obtaining spectrum emission data against which the RSEC mask limits can be assessed for any given radar transmitter.

Top: ITS engineer Geoff Sanders measures emissions of a new Ku band airborne radar system at the Table Mountain Field Site. Bottom, the device under test. Photos by Frank Sanders.

FY 2016 RSEC Measurements

In FY 2016, ITS staff completed field measurements at the Table Mountain Field Site on a new airborne radar system operating in the Ku band (12–18 GHz) designed by Sandia National Laboratories. The measurements were being performed under an Interagency Agreement with Sandia National Laboratories to verify compliance of the radar against the RSEC requirements.

Emission Measurements for AWS-3 Sharing

Several prior articles have referred to the FCC's auction of the AWS-3 bands (1695–1710 MHz, 1755–1780 MHz, and 2155–2180 MHz) that concluded in January 2015 and raised a record-breaking $44 billion. AWS stands for Advanced Wireless Services, which will be deployed rapidly as winning bidders move to recoup their investments by selling expanded cellular data services. In all the AWS-3 bands, some government systems will continue to operate, either permanently or temporarily, alongside the new radio services. These include a multitude of diverse systems, from meteorological satellite downlink stations (see page 61) to data telemetry links at test ranges. Thus, EMC studies to determine exactly how much interference might occur (in either direction) are critically important, and they need to use the best possible information about both AWS-3 transmitters and the potential victim receivers.

In other AWS bands transmitters currently use Long Term Evolution (LTE) technology for both user equipment (UE) and the eNodeB (eNB) base stations. In FY 2016, ITS worked with the NIST's Communications Technology Laboratory, under the umbrella of the National Advanced Spectrum and Communications Test Network (NASCTN), to address the need for high-quality AWS-3 transmitter characteristics for EMC studies. They took detailed emission spectrum measurements of existing transmitters now in use in other AWS bands. These measurements, funded by an other-agency sponsor, will lead to emissions measurements on actual AWS-3 UEs and eNBs when they become available next year.

The only measurement system that we know of that can achieve the necessary dynamic range with the required sensitivity is operated by ITS. It is the same dedicated, custom-built hardware and software system as the Institute has used to measure radar emissions since the late 1970s. The hardware consists of an RF front end containing 0-70 dB of selectable RF attenuation, a tunable yttrium-iron-garnet (YIG) microwave bandpass filter, and a high-performance low noise amplifier (LNA). When this hardware is combined with custom-written ITS measurement software that causes the measurement system to step across measurement frequency ranges instead of conventionally sweeping across those ranges, it comprises the core of the RSMS-4 system described on page 13.

It was this core RSMS-4 system that was used in 2016 to perform preliminary emission spectrum measurements on current-generation AWS UEs and eNBs for NASCTN at the ITS and NIST laboratory facilities in Boulder. Those measurement results have been provided to the sponsor. They show the emission spectra of the UE and eNB transmitters with 100 dB of dynamic range, meeting the requirement for effective data inputs for EMC studies.

In 2017 the same measurement system and stepped-frequency approach will be used to measure emissions from new AWS-3 UEs and eNBs for the same sponsor. With those emission measurement results in hand, EMC studies will be completed in preparation for band sharing between private sector AWS-3 systems and government telemetry systems at 1700 MHz. This sharing will in turn make more spectrum available for more Americans, contributing to the overall growth of the U.S. economy.

Receiver Characterization

The ultimate goal of receiver characterization is to provide policy makers with an estimate of the maximum amount of interference power a "victim" receiver can tolerate. This interference power is most commonly referred to as the victim receiver's interference protection criteria (IPC). In many cases the IPC is well below the victim receiver noise floor (the level of internal noise introduced by system components), making it a challenging parameter to predict analytically and verify through measurement.

First-order IPC are determined from estimates of interference power in the bandwidth of the victim receiver's detector. Often electromagnetic compatibility is only obtained by offsetting the interfering signal center frequency from the victim receiver's, producing what is known as frequency dependent rejection (FDR). This estimate requires measurement of the interfering signal power spectral density (PSD) and the victim receiver detector frequency response.

In addition to the FDR, first order IPC analysis generally includes an assessment of whether interfering signal power can drive receiver front-end components such as the low noise amplifier (LNA) into non-linear behavior. This behavior is detrimental because it can reduce LNA gain and receiver sensitivity. If severe enough it can also distort the signal, causing additional losses. The most common measure of this non-linear or "overload" behavior is the 1 dB compression point.

The most definitive assessment of IPC is obtained by evaluating the effect of the interfering signal on victim receiver performance. The IPC is the interference power that degrades the performance from that without interference to the minimally acceptable performance with interference. For communication systems this performance is evaluated with bit or frame errors, for radars with probabilities of false alarm and detection, and for geolocation systems such as the GPS with position error.

ITS has a long history of working closely with OSM on receiver characterization. Notable accomplishments in the past include work with communication signal interference into radar receivers, radar signal interference into communication receivers, and ultrawideband signal interference into satellite and GPS receivers. More recently efforts have focused on developing methods to perform faster, more accurate IPC assessments through simulation, and comparing measured and simulated results.

IPC Estimation Methods

In the past, ITS has estimated IPC with hardware test fixtures either set up in the laboratory or at the location where the equipment is operated. Briefly, the measurements consist of setting the victim receiver to a typical operating state and then incrementally increasing interference power until it can no longer provide the performance level needed to fulfill its mission.

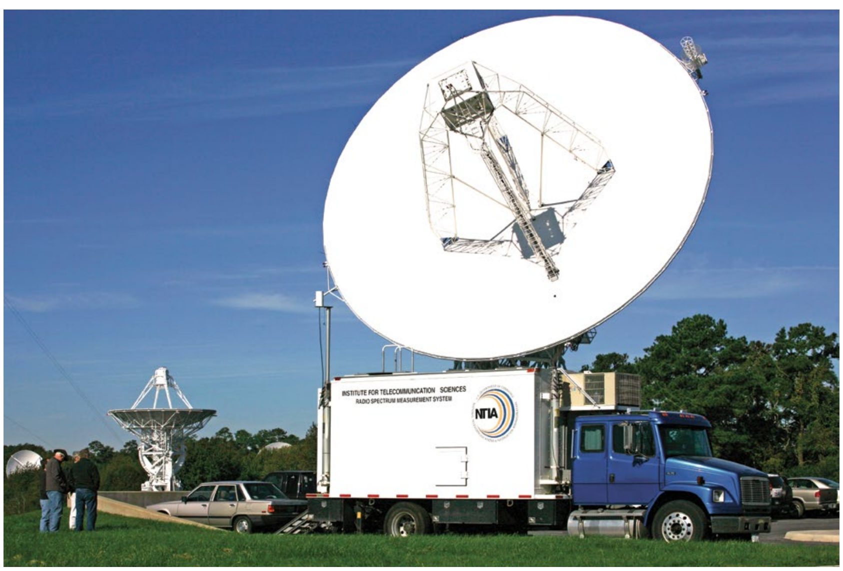
When performing these measurements, it is vitally important that signal and interference powers are set accurately and performance measurements are precise. Performance measurements that are repeatable and precise are the most problematic to accomplish.

For example, some radars have integrated performance measurement functions that generate, identify, and count test targets. While extremely useful, this approach requires the participation of a trained radar operator, who may not always be available. Consequently, ITS test engineers developed their own visual performance measurement method based on visually counting test targets on the radar display. NTIA Technical Report TR-06-444[1] describes the development of this method and a number of IPC measurement results for air traffic, maritime, and weather surveillance radars.

There are two problems with estimating radar IPC with the visual performance measurement method: 1) inconsistent performance metrics and 2) performance measurement uncertainty. Inconsistent performance metrics are due to difference in the radar signal processing. For example some radars have constant false alarm rate (CFAR) functions that automatically increase the threshold when interference is present. These radars lose targets when interference is present. Other radars have manual thresholds. When the radar operator neglects to raise the threshold manually, the radar display is overwhelmed with interference induced false alarms. Consequently the metric for radars with CFAR is the objective probability of detection. The corresponding metric for radars without CFAR is the objective "visibility." The high measurement uncertainty is due to the limited number of visual performance method test trials that can be performed in a reasonable amount of time.

Related to the lack of precise performance measurement is the problem of IPC measurement replication—what good is a precise measurement if it cannot be verified by others? The main impediment to replication is the lack of access to the interfering and victim system equipment. In many cases, the IPC measurements are executed on equipment that is in service. Thus, the engineers must travel with their test equipment to the location of the device under test, and when they arrive often have limited time for testing. Compounding this problem is that in many cases the test engineers do not have access to the signals they need to measure precisely or to the parameters that define typical operating conditions.

To address these problems, ITS engineers are currently investigating how they might use radio system simulation to estimate IPC. Off-the-shelf software radio system simulators are now tremendously more capable than just a few years ago. They now offer realistic emulations of most commercial systems that might share spectrum with federal systems. In addition, they have rich libraries of radio components that can be used to emulate federal radar, satellite broadcast, and other communication systems.



The RSMS mobile measurement platform being set up to measure the characteristics of a NOAA satellite Earth station at the NESDIS facility in Wallops Island, VA. The satellite downlink receiving dish antenna can be seen behind the truck. Photo by Ron Carey.

Test Studies for IPC Estimation through Simulation

Satellite Downlink Receiver

ITS engineers traveled to the NOAA NESDIS facility in Wallops Island, VA, and used the RSMS platform described on page 13 to measure the characteristics of the NOAA satellite Earth station

1 Frank Sanders, Robert L. Sole, Brent L. Bedford, David Franc, and Timothy Pawlowitz, "Effects of RF Interference on Radar Receivers," NTIA Technical Report TR-06-444, February 2006. Available https://www.its.bldrdoc.gov/publications/2481.aspx.

as part of the analysis for sharing described on page 61. Characteristics of the complete receive chain from the antenna through the receiver/demodulator were measured. Key characteristics include: noise figure, gain, IF and RF filter shapes, and the LNA compression point. The data collected during these measurements are being used to create an accurate model for simulation so that IPCs can be determined analytically. In addition to the simulation, the receiver/demodulator will be studied in the lab to measure performance degradation in the presence of interference. This data will be used to validate the findings of the simulation.

Air Surveillance Radar

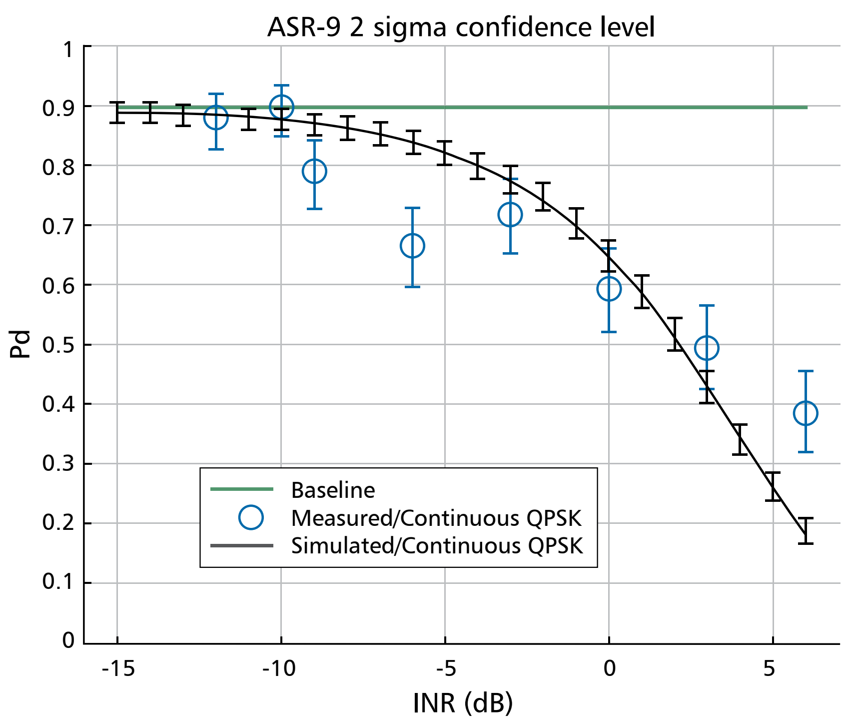
The figure below shows measured and simulated air surveillance radar IPC results. In both cases the radar baseline signal to noise ratio was set so that the probability of detection would be approximately 0.9. The interference power was then incrementally adjusted between probability of detection measurements. The data is presented with confidence intervals. The simulated confidence intervals are notably smaller than the measured confidence intervals because of the ease of performing more experimental trials. The measured and simulated confidence intervals overlap and therefore show agreement in five of the eight measurements. The reason three of the eight disagree is a matter of debate that remains to be investigated.

IPC and Low Noise Amplifier (LNA) Overload

When examining IPC, it is important to consider the entire RF receive path, as often a front-end LNA is used to increase the system's sensitivity. Poorly designed RF paths and co-channel interference can introduce a new interference mechanism, driving a front-end LNA into a non-linear operation because of a strongly received radio signal. In FY 2016, the ITS RSMS platform was used to explore LNA overload behavior of a small sampling of commercially-available LNAs in support of a larger spectrum sharing effort.

IPC and 5 GHz Dynamic Frequency Selection (DFS)

Good spectrum sharing is predicated on known IPC thresholds for the systems operating on or near the same frequencies. From this, a sharing mechanism can be devised and implemented. The 5 GHz Unlicensed National Information Infrastructure (U-NII) bands are a candidate example of this. Across much of the 5 GHz spectrum, federal radar systems now coexist alongside consumer U-NII systems. These U-NII devices are required to use a dynamic frequency selection (DFS) mechanism to detect and avoid radar systems by monitoring for bursts of RF energy indicative of a nearby radar system. The system then evacuates the channel to prevent interference into the radar. ITS has been involved with 5 GHz DFS spectrum sharing since its infancy and has provided technical and subject matter expert support to both industry and the FCC. In FY 2016, the ITS RSMS platform was used to explore potential DFS issues in new bands at 5 GHz that are being considered for expanded sharing.



Measured and simulated air surveillance radar IPC results.

Fiscal Year 2016 Research: Quality of Experience

The subject of quality in telecommunications is important in many ways. For speech communications intelligibility is vital to the fundamental purpose of communications: can the listener understand the speaker? Applications for public safety, firefighters, and emergency medical personnel are highly relevant. Likewise for image, video, and multimedia, the primary goal of this kind of telecommunications is to transmit information in a way that is understandable to the receiver. Beyond the functionality of telecommunications, we move into the realm of the pleasure of the experience.

A cell phone conversation or a television program might be functional but if the signal is highly compressed, errored, or distorted the experience might be irritating—even extremely irritating. A higher quality of experience is more enjoyable to the customer and thus more valuable to the provider. As with other consumer technologies, standardization opens the market to increased competition, which in turn drives technology improvement. While a police officer will continue to listen to a distorted speech signal because lives may be at stake, a cell phone or cable television customer will likely complain or even cancel their service if other, more enjoyable options are available.

Quality in telecommunications can be thought of as a continuum from non-functional to functional to delightful. As the level of quality increases, the bandwidth need of a transmitted signal also increases. The trick is to determine the minimum bandwidth needed for a given application in order to provide the optimally appropriate level of quality. This will result in efficient use of spectrum and/or wireline bandwidth. To use more bandwidth (or spectrum) than is needed would be wasteful of the spectrum resources entrusted to the care of the FCC and NTIA, to use less would make the service unattractive to the customer.

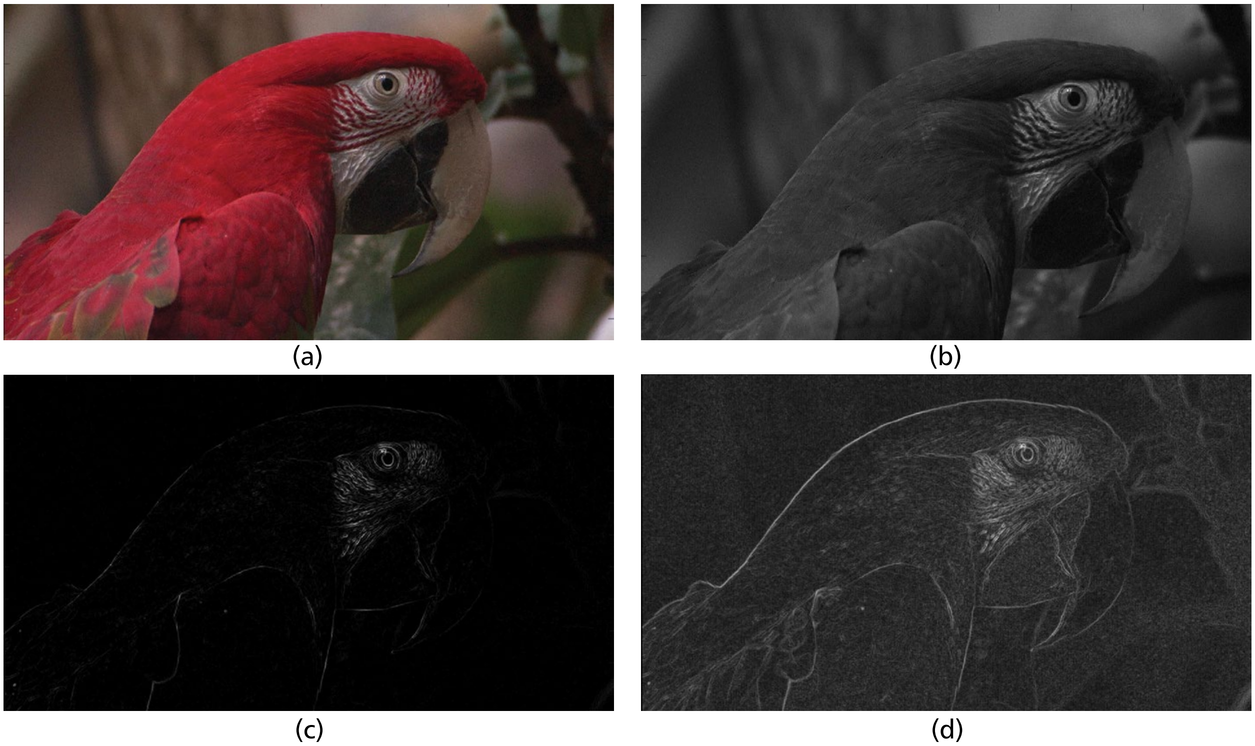
Hence, ITS plays an important role in defining objective measures of Quality of Experience (QoE) and providing technical parameters that can describe QoE for the benefit of the consumer, both public and private, as well as for public safety practitioners. Quality of service and quality of experience for networks, speech, and video have been topics of ITS research since the 1980s. Our laboratory and quality experts have become trusted expert sources of independent measurements and new quality measurement methods. As technology has evolved from analog to digital, from coax to wireless, from VHS tapes to streaming 4K video, ITS has developed new quality and intelligibility methods to address new needs.

In FY 2016, ITS QoE research addressed metrics for both video quality characterization and speech intelligibility. Research sponsored by the Federal Railroad administration specifically assessed speech intelligibility of very narrowband digitally modulated land mobile radios used by North American railroads.

Video Quality Characterization

In FY 2016, ITS began development of a metric that estimates the perceived quality of a video if it were either displayed as-is or encoded at a lower bit rate. Our goal is to enable intelligent networks that can understand the trade-offs between user experience and the network's decision to limit or apportion the available bandwidth. Existing metrics are either too inaccurate to be trusted or require intricate information about the encoder and the network—information that is likely to be proprietary and unavailable for testing. Industry has no incentive to open source metrics that enable efficient QoE, since having better ones than the competition provides a market advantage. Thus it is left to federal labs and standards organizations to develop objective and trusted metrics that can be used to promote a level playing field.

The type of metric we seek is called a "blind" or "no reference" metric, because it examines one video sequence with no additional information. This remains an intractable problem. Our strategy was to leverage prior ITS research as training data. This resulted in a model that exhibited erratic behavior: accurate and inaccurate by turns. We traced the primary problem to the training data. Our training data is mostly more than five years old, contains 8 to 15 second video clips, does a good job of describing video compression,



No reference video quality metrics must understand the relationship between how computers represent video and how humans perceive video. Computers use mathematical schema to approximately represent the colors of light. Consider the color image labeled (a). Most video metrics rely on the Luma plane (b). Luma plane edge filters, such as the Sobel filter (c) do not match human perception. Our research on the human perception of color edges in video produces a very different edge filter (d). More research is needed to understand the importance of this issue and how it can be applied to image quality estimation. Still image courtesy Consumer Digital Video Library (CDVL.org).

and does a bad job of describing all video content. This is a problem because video delivery has fundamentally changed in the past five years, encoders split each video into ¼ to 3 second segments, video coders are homogenous, and video content is heterogeneous. Basically, blind metrics are unlikely to encounter the unexpected compression artifacts that are the focus of our training data. We believe that all prior work on blind metrics was hindered by these same flaws in the training data: insufficient scene variability.

Work has begun on a subjective experiment spanning 800 different video scenes, emphasizing the unexpected video content that blind metrics are likely to encounter. This experiment will provide new training data for a blind metric with a limited scope. The main goal of this subjective test will be to characterize human perception of quality problems that stem from the original filming and editing. This includes the camera, lighting, videography, editing, reformatting, color space changes, and perhaps several recompressions—everything that occurs prior to the last leg where the video is encoded for final distribution to the end user. Until this occurs, professionally produced videos are typically compressed and stored at high bit-rates. Impairments from this portion of the video processing chain are explicitly excluded from the typical video quality subjective experiment. By looking at these impairments, we hope to obtain a new understanding of the features a blind metric must characterize to be a reliable indicator of perceived quality.

Speech Intelligibility

ITS audio quality researchers recently applied their unique expertise and built on previous successes to produce several advances, including two very significant contributions, to the field of speech intelligibility measurements.

These related yet separate advances both connect to the speech intelligibility testing protocol called the Modified Rhyme Test (MRT). In the MRT protocol listeners hear recordings of similar sounding words processed by systems under test. After each recording the listener attempts to select the correct word from six options. For example when "keel" is played, the listener must select between "peel," "reel," "feel," "eel," "keel," and "heel." If the correct word is selected, the trial is a success. Otherwise the trial is a failure. Trials are repeated using different listeners, talkers, and up to 300 different words. When all trials have been completed a success rate is calculated for each system under test and this average success rate then produces a measure of speech intelligibility.

Crowdsourced MRT

The MRT protocol is normally used in a controlled laboratory environment. For years now, ITS has performed MRT testing in sound-isolated laboratories with professional playback equipment and controlled noise injection. This is a slow and costly procedure. Typically it is practical to include only 20 to 40 listeners in these lab tests. Motivated by these limitations, ITS researchers recently elected to design, implement, and evaluate a strikingly different approach—a crowdsourced version of the MRT (CMRT).

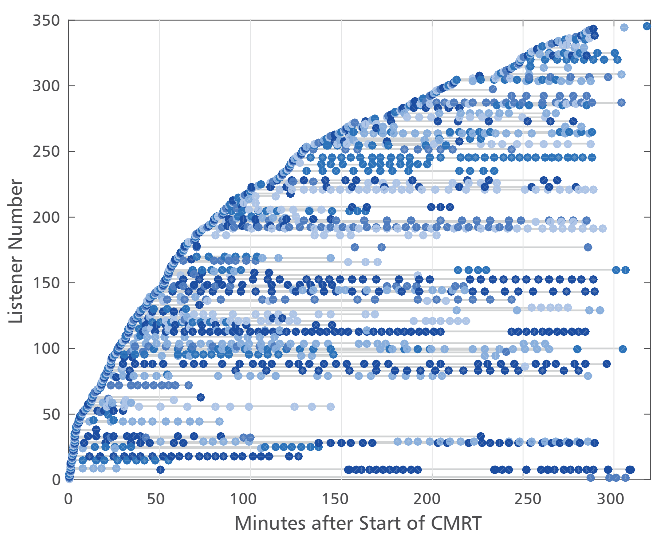
In the ITS CMRT, a self-selecting anonymous crowd of listeners participated via Internet. The test was divided into small portions requiring minutes rather than hours and hundreds of listeners participated. ITS had no control over listening equipment or environment. This test was designed to parallel a previously conducted lab MRT (LMRT), thus providing a reference point for comparing results.

The figure below summarizes several important aspects of this CMRT. It chronicles how 345 different listeners performed 1536 different tasks over a period of 318 minutes (5.3 hours). Each task is represented by a dot. Listeners are at liberty to perform as few or many tasks as they wish. When a listener completes more than one task the corresponding dots are connected by a horizontal line. To help differentiate between adjacent listeners the figure cycles through five shades of blue along the listener axis. Fifty-eight percent of the listeners performed a single task and the remaining listeners performed between 2 and 50 tasks each. The figure makes evident the temporal task patterns within and among the listeners.

Each task includes 56 MRT trials, so this CMRT collected 86,016 trials from 345 different listeners in 5.3 hours. Compared to a typical LMRT, the CMRT saved thousands of dollars, weeks of time, and incorporated ten times as many listeners.

ITS found that through careful test design and a simple yet effective data processing rule, CMRT can produce speech intelligibility results that are very similar to those produce by LMRT. When 56 systems were tested by CMRT and LMRT, speech intelligibly results were statistically equivalent for 55 of those 56 systems. Repeatability is a very important goal for any type of measurement and ITS found that the CMRT results can be more repeatable than LMRT results.

The improved repeatability is a direct consequence of the much larger numbers of listeners involved in CMRT. This causes listener variation to average out more quickly in CMRT and this in turn compensates for the loss of controlled conditions. The bottom line is that CMRT uses a set of anonymous, remote, listeners operating in uncontrolled environments who are every bit as effective as the listeners that are individually recruited and supervised in ITS laboratory tests.



Timeline showing 345 listeners completing 1536 CMRT tasks over 318 minutes. Each task is represented by a dot.

ABC-MRT16: Objective Estimation

ITS audio quality researchers also combined their signal processing expertise with their deep understanding of the MRT to produce the latest version of the Articulation Band Correlation Modified Rhyme Test (ABC-MRT16). This is a signal processing algorithm that uses recorded MRT trials to produce estimates of speech intelligibility without the use of human listeners. These are only estimates, not true MRT results, but they are produced almost instantly and they have perfect repeatability. The algorithm is unique among those that seek to estimate speech intelligibility or speech quality because it embodies a very close analogy to a specific human listening test protocol. The result is remarkably high correlations with actual MRT test results.

The ABC-MRT16 algorithm seeks to mimic the process of human MRT trials. The algorithm first generates correlation values for each of the articulation index bands. These correlation values are then processed with a simple attention model and the result is a word selection for each trial. This word selection is either correct or incorrect and the resulting success rate forms the speech intelligibility estimate, just as it does when human listeners are used. ABC-MRT16 can efficiently evaluate the speech intelligibly of large numbers of candidate systems. Systems with the most promising results can then be tested more thoroughly and precisely (and at greater expense) using CMRT or LMRT. These three tools are summarized in the table.

	LMRT	CMRT	ABC-MRT16
Features	Speech intelligibility values from vetted listeners in a single controlled environment	Speech intelligibility values from self-selecting listeners in real-world environments	Speech intelligibility estimates produced by signal processing software
Advantages	Uses listeners, minimal variation due to environment	Uses larger numbers of listeners, environments are varied but may be more realistic than lab	Fastest path to results, results are exactly repeatable
Benefits	Protocol is well established, results easily interpreted	Results have smaller uncertainty, costs are reduced	Results available immediately, costs are essentially zero

ITS audio quality researchers recently applied various combinations of ABC-MRT16, CMRT, and LMRT to answer important speech intelligibility questions for emerging technologies, transferring the results of this federally funded research to the larger stakeholder community to advance standardization and competition. The speech, audio, and measurement expertise of ITS is widely shared to support other researchers inside and outside of ITS, leveraging the government's investment in building this unique center of excellence.

Railroad Telecommunications Intelligibility

In FY 2016, work began on an experiment to assess the speech intelligibility of very narrowband (VNB) digitally modulated land mobile radios (LMR) in various railroad acoustical operating environments. The major North American railroads chose the NXDN™ modulation scheme for the radio platform to implement the spectrum efficiency goals set out by the FCC in its Fourth Memorandum Opinion and Order for *Promotion of Spectrum Efficient Technologies on Certain Part 90 Frequencies*.[1] As these radios are being deployed nationwide, the railroad industry seeks some level of assurance that speech intelligibility of radios that use this newer protocol is equal to that of the analog FM radio technology currently in use. The Institute's extensive experience in evaluating speech intelligibility of communications systems for public safety was applied to investigating the speech intelligibility of the railroad industry's chosen land mobile radio platform.

1 Federal Communications Commission, 47 C.F.R. Part 90 [WT Docket No. 99-87; RM-9332; FCC 08-127], Implementation of Sections 309(j) and 337 of the Communications Act of 1934 as Amended; Promotion of Spectrum Efficient Technologies on Certain Part 90 Frequencies. Accessed https://apps.fcc.gov/edocs_public/attachmatch/FCC-08-127A1.pdf May 22, 2017.

Test Bed

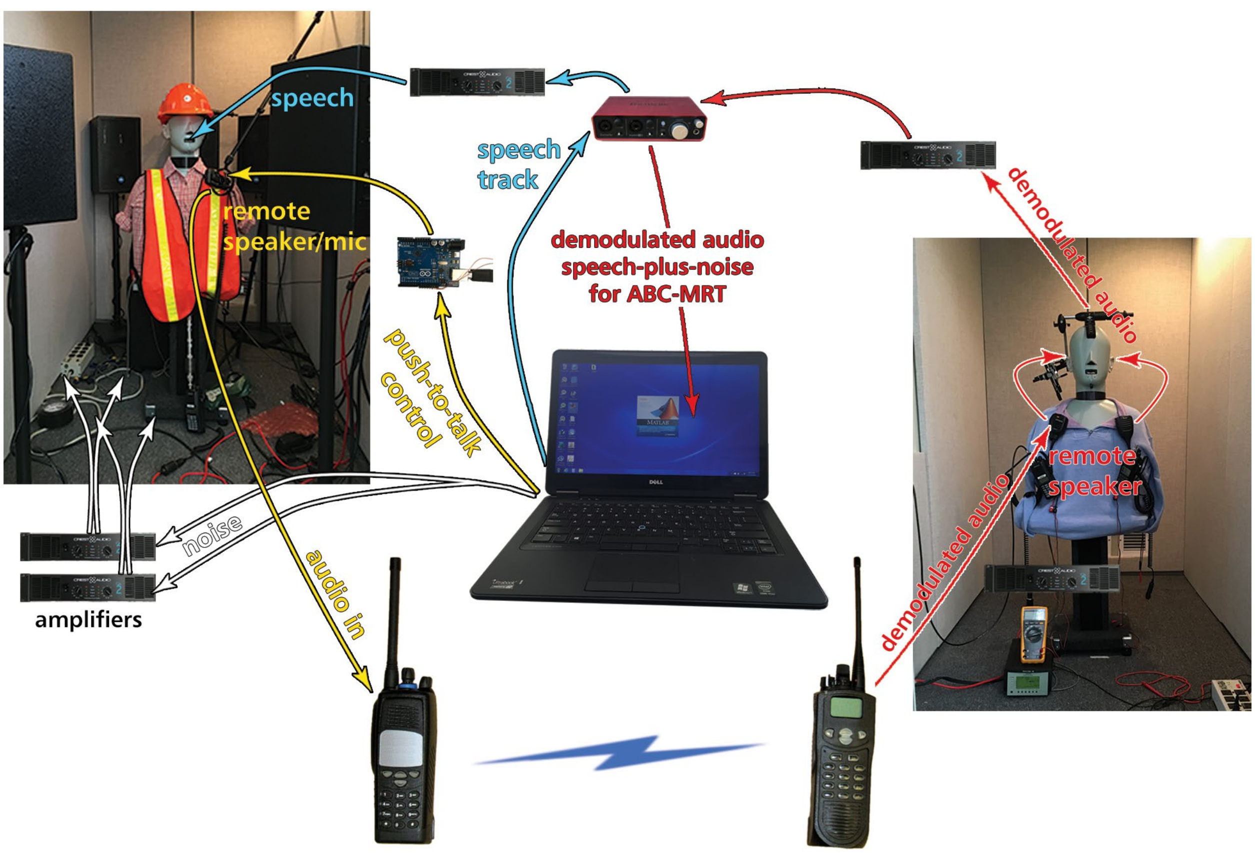
We designed a test bed to implement speech intelligibility assessment of impaired speech recordings using the ABC-MRT algorithm described in the previous article. The noise-impaired speech recordings of interest were demodulated audio from VNB digital LMRs representative of those now being fielded within the North American railroad industry. The noise environments of interest are:

- trackside next to idling stationary locomotive
- humpyard retarder squeal
- trackside, passing railcars
- interior locomotive cab

We went to two rail yards and made recordings of these noise environments. We then mixed the MRT speech recordings (.wav files) with the noise recordings to create a new set of .wav files with specific signal-to-noise ratios for each noise environment.

The figure shows a schematic of the test bed configuration. The test bed enables playing these new .wav files in a sound booth under computer control. The test bed computer also controls the push-to-talk (transmit) function of the transmitting radio under test. That radio's RF signal is delivered to a receiving radio under test, located in a second sound booth. The test bed automates recording the second radio's demodulated audio under control of the same test computer. The .wav files of demodulated audio are the material that undergoes ABC-MRT analysis.

Thus far, we have verified that the test bed works as intended, but additional work is needed before specific test results can be produced. This includes work with the radio manufacturers to resolve some configuration and other issues, as well as work with certain railroad technical staff to implement specific test set ups (in particular, internet back-hauled voice traffic between yardmaster office console and remote rail yard base station radio).



Schematic of the railroad radio speech intelligibility test bed.

Mission Critical Communications for Public Safety

The Government's interest in ensuring the availability of wireless communications for the public safety has been acknowledged since the earliest days of the 20th century. Only three years after the first two-way wireless telegraphy transmission across the Atlantic, the first wireless distress call led to the rescue of over a thousand people from a liner involved in a collision. The Wireless Ship Act of 1912, responding in part to the tragedy of the Titanic's distress signals going unheard by the closest ships, required all large ships to 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.

One hundred years later, another act of Congress mandated a nationwide, interoperable public safety broadband network, allocated the spectrum for it, and established the First Responder Network Authority (FirstNet) to administer it.[1] During the century between the two, the DoC radio laboratories continued to work 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 to present-day nascent public safety broadband technologies.

ITS works with the NIST Communications Technology Laboratory (NIST/CTL) through collaborative research projects in the Public Safety Communications Research (PSCR) program, a joint effort that leverages the complementary capabilities of the two laboratories. In close and constant coordination with public safety practitioners and other federal agencies such as the Department of Homeland Security (DHS) and FirstNet, In particular, ITS has been working closely with other federal stakeholders like FirstNet and DHS to advance the interests of public safety broadband through leadership and critical technical contributions to the 3GPP on their behalf.

The unique needs of public safety wireless broadband users compared to commercial wireless customers drive specialized public safety communications research efforts. While commercial wireless broadband network development is primarily driven by the need to continually add capacity, for public safety networks expanding coverage is often more critical than expanding capacity—incidents are obviously not constrained to occur only within areas of high population density. Public safety users also have unique needs with respect to image, audio, and video 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 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 support and inform 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.

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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.

Image Quality Study

With the proliferation of the Internet and mobile devices, cameras are everywhere. Countless public safety practitioners take photos daily and receive photos from the public. Interviews tell us that over half of these photos have quality problems that prevent their use in law enforcement, leaving victims and store owners heartbroken. This indicates vast opportunities for technology innovation.

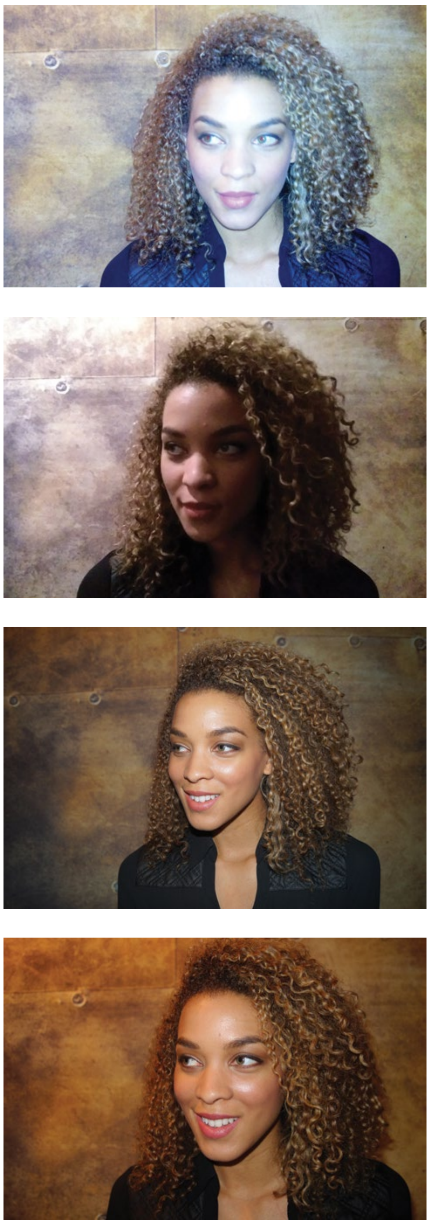


Figure 1. These images demonstrate the color differences that occur when the same scene is photographed by different cameras. Images are from Michele A. Saad et al., "Impact of Camera Pixel Count and Monitor Resolution Perceptual Image Quality," Colour and Visual Computing Symposium (CVCS), 2015, Gjovik, Norway, 25-26 August 2015 and available at http://www.cdvl.org/

ITS surveyed over 100 first responders and asked how their departments use cameras and what quality problems they encounter. We consulted a variety of first responders, because each department has different local problems, funding, geography, climate, and population density. Every first responder provides us with a new perspective, which helps build a more robust understanding of bigger problems. By categorizing and describing the problems in measurable ways, we hope to encourage development of new camera technologies that will let anyone produce photos that meet first responder needs.

From this feedback, we put together the following context. First responders multitask in a time-critical and potentially dangerous environment. The camera must do its job efficiently, so the first responder can quickly move to the next task. The typical first responder needs a fully automatic camera that is easy to use, requires minimal training, and interoperates with all other software. First responders have competing priorities and a limited budget, so cameras must be inexpensive—cameras are never in the top 10 priorities. As an added challenge, the quality of the images and videos is determined primarily at the point of purchase—and the person who uses the images may have no ability to influence the camera specification or operation.

Inefficiency is the most commonly quoted reason for first responders to reject a camera. For example, some firefighters don't use their infrared camera because no one picked it up, a seemingly trivial task that is lost in the shuffle. Basically, compact cameras and phones meet first responder needs; high end digital single-lens reflex cameras (DSLRs) do not.

Our original vision was a camera that tells you how the image will look on a 24-inch monitor, offers suggestions on how to take a better photo, and gives laypeople insight into first responder needs. Basically, the camera would examine the image and provide feedback. Over the course of our investigations during FY 2016, we discovered that such utilities will only be helpful after more fundamental problems have been addressed.

Color inaccuracy provides an example. Digital images and digital video have such erratic color response that first responders assume they cannot trust colors—skin color, hair color, shirt color, car color, etc. Color inaccuracy comprises four types of color errors. First, color differences occur when you take a picture of the same scene with different cameras, in rapid succession (see Figure 1). Second, color differences occur when you take pictures of the same object with the same

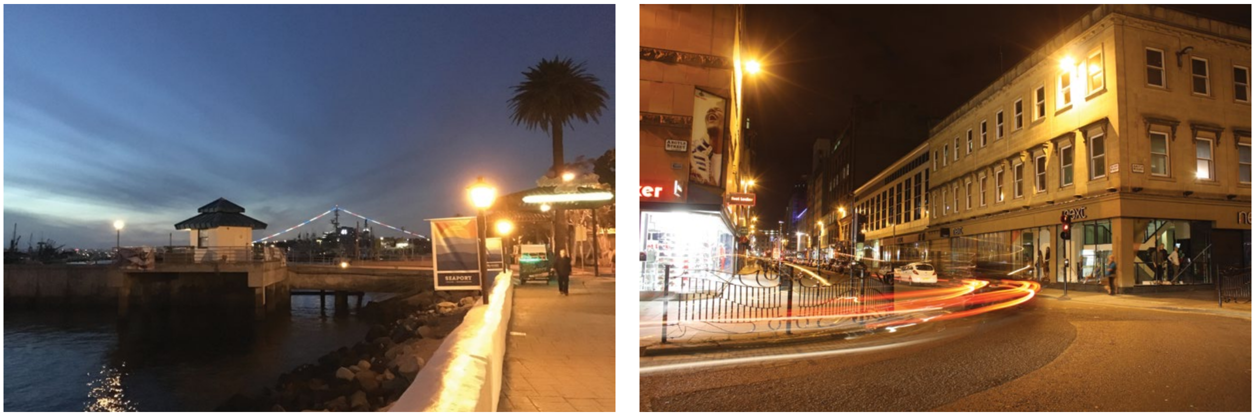


Figure 2. These images demonstrate the color differences that occur when the one scene is lit by two different types of lighting. In the left picture, the area lit by the setting sun has cool blue tones, while the area lit by artificial lights has warm yellow tones. In the right picture, the outdoor areas have a yellow tone, while the store interior is bright white. IMG_0571 (left) and IMG_3708 (right) from the VIME Flickr group, https://www.flickr.com/groups/vime/

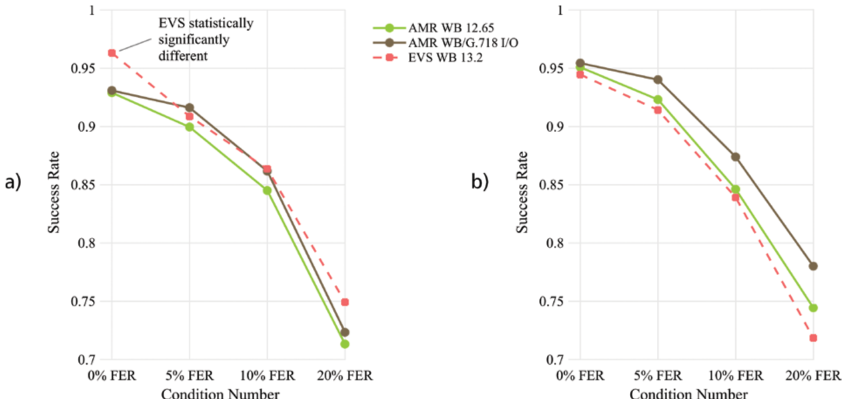
camera under different lighting conditions. Third, color differences occur when two or more very different lighting conditions appear within a single scene (see Figure 2). Fourth, the camera might not be able to detect some portions of the visible light spectrum. These camera problems are confounded by color issues in the encoder, decoder, monitor, and printer. Today, color errors are eliminated through manual processes. These manual color correction tools do not meet first responder needs for fully automated solutions.

ITS continues to work closely with first responders and federal public safety agencies to define and prioritize future research projects that might contribute to mitigating or resolving these problems.

Speech Intelligibility Testing for Mission Critical Voice

The audio quality research program also applies ITS expertise to support public safety communications. An important contribution is work to quantify speech intelligibility associated with a range of LTE-compatible digital audio coding algorithms in various acoustic noise and impaired radio channel environments. The results of this research are widely shared and contribute to shaping industry standards for the development of new equipment suitable for use by public safety on LTE networks such as the nationwide, interoperable public safety broadband network being deployed by FirstNet. The work was funded by the Department of Homeland Security Office for Interoperability and Compatibility (DHS/OIC) and motivated by high-level requirements for mission-critical voice (MCV) networks for public safety that were set out by the National Public Safety Telecommunications Council.

Program staff designed, implemented, and analyzed a new study of speech intelligibility for some digital speech codecs that can be used to provide MCV over LTE based radio networks. This study focused on the relationship between radio channel degradations and speech intelligibility. This relationship is particularly important for MCV because the events that stress the radio access network (RAN) may very well be events that also have critical intelligibility requirements. One example would be first responders moving deeper into a building to perform critical functions. Unless mitigation measures are in place, the radio link will suffer additional attenuation and there may then be negative consequences for the speech intelligibility even as it is becoming more and more critical. A second example would be an event that is escalating and requiring additional personnel to report to the scene. As more and more personnel share radio resources on the scene, those radio resources will (barring any mitigating measures) inevitably be spread thinner and thinner. Here again there may be negative consequences for speech intelligibility even as it becomes particularly important to coordinate the new personnel.



Word success rates for three codec modes in (a) coffee shop noise and (b) siren noise. Figure 1 from TR-16-522.

The study produced quantitative results for three important speech coding algorithms, allowing stakeholders to anticipate how speech intelligibility will be reduced as the RAN is stretched to its limits. For two other speech coding algorithms the results were more qualitative: promising new robustness enhancements did not activate as they were designed to under degraded RAN conditions and no additional robustness was produced. This outcome is every bit as important as the others and naturally motivated stakeholders to work towards a resolution of the problem. This most recent study is fully described in NTIA Technical Report 15-522, Andrew A. Catellier and Stephen D. Voran, "Intelligibility of Selected Speech Codecs in Frame-Erasure Conditions," November 2016, available at https://www.its.bldrdoc.gov/publications/3165.aspx.

Public Safety Broadband In-Building Testing

The Public Safety Band 14 network that FirstNet will soon deploy across the United States will be used to provide both outdoor and indoor communications. Whether on this network or others, first responders need to be able to communicate within, into, and out of buildings within their jurisdictions. But indoor radio propagation is extraordinarily difficult to predict and accomplish. It is influenced by building design and materials, and may be unique for every building. Engineers from PSCR are exploring practical, low-cost ways to empower public safety practitioners to perform their own LTE coverage measurements inside buildings. This capability will promote a robust conversation between public safety, building owners, and network operators on in-building coverage issues and expedite solutions that lead to reliable and robust coverage wherever it is needed. In order to make this a reality, we need:

- An affordable, low-cost LTE radio receiver with access to selected LTE parameters
- Measurements that are both accurate and trustworthy
- Straight-forward measurement procedures
- A simple and meaningful scoring system to quantify in-building LTE coverage
- A controlled in-building environment and LTE network for testing and system verification

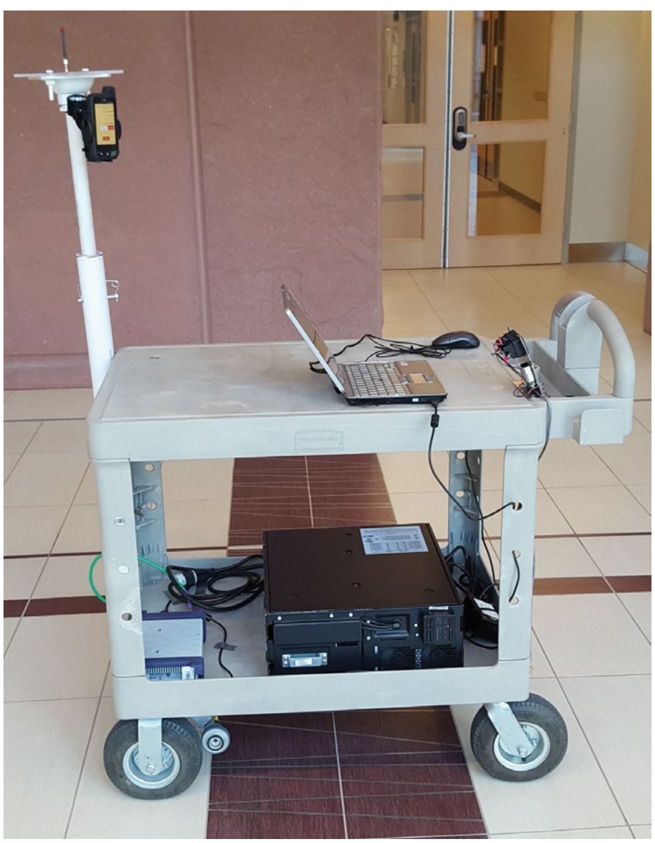


Figure 1. The measurement cart in the Precision Measurement Laboratory.

One approach being investigated is to use existing Public Safety Band 14 Android phones with a PSCR-developed experimental app to take in-building measurements of the LTE reference signal received power (RSRP). Using a phone to do RSRP measurements presents several challenges. First, Android phones have different antenna designs as a function of case size and layout. Second, RF receiver circuit configurations and performance vary by design. Finally, the signal processing algorithms used by each phone influence the reported signal levels. These factors are unique to different manufacturers and even particular phone models. As a result, we see large variations in measured RSRP levels from phone to phone for a common level and configuration of LTE signal. In fact, the 3GPP standard TR36.133 sections 9.1.2 and 9.1.3 specify uncertainties of either ±6 dB (inter-frequency) or ±8 dB (intra-frequency) in absolute UE RSRP measurements. The ±8 dB uncertainty translates into a 16 dB spread in the data which corresponds to a range of 40 to 1 in linear power—a huge variation!

Tests and Measurements

An extensive series of measurements were undertaken at the Precision Measurement Laboratory (PML) located at the U.S. Department of Commerce Boulder Laboratories. The PML is a state-of-the art facility and it houses measurement laboratories, semiconductor fabrication facilities, offices, conference rooms, and a variety of utility rooms. It has three levels and 283,000 square feet of floor space.

ITS and PSCR engineers have designed a special cart for in-building measurements, shown in Figure 1. The cart has a power supply, a wheel-mounted generator, and a digital voltmeter that is calibrated to measure speed. The cart has a monopole antenna mounted on a plastic mast that is connected to a precision LTE scanner. The Band 14 LTE Android phones are mounted on a special holder just below the monopole antenna. This arrangement provides a side-by-side comparison of phone and scanner measurements. The scanner/monopole antenna provides a precision reference against which phone measurements can be compared.

Measurement efforts were undertaken in order to:

- Investigate the differences between the data obtained by the scanner and the phone/experimental app
- Look at the repeatability and the statistics of data collected by the scanner and the phone
- Study ways to map the measured RSRP data into a simple coverage score that relates to actual LTE system performance
- Examine phone-to-phone received RSRP characteristics and look at ways to correct for variations between different devices
- Investigate the impact of both phone positioning and cart speed

Results

Figure 2 shows a significant 6 dB offset between the scanner and an Android phone. PSCR engineers used side-by-side comparisons to develop the mean correction algorithm. This algorithm corrects the phone measurements to levels similar to those of the reference scanner. Figure 3 demonstrates the effectiveness of the mean correction algorithm, where good agreement is seen between the scanner and corrected phone data.

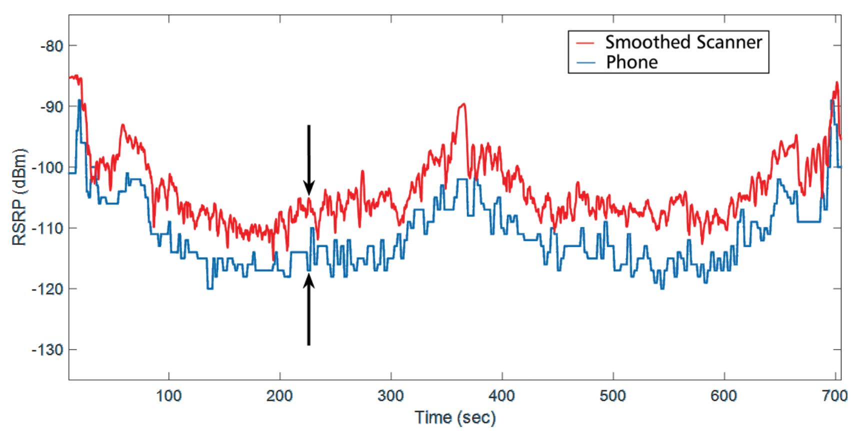


Figure 2. Phone A and window-averaged scanner data in the main hallway of the PML. The black arrows highlight the offset between the received RSRP levels of the phone and the scanner.

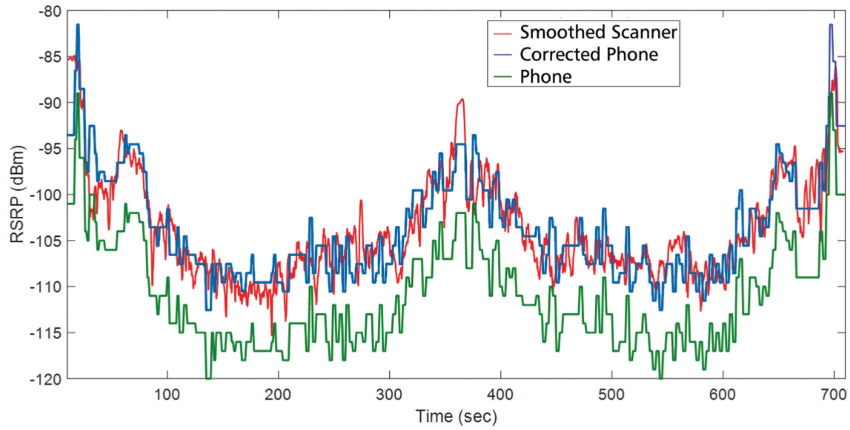


Figure 3. Comparison of raw and mean-corrected phone A data with smoothed scanner data.

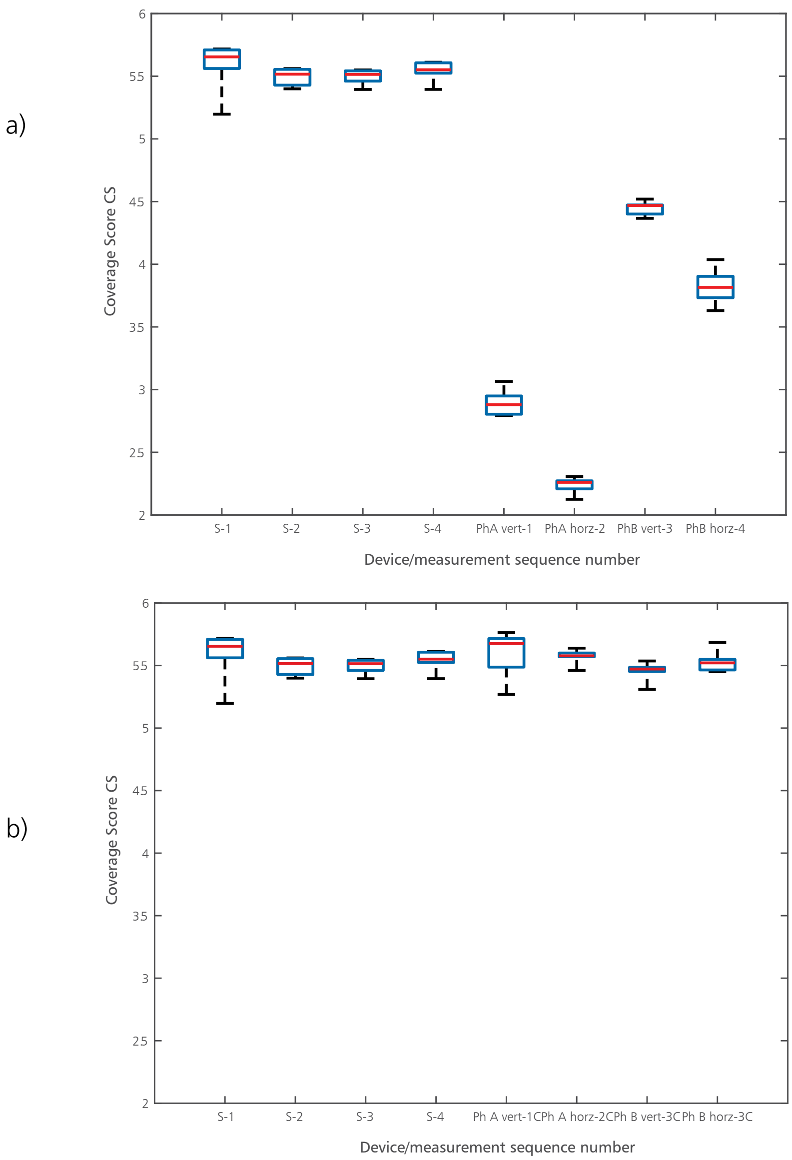


Figure 4. a) Scanner and uncorrected phone coverage scores. b) Scanner and corrected phone scores. S denotes the scanner, PhA denotes Phone A, and PhB denotes Phone B. The numbers 1-4 indicate a selected six-run sequence.

PSCR engineers also developed an in-building scoring system that takes all of the measured RSRP data within a zone inside a building and maps it to a coverage score between 1 and 10. Scores in the range of 1 to 4 are classified as "poor" coverage, scores in the range of 4 to 7 are classified as "ok" coverage, and scores in the range of 7 to 10 are considered "good" coverage. This signal classification provides a simple assessment of in building coverage and it directly relates to the ability of a first responder to communicate in an in-building environment. For instance, if the coverage score is "poor" it will not be possible to stream video. If the coverage is "ok", it will be possible to stream video at reduced rates. The highest data rates and video quality will be obtained when the coverage is "good".

Figure 4a shows the results of a series of measurements in the form of a box-and-whisker plot. These plots show the range of RSRP data for the scanner and two different phones. Measurements were taken with the phones in two different orientations. The phone results clearly depend both on the model and the orientation. If the mean-correction algorithm is used, the phone scores can be harmonized to those of the scanner. Figure 4b shows the results of this and the coverage scores line up quite well.

The mean correction algorithm works well inside of the PML for the phones tested. PSCR engineers plan to measure more buildings to see how well this harmonization of coverage scores works.

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.

National Security/Emergency Preparedness

ITS expertise also supports the evolution of fundamental public safety emergency communications infrastructure programs such as the Government Emergency Telecommunications Service (GETS) and the Wireless Priority Service (WPS) programs. These 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 on land lines dial a specific access telephone number followed by their 12 digit personal identification number (PIN) and intended destination number.

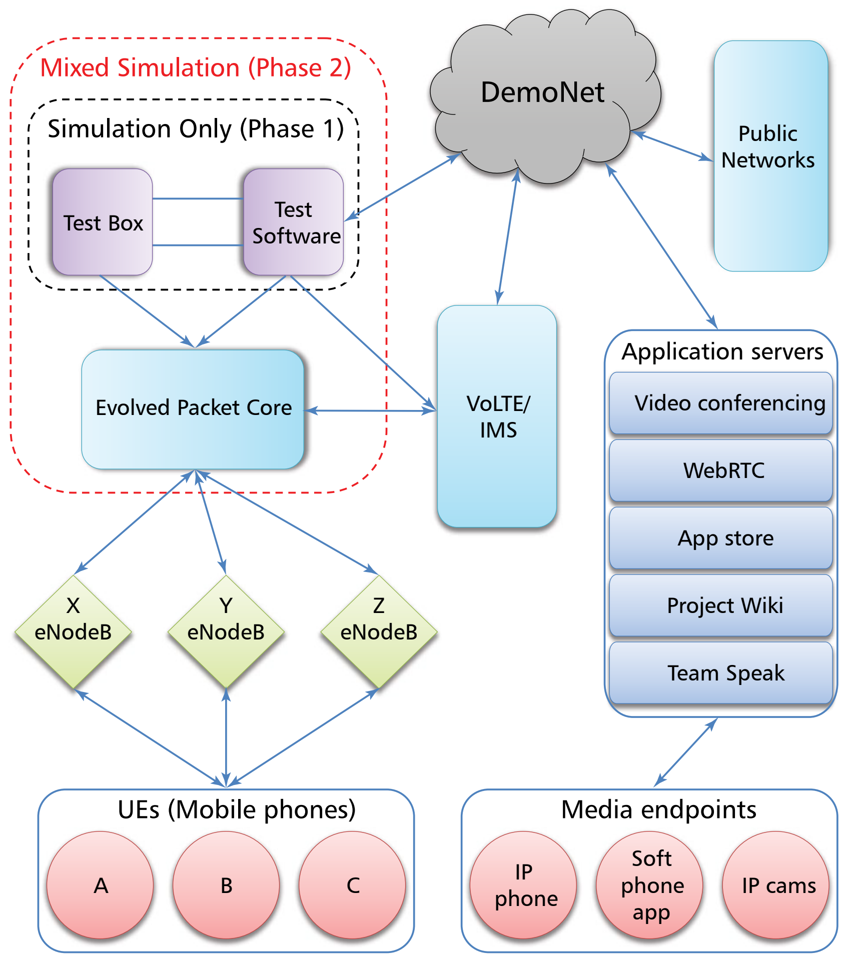
Both WPS and GETS are administered by the Department of Homeland Security's Office of Emergency Communication (DHS/OEC) and implemented via contracts with the major wireline and wireless carriers. WPS is not yet implemented in LTE, and ITS performs research and testing to evaluate current commercial LTE implementations to ensure emerging technologies preserve robust and reliable public safety communications functions.

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 DHS/OEC can use 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). 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 2016 Research

In FY 2016, 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. Both simulated and real User Equipment terminals (UEs—e.g., mobile phones) were tested along with two Evolved NodeB (eNodeBs—i.e., base stations). Of particular importance were tests performed on the Automatic Access Class Barring (AACB) mechanisms of two eNodeBs in highly congested scenarios. The AACB is an algorithm that controls which UEs are allowed to connect to the network based on their assigned access class. The goal is to make sure that National Security/Emergency Preparedness (NS/EP) users are able to communicate during emergency situations by granting UEs identified as NS/EP access to network resources while temporarily barring other UEs from connecting.

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 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



Schematic of the PSCR NGN-PS test bed.

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. A 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 2017, performance tests will be 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 2017 testing will use an IP Multimedia Subsystem (IMS) network VoLTE solution that has been acquired for the lab. Testing on IMS VoLTE-dependent mechanisms will be done on two IMS core solutions.

DHS/OEC has identified control plane eNodeB testing as their top priority for the next fiscal year, with performance oriented examinations of High Priority Access, AACB, 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 complete testing in these areas first 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.

Systems, Software, and Analyses for Spectrum Sharing

Wireless communications is one of the most rapidly growing and rapidly changing sectors of the economy. Barely more than 20 years ago, wireless communications spectrum sharing issues primarily revolved around siting television and radio antennas to avoid interference—deconflicting a handful of very similar transmitters. The expansion of the cellular industry added new challenges: the density of adjacent transmitters increased to hundreds, the nodes became mobile, and cumulative effects had to be taken into account. In the emerging Internet of Things (IoT), the density of transmitters will increase dramatically – 20 to 30 billion devices are predicted to be connected to the internet, many wirelessly, by 2020.[1]

The Oxford English Dictionary defines the IoT as "the interconnection via the Internet of computing devices embedded in everyday objects, enabling them to send and receive data." Those "everyday objects" include everything from buildings and bridges to watches and waffle-makers, from washing machines that connect to the power grid to turn themselves on when the rates are lowest to fitness trackers that report athletes' pulse rates to their trainers. The potential ramifications of the IoT on spectrum are currently unknown. Installations are typically small scale and developed in isolation one from the other. Device manufacturers have not investigated issues such as self-interference and spectral occupancy. The IoT community has largely assumed that spectrum will be available, and have not systematically investigated the effects of unprecedentedly high numbers and densities of wireless devices. In FY 2016, ITS initiated a small-scale IoT project to develop a laboratory capability to study the impacts of IoT on spectrum.

IoT deployments are examples of collections of devices operating together as a system. As devices become cheaper, more and more systems are being developed and deployed. Once a system grows bigger than a handful of devices, the complexities of possible interactions—both within the system and between multiple systems—become impossible to analyze by hand or with the use of simple tools. Instead, simulation informed by good systems engineering analysis must be used. In FY 2016, ITS took the first steps towards developing a 21st century systems engineering and systems simulation laboratory to develop the tools and techniques to analyze large-scale systems.

Nearly all the tools that ITS develops to analyze and solve the telecommunications problems of the future will be software tools. The complexity of the environment, the scale of the problem, and the variability among potential scenarios can only be addressed with sophisticated software, and ITS has a mandate to make such software freely and widely available to other government agencies and the private sector. Since the first FORTRAN implementations of propagation models in the 1960s, software published by ITS has had a strong reputation for quality and accuracy of output. As software tools become more complex and voluminous, high quality must be baked into the development process as well. Therefore, ITS has made a commitment to making software engineering a core capability. In FY 2015, ITS created a software engineering center of excellence and in FY 2016 ITS made significant progress defining and promulgating Institute-wide software best practices under the Capability Maturity Model Integration (CMMI)® model.

These nascent capabilities have already been used to augment and enhance research results.

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1 Amy Nordrum, "Popular Internet of Things Forecast of 50 Billion Devices by 2020 Is Outdated," *IEEE Spectrum,* August 18, 2016. Accessed http://spectrum.ieee.org/tech-talk/telecom/internet/popular-internet-of-things-forecast-of-50-billion-devices-by-2020-is-outdated January 20, 2017.

Studying IoT in the Laboratory

Each one of the devices that populate the Internet of Things will, by definition, be communicating electronically with another IoT-related device or gateway. Some fraction of that communication will happen over-the-air, using wireless spectrum as the communication medium. This is notable for a few reasons. Some IoT devices that communicate wirelessly will be competing for space in the already-crowded unlicensed spectrum bands. Others will use spectrum allocated for cellular communications. Yet others will use solely wired media to communicate. Even when each device transmits only a small amount of data the aggregate bandwidth requirement can be very large. Understanding how to manage the spectrum demanded by billions of ultra-low-powered devices requires entirely new measurement and modeling techniques.

The spectrum-wide implications of malware attacks on IoT infrastructure that primarily communicates using wireless signals are also of significant concern. A small subset of malware-compromised IoT devices has already caused an immense and widely publicized Internet communication disruption through a massive distributed denial of service (DDoS) attack. That attack used wired devices, but wireless IoT devices could be similarly reprogrammed to transmit continuously, thus crowding wireless spectrum and potentially overwhelming other wireless services. After long periods of uninterrupted transmission, battery-powered devices could become inoperable due to power loss—a new kind of denial of service attack.

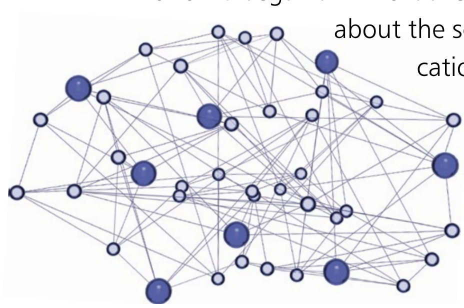
Successful wireless communication requires available spectrum. Spectrum availability is affected by all of the following five dimensions: transmission center frequency and bandwidth; geospatial location; time and length of transmission (more concisely, duty cycle); required transmit/receive power; and radio access technology. Understanding how these many IoT devices will affect or be affected by those five dimensions is a significant challenge—a challenge that ITS is uniquely suited to address.

ITS has begun building a commercial-grade IoT test bed that will give us the capability to conduct research by methodically varying the five dimensions of spectrum availability. Leveraging its decades of RF measurement expertise and its ability to quickly mobilize cross-disciplinary teams to address unique problems, ITS will conduct scientifically rigorous investigations exploring how in-use and future IoT devices affect and are affected by those five dimensions. In addition to facilitating investigation into undiscovered IoT spectrum impacts, this test bed will aid in the creation of an IoT modeling library. Coordinating with other ITS modeling efforts will enable us to simulate IoT systems too large to build in the lab.

System Simulation and Evaluation

Validated ITS-developed propagation models that predict the behavior of individual transmitters have been trusted for decades, but, as described on page 29, models to reliably predict the aggregate behavior of many transmitters operating at the same time in the same geography and frequency are just now being developed. Similarly, ITS has developed and provided to others computerized simulations of single radio links for 50 years, but simulations of complex broadband wireless networks consisting of large numbers and types of devices (e.g., receivers, transmitters, and interferers) are a different matter.

In FY 2016 ITS began an innovative technical effort to develop simulations that can help answer questions about the scalability and density of telecommunication systems (i.e., users, applications, devices, and networks) sharing spectrum. Such networks cannot be measured in a laboratory test bed, whether because (as for IoT) of the sheer numbers and diversity of devices involved, because (as for newly shared spectrum) the devices that will operate in the network are still under development, or because testing must involve interaction with devices (such as radars) operating in the same frequencies that cannot be taken out of service for testing. Systems simulation



must be used to identify, describe, and address the significant systems problems that may arise in such networks. A wide variety of stakeholders, including other offices of NTIA itself, need the data that could be provided by widely trusted systems modeling and simulation tools, and ITS is working to meet that need.

Recognizing that innovation is required in defining relevant research goals, developing and applying applicable tool(s), and validating and applying research results, initial research efforts included evaluation of modeling and simulation aspects for several problem domains. For example, the emerging problem domain of spectrum sharing by IoT devices, networks, and systems presents numerous technical challenges. An example is the problem of how to specify performance rules for IoT device use of unlicensed spectrum bands through disparate Radio Access Technologies (RATs). The different RATS include LTE-U, Wi-Fi, Bluetooth, and Fifth Generation Radio Access Networks (5G RANs).

The various ways physical layer radio resources can be shared by IoT devices makes it very difficult to understand or estimate occupancy and throughput rates. Another technical challenge concerns how to determine when spectrum shared by IoT devices is saturated, which can be illustrated by considering a Wi-Fi access point (e.g., 2.4 GHz) that can support several hundreds of megabits of throughput for one or more users. Eventually, the number of IoT devices will saturate that router's capacity; however, adding another access point will not necessarily resolve this issue and may even reduce overall throughput unless special care is taken to use different channels and to spatially separate the access points. To compound the problem, assume that 10% of the users also have several Bluetooth devices (also 2.4 GHz) connected to their personal area network. How does that additional spectral loading affect Wi-Fi throughput? Such scenarios become complicated quickly with many variables at play, including but not limited to spectrum location, physical location, and radio access technology.

The project's baseline research goal has been formulated to help address telecommunications systems questions raised by technologists, policy makers, regulators, and industry concerning how to better deploy and operate broadband wireless networks that meet user needs, including how to realize better use of spectrum and spectrum-sharing technologies. Among the questions that continue to be raised is the viability (e.g., due to interference) of radio systems when large numbers of diverse types of transmitters and receivers that share a particular spectrum band are deployed, especially when such systems cannot be operationally configured or directly measured.

The work conducted during this fiscal year established an initial framework upon which systems modeling and simulation approaches will be investigated, supporting a variety of the Institute's research efforts to realize this goal. In FY 2017, the focus will be on initiating simulation studies of telecommunication systems that share unlicensed spectrum bands, with the goal of providing data to realize efficient and effective deployment of IoT technologies and services. This supports NTIA in facilitating the DoC objective to foster the advancement of the Internet of Things in the near- and long-terms.

Software Engineering Excellence

ITS published the first computer method for propagation prediction in 1968[1] and connected its main laboratory and Table Mountain to ARPAnet (the predecessor of the Internet) in 1972. ITS software implementations of propagation models and technical data were being disseminated via Internet by the early 1990s on one of the first federal web sites: www.its.bldrdoc.gov, through which ITS continues to transfer research results to the public, including software listed on page 87. In FY 2016, ITS also significantly expanded its participation in the open source development platform GitHub through several public repositories at https://github.com/NTIA.

1 Anita G. Longley; Philip L. Rice, "Prediction of Tropospheric Radio Transmission Loss Over Irregular Terrain: A Computer Method - 1968," NTIA Technical Report ERL 79-ITS 67, July 1968 (available https://www.its.bldrdoc.gov/publications/2784.aspx) continues to be cited to this day in the scholarly literature on propagation modeling.

In the 1980s, Telecommunications Analysis (TA) Services anticipated the Software-as-a-Service (SaaS) paradigm with a dial-in connection that allowed a user to input transmitter, frequency, and geographic parameters to be fed into a computerized propagation model. A predicted coverage map was plotted and sent to the client. By the 1990s, clients could request and receive propagation predictions electronically. TA Services continued to provide web-based analysis support on a cost-reimbursable basis for wireless system design/evaluation and site selection to private industry and public agencies through on-demand electronic CRADAs through FY 2012. Meanwhile, the software was modified to use commercial-off-the-shelf GIS products for propagation mapping. In the 2000s, ITS delivered the first off-site installation of the Communication Systems Planning Tool (CSPT), a menu-driven propagation modeling software package delivered to an other agency sponsor for installation on a classified network.

Today, the ITS Propagation Modeling Website (PMW), a web-based propagation analysis software suite, gives intranet users the ability to perform RF propagation analysis for different frequencies and geospatial scenarios using a broad variety of propagation models and either locally or publicly hosted terrain databases. PMW and its predecessor propagation analysis software programs have been widely used by both industry and other federal agencies. DoD agencies in particular continue to sponsor improvements to PMW to incorporate more frequency bands and terrain databases, as well as usability improvements to facilitate more widespread use by non-experts.

The National Weather Service (NWS) was one of the first subscribers to TA Services and ITS now provides NWS with a customized ITS-hosted PMW instance. The NWS PMW is used to plan and optimize the location and characteristics of new transmitters on the NOAA Weather Radio All Hazards (NWR) nationwide network, which broadcasts continuously on specified frequencies. NWS must provide access to the potentially life-saving NWR broadcasts to at least 95 percent of the U.S. population and uses the NWS PMW to verify population coverage for selected transmitters by incorporating U.S. Census 2010 population data into the propagation analysis output, which is mapped with a granularity of 90 square meters.

With the increasing complexity of sharing scenarios that rely on software defined radio, dynamic frequency selection, and other software-dependent spectrum management tools, accurate and computationally efficient software implementations of modeling and simulation algorithms have become a significant portion of ITS research outputs. Some years ago, ITS identified the need for Institute-wide best practices to ensure consistently excellent quality software products for both internal and external sponsors, and in FY 2015 ITS began an effort to achieve Level 2 Capability Maturity Model Integration (CMMI)®, an international standard of excellence that began as a software development quality assurance method but has application for other processes. We began with a commitment to adopting Agile software management practices to streamline our critical tasks, create a minimum viable product, and cultivate heathy teams. ITS is already recognized as a quality leader in developing the algorithms used for propagation modeling that have been implemented in ITS-developed technical software; ITS has set a strategic goal to claim a similar leadership position in project management and software development, and has chosen the CMMI process model to assist in reaching that goal.

Figure 1. CMMI for Development process areas.

The CMMI assessment model provides a framework for evaluating and adjusting business processes to improve efficiency across an organization. ITS is currently pursuing CMMI Level 2 for Development certification, which requires improving processes in seven areas:

1. Project Planning
2. Project Monitoring and Control
3. Requirements Management
4. Configuration Management
5. Measurement and Analysis
6. Process and Product Quality Assurance
7. Supplier Agreement Management

In FY 2016 ITS engaged a certified CMMI coach to evaluate existing processes and train ITS personnel in the CMMI framework. We created artifacts for first three of the seven listed process areas (highlighted in green in Figure 1). In FY 2017 these artifacts will undergo a series of gap analyses to ensure that our approach addresses the intent of the practices. In FY 2017, we will begin working on the fourth process area in the list above (in yellow in Figure 1) while we continue to improve the first three process areas and demonstrate repeatability in using the artifacts.

Figure 2. A CMMI team in action. At the display, Kristen Davis, Project Leader. Photo by Earl Dean.

Our method for achieving CMMI Level 2 is to demonstrate a managed capability using a continuous integration approach. This enables us to focus on improving the processes organically throughout the organization and gaining buy-in from our primary stakeholders: ITS employees. This is demonstrated in Figure 2, a photo of a CMMI team meeting to discuss FY 2017 goals and identify critical tasks. ITS believes this approach generates interest in process improvement and allows team members to provide continuous feedback for the processes they deem important.

Applications of Systems, Software, and Analyses for Spectrum Sharing

Enabling Sharing at 1695–1710 MHz

Scenario

The National Oceanographic and Atmospheric Administration (NOAA) manages and operates the Nation's operational environmental satellites through its National Environmental Satellite, Data, and Information Service (NESDIS) office. NESDIS provides timely access to global environmental data from satellites to promote, protect, and enhance the Nation's economy, security, environment, and quality of life. NESDIS operates both polar-orbiting and geostationary satellite constellations using L-Band, S-Band, and X-Band frequencies. These frequencies are used to command satellites as well as to receive state of health and mission data from the satellites.

The Middle Class Tax Relief and Job Creation Act of 2012 directed[1] the Secretary of Commerce to identify 15 megahertz (MHz) of U.S. Government use spectrum suitable for repurposing, i.e., sharing with commercial wireless carriers. The Secretary of Commerce identified 1695–1710 MHz as a band to be designated for sharing with the wireless carriers.

As a result, in January 2015, the Federal Communications Commission (FCC) held the Advanced Wireless Service-3 (AWS-3) auction, also referred to as Auction 97, to sell licenses to spectrum in the 1695–1710 MHz frequency band to wireless carriers to deploy wireless technologies such as Long Term Evolution (LTE). These frequencies are currently used by NOAA/NESDIS to receive L-Band satellite downlink signals at 17 Earth station locations across the United States. Moving forward, NOAA will have to share these frequencies with wireless carriers who are now licensed to operate wireless networks in the same geographic location as these 17 NOAA federal Earth stations. Spectrum sharing is anticipated to begin as early as Spring of 2018.

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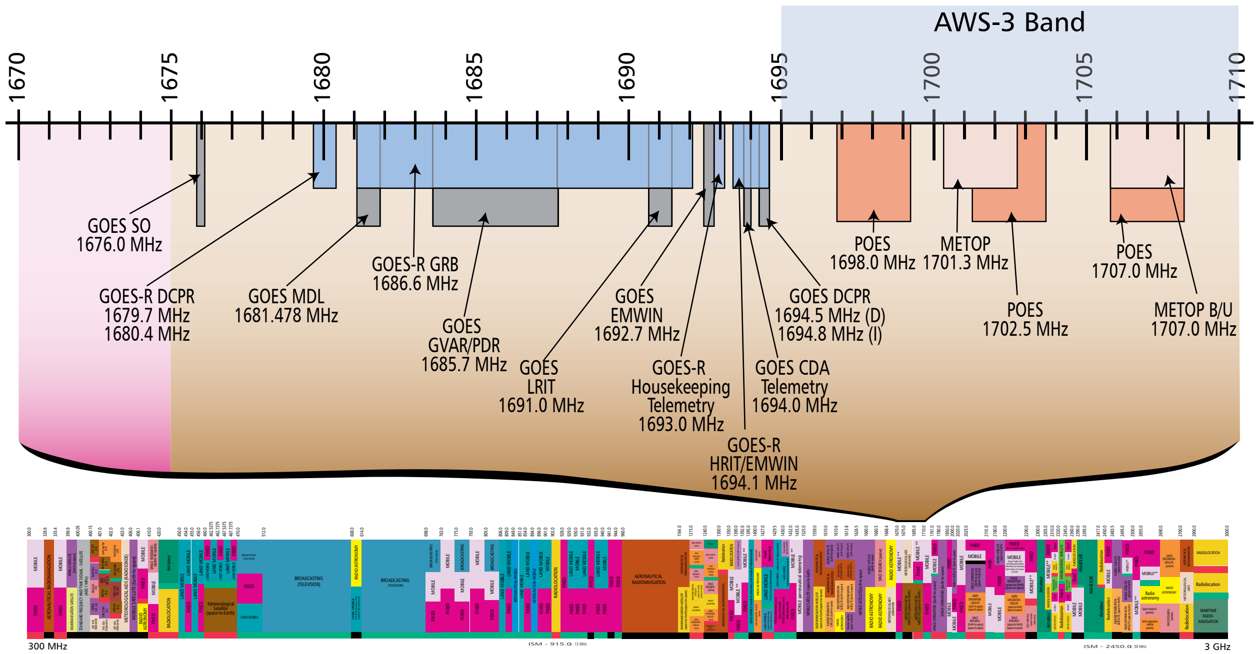
1 Public Law 112-96, Middle Class Tax Relief and Job Creation Act of 2012, Section 6401 (Deadlines for the Auction of Certain Spectrum), February 22, 2012; Section 6401 (a), (3). Accessed https://www.gpo.gov/fdsys/pkg/PLAW-112publ96/pdf/PLAW-112publ96.pdf December 22, 2016.



NOAA downlink frequencies in the 1695-1710 MHz band.

The FCC adopted new rules to allow commercial entities to share the 1695–1710 MHz band with federal agencies conditioned on Protection Zones around these 17 Earth stations. If protected federal operations receive harmful interference from AWS-3 operations in the band, the AWS-3 licensee must, upon notification, modify its operations and/or technical parameters as necessary to eliminate the interference.

This spectrum sharing agreement represents the first time the federal government will share satellite communication frequencies with licensed, non-federal users. The wireless carriers plan to use the 1695–1710 MHz band for uplink communications from LTE user equipment (UE) to network base stations on a non-interference basis only. To that end, a Radio Frequency Interference Monitoring System (RFIMS) was proposed to monitor and detect wireless carriers' LTE RF services with the aim of preventing interference with the 17 NOAA Earth stations where the 1695–1710 MHz band is shared with AWS-3 licensees.

To be successful, RFIMS must perform four basic functions: detect, classify, and identify the source of the interference, and notify relevant parties of an interference situation.

- **Detect:** The system should detect, in real-time, "events" in which the interference level exceeds a preset threshold at a NOAA's Earth station.
- **Classify:** The system should classify, in real-time, the nature of the interference; that is, the system must be able to discriminate between 1695–1710 MHz LTE UE uplink signals and all other radio frequency interference (RFI) such as background impulsive noise and out-of-band emissions from other RF sources.
- **Identify:** If the system determines the RFI is related to 1695–1710 MHz LTE UE uplink signal interference, then it should identify the source(s) of interference in real-time or as near to real-time as possible.
- **Notify:** The system should notify NOAA operators, and potentially the wireless carriers, that wireless carriers are creating interference to NOAA transmissions.

Enabling Research

In 2016, ITS executed a multi-year Interagency Agreement with NOAA/NESDIS to provide both technical subject matter expertise and non-recurring engineering support to NOAA in the acquisition of the RFIMS. Of particular value to NOAA with respect to the RFIMS acquisition is ITS's expertise and strengths in electromagnetic compatibility studies, interference resolution, developing and deploying spectrum measurement systems, performing complex RF measurements on government and non-government systems, signal propagation, and developing sophisticated simulations and models.

To support the four major functions of the RFIMS, ITS is performing several parallel studies. The first study models the link budget of the satellite system, propagation channels, Earth station receive systems, external RF environment, and aggregate LTE UE interference in both the main-beam and side lobes of the Earth station antennas to determine necessary sensitivity requirements of the RFIMS. The second study characterizes Earth station receive signal paths and tests an actual satellite signal receiver against synthesized LTE and other signals under controlled conditions. The third is a long-term study that deploys spectrum monitoring systems, developed by ITS, at several key NOAA sites to examine long-term spectrum usage and trends in the 1695-1710 MHz band and adjacent bands before and after new AWS-3 commercial wireless systems are deployed. The fourth study creates and refines an aggregate LTE UE emission model to create RFIMS use case scenarios. This model will also be used to better refine synthesized aggregate LTE emissions.

Once an RFIMS system has been contracted, ITS will serve as NOAA's test and evaluation support agent for the RFIMS acquisition. ITS will establish a field-based test and evaluation capability to conduct objective assessments of contractor-developed RFIMS hardware and software.

ITS is uniquely qualified to assist NOAA with spectrum sharing in the 1695–1710 MHz band thanks to its fusion of world-class RF engineering expertise, state-of-the-art test equipment, and sophisticated proven measurement and analysis techniques. Access to unbiased expert ITS capabilities will enable NOAA to confidently move forward in acquiring and ultimately deploying the RFIMS.

Enabling Sharing at 3.5 GHz

A novel approach to spectrum coexistence is underway in the 3.5 GHz band, until now used predominately for long range radar operations along the coasts and at inland test facilities by the U.S. Navy and DoD, fixed satellite services, and a sprinkling of commercial fixed wireless services. Multistakeholder groups are now designing commercial small cell broadband wireless services that will operate in the band under an innovative three-tiered access regulatory framework adopted by the FCC in 2016.

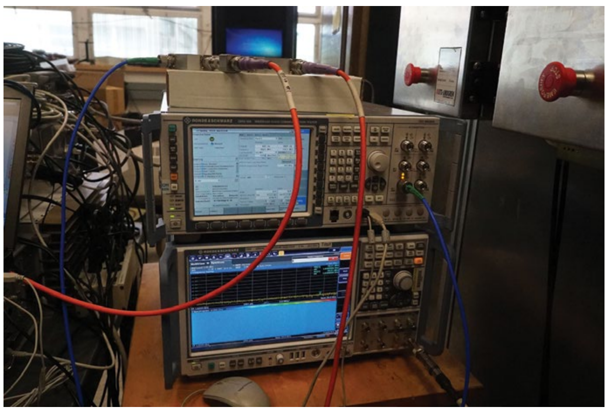
The anticipated Citizens Broadband Radio Service depends on Spectrum Access Systems (SAS) that will dynamically manage use of the spectrum by both licensed and unlicensed commercial broadband service providers and users, while ensuring no interference to the completely different operations of the incumbents. Detection and protection of federal incumbent radar operations depends on environmental sensing capabilities (ESC) that communicate with the SAS.

ITS is providing guidance to industry stakeholders on adapting and using existing propagation models to the antenna heights, distance ranges, and power levels of the small cell architecture in the 3.5 GHz band. These models will be used to calculate protection contours where internal unconnected voids or external islands exist, facilitating the ability of the SAS to manage spectrum utilization by the commercial users. Working with the FCC and industry, ITS is developing a test system to enable the FCC to certify that SAS systems are compliant with the rules published in the Code of Federal Regulations in Title 47 Part 96 - Citizens Broadband Radio Service (47 C.F.R. §§96.1–96.67).

ITS is also providing guidance on use of propagation and aggregate interference models to calculate exclusion zones for federal incumbent protection. Exclusion zones define geographic areas where Citizen Broadband Radio Service devices may not operate at all because the likelihood of interference is just too great. As trust in the ability of the SAS-ESC system to protect incumbent operations grows, exclusion zones will become coordination zones. ITS is also working with federal stakeholders to develop a test system to ensure the critical ESC sensors detect and protect federal operations from both interference to and disclosure of their operations. These efforts, initiated in FY 2016, use the unique skill set and expertise of ITS engineers and staff in radar, radio frequency theory, propagation analysis, signal aggregation modeling, software development, and radar system testing and certification.

Building Best Practices for Sharing Analyses

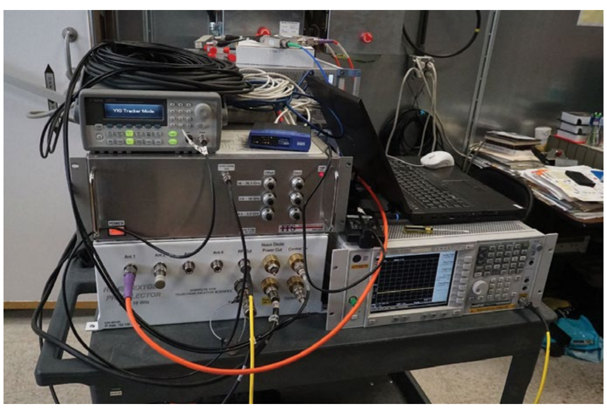
ITS is a charter partner, along with NIST and the DoD, in the National Advanced Spectrum and Communications Test Network (NASCTN), initiated under the auspices of the Center for Advanced Communications (CAC).[1] NASCTN was created to provide a framework to improve opportunities for spectrum sharing through accurate, reliable, and unbiased test measurements and analysis. Its mission is to provide robust test processes and validated measurement data necessary to develop, evaluate, and deploy spectrum sharing technologies that can increase access to the spectrum by both federal agencies and non-federal spectrum users. NASCTN tests provide the highest-quality data obtainable within the state-of-the-art of measurement capabilities, and are conducted with rigor and transparency. The validated test plans published by NASCTN can be used by others to conduct similar and reproducible test measurements. NASCTN does not interpret the data or test results—that is left to the spectrum sharing community.



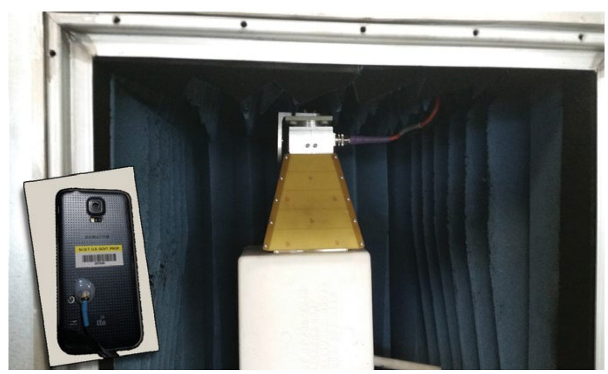
A goal of NASCTN is to develop and publish validated test plans for use in EMC studies for sharing analyses. Here, a base station emulator (top) and spectrum analyzer (bottom) are used to troubleshoot and verify the measurement setup.

In FY 2016, three distinct spectrum sharing tests were conducted by NASCTN. ITS Director Keith Gremban and ITS staff were involved in screening the test proposals, ensuring the validity and integrity of the measurements and tests, and reviewing and disseminating preliminary findings from the tests. ITS staff participated on all three test teams and led one.

ITS led the test team responding to a proposal from Edwards Air Force Base (EAFB) to test and measure the out of band emissions (OOBE) expected from terrestrial commercial wireless service base stations



Test set up for emission measurements of terrestrial commercial wireless service base stations (eNodeB) and user equipment (UE) in the AWS-3 band. The spectrum analyzer is at bottom right, with the acquisition laptop on top, and the three-box stack on the left is the RF preselector.



To develop test plans for the widest possible variety of instruments,the first NASCTN project took measurements with a UE hardline connected to the test instrumentation (inset) as well as with the UE placed immediately in front of the aperture of a dual-ridged horn antenna inside a small anechoic chamber. The UE us barely visible as a thick a silver line immediately underneath the horn antenna.

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1 The Center for Advanced Communications (CAC) was started in 2013 as an integrated focal point for spectrum and innovative advanced communication research through collaboration between ITS and NIST's Communications Technology Laboratory. The ITS Director and the NIST CTL Director as co-directors of CAC exercise oversight over the spectrum sharing testing and evaluation capabilities provided under the auspices of NASCTN.

(eNodeB) and user equipment (UE) in the AWS-3 band, into adjacent L and S frequency band aeronautical mobile telemetry (AMT) systems. The AWS-3 frequency band had recently been reallocated and auctioned for sharing. Anticipating deployment of AWS-3 near its operations and facilities, EAFB needed reliable and accurate information on OOBE to determine the appropriate RF filters to protect AMT operations. But no equipment had yet been developed or certified for commercial use in the AWS-3 band. Under ITS engineering staff leadership, the NASCTN team developed a test plan and tested its efficacy by performing measurements of emissions from 3GPP Band 3 equipment. The results of those validating tests, along with the draft test plan, were published in 2016. In FY 2017, tests using AWS-3 equipment will be conducted by the NASCTN test team using the final test plan.

ITS radar expert and senior technical fellow Frank Sanders participated on the NASCTN test team investigating the impact of LTE signals on GPS devices. This project has been controversial. The sponsor, Ligado Networks, proposes new spectrum sharing scenarios in bands adjacent to GPS systems, and had previously commissioned tests that supported its policy position that its proposed terrestrial wireless communications system would not adversely impact or cause interference to GPS. The NASCTN team developed a completely independent test plan that was fully vetted by government and industry stakeholders and the public. Testing occurred for over 1500 hours during several months during FY 2016 in two different anechoic chambers. In depth tests were conducted on a limited number of devices representative of the types of GPS devices in the market, including general location and navigation, precision location, and real-time kinematics, and precision timing devices. Measurands included carrier-to-noise-density ratio (C/N0), pseudo range error, position error, timing deviation, and carrier phase. Tests included stepped power increases that cleared all residual data in the devices at each step, separate and simultaneous uplink and downlink activity measurements, and precision timing measurements. Test results will be released in a NASCTN report in FY 2017.

The third NASCTN test project, which began as a sponsored project, has measured actual radar wave forms from unclassified SPN-43 Navy radars from locations on both the West and East coasts. The measurement project built upon the results of the spectrum occupancy study conducted by ITS in 2013, was conducted at the same locations, and used ITS specially designed high dynamic range Radio Spectrum Measurement System components. Unclassified samples of radar wave forms were provided to FCC applicants for authority to operate ESC sensors as part of the 3.5 GHz Citizens Broadband Radio Service. The final NASCTN reports on the results of the 3.5 GHz radar measurements will be released in FY 2017.

SPN-43 radar aboard the aircraft carrier USS John C. Stennis (CVN 74). Electronics Technician 3rd Class N. Blomgren, top, is performing maintenance (U.S. Navy photo by Mass Communication Specialist 3rd Class W. Tyndall/Released)

"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 9.

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-relevant 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 publications
- Participation in the development of requirements and standards
- Conferences, workshops, and symposia
- Open source software

1 Executive Office of the President, Office of Science and Technology Policy, Multi-Agency Science and Technology Priorities for the 2017 Budget, July 9, 2015. Accessed https://www.whitehouse.gov/sites/whitehouse.gov/files/omb/memoranda/2015/m-15-16.pdf June 30, 2017.

2 15 U.S.C. §3702 (3).

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 2016, 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 or LIDAR), 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 Network 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 2016, 54 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 18 for a full description). The site provides a unique opportunity for radio research and experimentation in a controlled outdoor environment because the strength of external RF signals reaching TMFS is severely restricted under both state law and federal regulation. To further minimize interference to sensitive research projects, all RF emissions on or near Table Mountain are coordinated through the Regional Frequency Coordination Office. Partnerships and cooperative research activities with other entities are encouraged to maximize the utility of 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 any of the features described in the *ITS Resources* section on page 18. In FY 2016, ITS participated in seven CRADAs for research conducted at the Table Mountain Field site, three of which were with small businesses.

Ad Hoc Communication Networks

The University of Colorado is experimenting with communication networks between low-cost small unmanned aircraft (UA) similar to model radio control 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 and the goal is to develop autonomous "flocking" where the UAVs collectively and autonomously complete sensing and communication tasks. Work in FY 2016 included continued development of unmanned aircraft systems for atmospheric science applications. Flight experiments validated the airframes and avionics systems, including flight testing of a wind sensor, cooperative control flight experiments, and aircraft launch system testing. Experiments were also conducted to model the radio frequency environment between unmanned aircraft and ground nodes, including communication channel mapping flight experiments and flight testing of RF source localization algorithms.

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. Using the large turntable at the facility, in FY 2016 First RF was able to obtain antenna patterns of various antennas over a wide range of frequencies ranging from HF to C band. They also performed high level tests of cutting edge antenna systems ranging in frequency as high as 80 GHz. These antennas are used in ground vehicular, fixed-site, and airborne platforms, and apply to systems including communications, electronic warfare, direction finding/geolocation, and radar.

Laser Radar (LADAR) 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 LADAR system development in atmospheric conditions and at distances relevant to potential applications. Areté is developing a variety of new airborne LADAR 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 2016, Areté used the site to conduct a LADAR Fusion functional test in preparation for an off-site flight demonstration.

Laser Radar (LIDAR) System Testing for Multiple Applications

Ball Aerospace is currently engaged in building and testing multiple lidar systems, and entered into a CRADA for the use of TMFS for testing that requires a large open space with restricted access for safe propagation of laser beams. For each test, a Ball Lidar Laboratory trailer is towed to TMFS and, as required, a range of targets is set out so that system checks, alignments, and other tests can be performed. Systems being tested under this CRADA include a wind lidar (for use by NASA), a 3D full motion video lidar (for use by the DoD), and sensing lidars for hazardous liquids and methane (for use in various federal and commercial applications).

Laser Radar (LIDAR) Testing for Industry Applications

Lockheed Martin Coherent Technologies (LMCT) has had CRADAs with ITS for many years to conduct a long-term long-range wind measurement experiment to expand the utility of its WTX WindTracer® long-range scanning Doppler lidar. WindTracer® has been used at airports for the detection and tracking

WindTracer® Doppler lidar system being readied for testing at the TMFS. Photo courtesy Lockheed Martin.

of wind shear and wake vortices since 2002, but recently LMCT has seen interest from the offshore wind energy industry for use during site prospecting operations. The WindTracer® has previously demonstrated long range capabilities (12 to 15 km) in scanning operations, but the wind energy industry has challenged LMCT to demonstrate the WindTracer in staring beam operations at even longer ranges to fulfill industry requirements. Experiments were conducted to demonstrate WindTracer® performance could meet this challenge by measuring winds above the Boulder Atmospheric Observatory, which is located 23 km away from the TMFS. The findings offer promise for a new method to obtain precise remote wind measurements for the offshore wind energy industry.

NOAA Weather Radio (NWR) Testing

NOAA Weather Radio (NWR) provides continuous information from the National Weather Service (NWS) offices directly to the public on "all hazards"—the latest weather conditions as well as natural disasters such as earthquakes or avalanches, environmental catastrophes such as chemical releases or oil spills, and public safety emergencies such as AMBER Alerts™ or 911 telephone outages. NOAA allows receivers that meet the required Consumer Electronics Association (CEA) performance specifications to bear the NWR logo, which certifies to the public that a model is capable of receiving weather and/ or warning information from NWS Forecast Offices, Department of Homeland Security offices, and Emergency Operation Centers. ITS has developed simulated broadcasts and a series of repeatable measurement methods to test the performance of NWR receivers and serves as the NWS's independent CEA-2009-B surveillance test lab for NWR receivers. In FY 2016, NWR receiver manufacturers Halo Smart Labs and E&S International Enterprises entered into CRADAs with ITS to have their equipment tested for CEA 2009 compliance using simulated NWR transmissions.

All Hazards NOAA Weather Radio NOAA's National Weather Service

Interagency Research and Development Agreements

Interagency agreements (IAA), authorized by the Economy Act (31 U.S.C. §1535), allow one federal agency to reimburse another for the use of staff or physical resources. This leverages the government's investment in building unique expertise or acquiring and maintaining specialized resources. 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 (TMFS) are some of the unique resources that ITS makes available to other agencies through interagency agreements.

Wherever possible, research funding is leveraged to benefit multiple agencies. For example, five different agencies who have frequency assignments in the 1695–1710 MHz band supported the development and deployment of the Radio Frequency Coordination Portal (RFCP), through which each incumbent user will coordinate use of the band with commercial entrants, reducing the cost for each individual agency. Public safety communications research is also funded by multiple agencies, each of which may bring a specific question to the ITS laboratories for investigation. Addressing each question in the context of all the questions eliminates rework, enhances interoperability, and allows faster dissemination of solutions.

Interagency Agreements for the Use of Table Mountain

Though IAAs are sometimes written to use the TMFS for measuring radar emissions against the radar spectrum engineering criteria (RSEC) as described on page 39, the majority of IAAs for the use of the TMFS are with NOAA and NIST laboratories collocated with ITS on the DoC Boulder Laboratories campus. NOAA's National Geodetic Survey (NGS) Operations and Analysis Division operates the Table Mountain Gravity Observatory (TMGO) on the site. In addition to having 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

Top: Researchers from Germany, Brazil, Italy, Canada, the Netherlands, Saint Lucia, Luxembourg, and elsewhere brought equipment to set up for the annual "North American Comparison of Absolute Gravity Meters" at the Table Mountain Gravity Observatory. Bottom: The gravimeters in place during testing. Photos by Derek vanWestrum, NOAA.

Reference Station (CORS) on Table Mountain, one of over 2000 stations that provide Global Navigation Satellite System (GNSS or GPS) data to support three-dimensional positioning, meteorology, metrology, space weather, and geophysical applications throughout the U.S.

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.

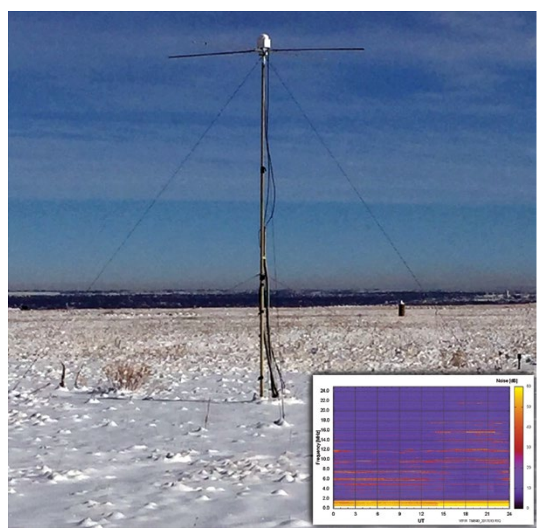
NOAA's Earth System Research Laboratory Global Monitoring Division maintains a SURFRAD (Surface Radiation) Network monitoring station on Table Mountain. SURFRAD stations perform ground-based measurements of upwelling and downwelling solar and infrared radiation; ancillary observations include direct 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.

NOAA's Solar-Terrestrial Physics (STP) team within the National Centers for Environmental Information (NCEI) takes advantage of the radio quiet at the TMFS to collect data on atmospheric noise. STP is responsible for the archive and access of solar and space environmental data and derived products collected by NOAA observing systems. One application of this data is space weather prediction, which is important to protect HF communications, satellite communications, radio navigation systems like GPS, electric power distribution, and many other technologies that are vulnerable to the impact of space weather such as solar flares.

Craig Moulton, USGS, towing a geophysical sensor used to map shallow electrical conductivity at the TMFS. Photo by Burke Minsley, USGS.

Telescope and gimbal control for a dual-comb laser spectrometer instrument being tested at the Table Mountain Field site by the Applied Physics Division of NIST and University of Colorado to locate and size methane leaks from oil and gas production sites with high precision. Photo by Sean Coburn.



This active crossed dipole antenna is monitoring the atmospheric noise environment. The inset shows diurnal variation of signals in the MF-HF band during a 24 hour survey. Photo by Terry Bullett, NOAA.

Requirements and Standards

Strong unbiased standards are fundamental for advancing new technologies in a shared spectrum environment and globally competitive marketplace. For close to a century, ITS and its predecessors have provided leadership and technical contributions to national and international telecommunication standards development organizations (SDO). ITS works with industry and other stakeholders to perform the research needed to inform standardization. In recent decades, ITS research and advocacy has played an important role in ensuring that commercial standards incorporate the unique needs of public safety communications. This supports competitive market solutions that can cost-effectively provide reliable, dependable, secure communications with interoperability among agencies and vendors' products and services.

ITS technical inputs are well regarded by commercial interests and treaty partners as technically sound and unbiased. They influence national and international standards for radio devices, spectrum allocation, propagation modeling, delineating interference protection criteria, assessing quality of experience, and describing performance parameters for transmitting and receiving equipment. ITS provides technical expertise and guidance in the development of telecommunications standards to SDOs such as the International Telecommunication Union (ITU), 3rd Generation Partnership Project (3GPP), Institute of Electrical and Electronics Engineers (IEEE) Standards Association, and the Alliance for Telecommunications Industry Solutions (ATIS) and, through interagency agreements, to other federal agencies as needed. Other offices of NTIA participate in the same SDOs in different, non-technical capacities. In FY 2016, 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 (complete list on page 81). 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 United Nations 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. In the 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. 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) are developed by consensus in Study Groups of public and private sector experts and act as defining elements in the global infrastructure of information and communication technologies. They play a critical role in advancing global interoperability and creating a level playing field in which companies can compete internationally. ITS also develops and coordinates approval of related U.S. voluntary consensus standards where appropriate.

SDOs depend to varying degrees on other formal and informal stakeholder organizations to develop requirements and perform preliminary research to ensure that the approved standards meet the needs of all stakeholders. ITS has worked with the National Public Safety Telecommunications Council (NPSTC), a federation of public safety organizations focused on improving public safety communications and interoperability, and with the Association of Public-Safety Communications Officials (APCO) on requirements definition for both P25 (page 73) and LTE (page 74) standards for public safety communications. ITS founded and continues to play a significant role in the Video Quality Expert Group (VQEG), which submits new and improved methods for subjective and objective video quality assessment to SDOs, including the ITU-T, for standardization. Key national quality-of-service standards developed under the American National Standards Institute (ANSI) accredited Accredited Standards Committee T1 – Telecommunications (ASC T1) for video, audio, and digital data also incorporate ITS research results.

Public Safety Requirements and Standards

As reported on page 49, ITS has been working closely with practitioners for decades to develop the standards, technologies, and test methods that support continued development of communications systems that meet the unique requirements of the law enforcement, fire, emergency medical response, and emergency preparedness communities. A list of the principal relevant requirements and standards documents to which ITS staff have contributed begins on page 75.

In FY 2016, this work proceeded largely along two fronts: technical guidance to the Project 25 (P25) compliance assessment program (CAP) for digital land mobile radio (LMR) systems, and promoting inclusion of features that meet public safety broadband mobile communications requirements in 3GPP LTE and next generation standards. Work on the P25 CAP reflects the reality that the time it will take for 60,000 public safety organizations in the U.S. to transition from LMR to mission critical voice over LTE will be measured in decades, and that in the interim LMR equipment will continue to evolve. At the same time, early and ongoing participation in the development of broadband mobile standards can help ensure that public safety users can take advantage of broadly deployed commercially available technology.

Project 25 Compliance Assessment Program

Historically, public safety agencies have purchased and used equipment made by different manufacturers with inconsistent manufacturing practices and using different spectra. As a result of these inconsistencies, the equipment could not interoperate, preventing many public safety agencies from communicating when lives were in danger. Public safety organizations and the communications industry partnered through Project 25 (P25) to eliminate these issues by developing standards for easy interoperability of radios and other components across agencies and jurisdictions, regardless of manufacturer. The goal of P25 is to specify formal standards for interfaces between the various components of the LMR systems commonly used by emergency responders. In addition to interoperability, the P25 standards also address spectral efficiency at multiple frequencies.

After years of effort, industry was successfully incorporating standards into much of the radio and communications equipment used by public safety. However, preliminary test data indicated that some radios sold under the P25 label did not meet all of the standards' requirements. The problem was the lack of a reliable method to verify equipment compliance with P25 standards.

In 2008, ITS, NIST/CTL and the Department of Homeland Security's Office of Interoperability and Compatibility (DHS OIC) worked together to build an independent coalition of public safety users and communications equipment manufacturers to address this issue. This led to the creation of the congressionally-mandated P25 Compliance Assessment Program (CAP) to test equipment for standards compliance.

Program Structure

The P25 CAP is a unique partnership among ITS, DHS OIC, industry, and public safety practitioners from different countries representing different levels of government to achieve user-driven standardization. It provides a forum where performance, conformance, and interoperability issues that emerge as the technology and the user needs evolve can be recognized and resolved before product launch and deployment. This voluntary program that allows P25 equipment suppliers to formally demonstrate their products' compliance with a select group of requirements within the P25 suite of standards in order to provide emergency response agencies with evidence that their communications equipment meets P25 standards for performance, conformance, and interoperability. Rather than relying on a large centralized test facility, the program recognizes independent laboratories authorized to conduct testing. It is an outstanding example of Government making a minimal investment that catalyzes industry and the community it serves to develop a solution that will affect billions of dollars in purchases.

Results

The P25 Compliance Assessment Program impacts billions of dollars in purchases of public safety equipment by providing a mechanism to ensure that purchased equipment conforms to interoperability standards. By supporting the migration from proprietary and stove-piped communications systems to open, standards-based infrastructure, the P25 CAP ensures that emergency response technologies effectively meet the needs of practitioners in the field. The P25 CAP provides emergency response agencies nationwide a consistent and reliable indicator of P25 product compliance. It also provides a means of verifying that billions of federal grant dollars and federal procurements of LMR systems are being invested in standardized solutions and equipment that promotes interoperability.

ITS is assisting DHS OIC in the process of transitioning the assessment and recognition of participating P25 CAP test laboratories to commercially available ISO/IEC 17011 based accreditation bodies. Working independently of the American National Standards Institute (ANSI) accredited Telecommunications Industry Association (TIA), ITS is developing conformance tests appropriate for compliance assessment for inclusion in the P25 CAP. ITS also assisted in developing federal grant guidance language for DHS that affects how federal grant money is used by state and local public safety to purchase communications equipment.

LTE Standards for Public Safety Broadband

The nationwide public safety broadband network being built by FirstNet is required to be based on the minimum technical requirements of the commercial standards for Long Term Evolution (LTE) cellular service, which are developed by the 3rd Generation Partnership Project (3GPP). 3GPP publishes contribution-driven specifications and standards for the technologies that enable complete cellular network systems, including radio access, the core transport network, service capabilities (e.g., codecs, security, quality of service). Because the "Organizational Partners" of 3GPP are seven key wireless standards development organizations from Asia, Europe and North America, these standards have global reach.

LTE was chosen as the most promising technology for the nationwide public safety broadband network because it is both robust and efficient, so much so that it is the world's largest deployed cellular broadband technology. However, development of the LTE standard was initiated by cellular carriers eyeing the commercial market, and many features essential to public safety—including mission critical voice communications requirements defined by the National Public Safety Telecommunications Council (NPTSC) Broadband Working Group—were not included in early releases of the LTE standards.

Moving from custom-designed proprietary technologies to standards-based commercially competitive technologies for public safety significantly advances the potential for all public safety agencies to be equipped with efficient, fully capable, and interoperable communications systems. With this in mind, for several years ITS has been partnering with FirstNet, DHS, and PSCR to advance the interests of public safety in the evolution of the LTE standards. In late spring of 2016, a significant milestone in this effort was reached when dozens of standards that included all of the mission critical public safety voice requirements and many ancillary features of interest to public safety were codified in Release 13 of the 3GPP specifications. These features are critical to ensuring that LTE can meet public safety's requirements and a prerequisite to allowing FirstNet to offer mission-critical voice (MCV) on the new Band Class 14 nationwide interoperable public safety communications network when these capabilities become available.

A key ITS contribution to this release was technical expertise regarding speech intelligibility as it relates to speech codecs for Mission Critical Push-to-Talk Voice over LTE. The results of the research reported in the article on *Speech Intelligibility Testing for Mission Critical Voice* on page 51 were provided directly to 3GPP Working Group meetings throughout the fiscal year and an ITS staff person facilitated their interpretation. Other ITS staff contributed to standardization of features of interest to public safety at the radio access network (RAN), overall systems architecture and service, and core network levels.

Principal Public Safety 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 15) V15.0.0 (2016-12); (Release 14) V14.2.0 (2016-12); V14.1.0 (2016-09); V14.0.0 (2016-06)
- 3GPP TS22.115 Service aspects; Charging and billing (Release 15) V15.0.0 (2016-12); (Release 14) V14.1.0 (2016-09); V14.0.0 (2016-06)
- 3GPP TR 22.891: Feasibility Study on New Services and Markets Technology Enablers; Stage 1 (Release 14) V14.2.0 (2016-09); V14.1.0 (2016-06); V14.0.0 (2016-03); (Release 13) V13.2.0 (2016-02)
- 3GPP TR 22.862: Feasibility Study on New Services and Markets Technology Enablers - Critical Communications; Stage 1 (Release 14) V14.1.0 (2016-10); V14.0.0 (2016-06); V2.0.0 (2016-06); V1.1.0 (2016-06); V1.0.0 (2016-03); V0.3.1 (2016-02); V0.3.0 (2016-02); V0.2.0 (2016-01)
- 3GPP TS22.261 Service requirements for next generation new services and markets; Stage 1 (Release 15) V1.0.0 (016-12); V0.2.0 (2016-12); V0.1.1 (2016-10)
- 3GPP TR 22.879 Feasibility Study on Mission Critical Video Sevices over LTE; (Release 14) V14.0.0 (2015-12)
- 3GPP TR 22.880 Feasibility Study on Mission Critical Data Communications; (Release 14) V14.0.0 (2015-12)
- 3GPP TS 22.179 Mission Critical Push To Talk (MCPTT) over LTE; Stage 1 (Release 14) V14.3.0 (2016-12); V14.2.0 (2016-09); V14.1.0 (2016-06); V14.0.0 (2016-03)
- 3GPP TS 22.280 Mission Critical Services Common Requirements (MCCoRe) ; Stage 1 (Release 14) V14.2.0 (2016-12); V14.1.0 (2016-09); V14.0.0 (2016-06); V2.0.0 (2016-06); V1.0.0 (2016-03); V0.1.0 (2016-02)
- 3GPP TS 22.281 Mission Critical video services over LTE (MCVideo) (Release 14) V14.2.0 (2016-12); V14.1.0 (2016-09); V14.0.0 (2016-06); V2.0.0 (2016-06); V1.0.0 (2016-03); V0.1.0 (2016-02)

3GPP SA2 WG

- 3GPP TS 23.303 Proximity based services (ProSe); Stage 2 (Release 14) V14.1.0 (2016-12); V14.0.0 (2016-09); (Release 13) V13.6.0 (2016-12); V13.5.0 (2016-09); V13.4.0 (2016-06); V13.3.0 (2016-03)
- 3GPP TR 23.785 Study on architecture enhancements for LTE support of V2X services (Release 14) V14.0.0 (2016-09); V2.0.0 (2016-09); V1.1.0 (2016-07); V1.0.0 (2016-06); V0.4.0 (2016-06); V0.3.0 (2016-04); V0.2.0 (2016-02); V0.1.1 (2016-01); V0.1.0 (2016-01)
- 3GPP TS 23.285 Architecture enhancements for V2X services (Release 14) V14.1.0 (2016-12); V14.0.0 (2016-09); V1.0.0 (2016-09); V0.2.0 (2016-09); V0.1.0 (2016-07)
- 3GPP TR 23.799 Study on Architecture for Next Generation System (Release 14) V14.0.0 (2016-12); V2.0.0 (2016-12); V1.2.1 (2016-12); V1.2.0 (2016-11); V1.1.0 (2016-10); V1.0.2 (2016-09); V1.0.1 (2016-09); V1.0.0 (2016-09); V0.8.0 (2016-09); V0.7.0 (2016-08); V0.6.0 (2016-07); V0.5.0 (2016-06); V0.4.0 (2016-04); V0.3.0 (2016-03); V0.2.0 (2016-02); V0.1.1 (2016-01); V0.1.0 (2016-01)
- 3GPP TS 23.501 System Architecture for the 5G System (Release 15) V0.0.0 (2016-12)
- 3GPP TS 23.502 Procedures for the 5G System (Release 15) V0.0.0 (2016-12)
- 3GPP TS 23.203 Policy and charging control architecture (Release 14) V14.2.0 (2016-12); V14.1.0 (2016-09); V14.0.0 (2016-06); (Release 13) V13.10.0 (2016-12); V13.9.0 (2016-09); V13.8.0 (2016-06); V13.7.0 (2016-03)
- 3GPP TS 23.214 Architecture enhancements for control and user plane separation of EPC nodes (Release 14) V14.1.0 (2016-12); V14.0.0 (2016-09); V1.0.0 (2016-09); V0.2.0 (2016-09); V0.1.0 (2016-07)
- 3GPP TS 23.401 General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access (Release 14) V14.2.0 (2016-12); V14.1.0 (2016-09); V14.0.0 (2016-06); (Release 13) V13.9.0 (2016-12); V13.8.0 (2016-09); V13.7.0 (2016-06); V13.6.0 (2016-03)
- 3GPP TR 23.733 Study on architecture enhancements to ProSe UE-to-Network Relay (Release 15) V0.1.1 (2016-12); V0.1.0 (2016-12)

- 3GPP TR 23.798 Study on Isolated E-UTRAN Operation for Public Safety; Enhancements (Release 15) V0.3.0 (2016-12); (Release 14) V0.2.0 (2016-11); V0.1.0 (2016-05);

3GPP SA6 WG

- 3GPP TS 23.179 Functional architecture and information flows to support mission critical communication services; Stage 2 (Release 13) V13.4.0 (2016-12); V13.3.0 (2016-09) ;V13.2.0 (2016-06); V13.1.0 (2016-03); V13.0.0 (2015-12)
- 3GPP TS 23.280 Common functional architecture to support mission critical communication services; Stage 2 (Release 14) V14.0.0 (2016-12); V1.0.0 (2016-12); V0.6.0 (2016-11); V0.5.0 (2016-10); V0.4.0 (2016-09); V0.3.0 (2016-08); V0.2.0 (2016-06); V0.1.0 (2016-06)
- 3GPP TS 23.281 Functional architecture and information flows to support Mission Critical Video (MCVideo); Stage 2 (Release 14) V14.0.0 (2016-12); V0.4.0 (2016-11); V0.3.0 (2016-10); V0.2.0 (2016-08); V0.1.0 (2016-06); V0.0.0 (2016-06)
- 3GPP TS 23.282 Functional architecture and information flows to support Mission Critical Data (MCData); Stage 2 (Release 14) V14.0.0 (2016-12); V1.0.0 (2016-12); V0.3.0 (2016-11); V0.2.0 (2016-10); V0.1.0 (2016-08); V0.0.0 (2016-08)
- 3GPP TS 23.379 Functional architecture and information flows to support Mission Critical Push To Talk (MCPTT); Stage 2 (Release 14) V14.0.0 (2016-12); V1.0.0 (2016-12); V0.5.0 (2016-12); V0.4.0 (2016-10); V0.3.0 (2016-09); V0.2.0 (2016-06); V0.1.0 (2016-06)
- 3GPP TR 23.781 Study on migration and interconnection for mission critical services (Release 14) V0.4.0 (2016-11; V0.3.0 (2016-10); V0.2.0 (2016-08); V0.1.1 (2016-06); V0.1.0 (2016-06); V0.0.1 (2016-06)
- 3GPP TR 23.782 Study on mission critical communication interworking between LTE and non-LTE systems (Release 14) V0.3.0 (2016-10); V0.2.0 (2016-08); V0.1.0 (2016-07)

3GPP SA3 WG and LI

- 3GPP TR 33.833 Study on security issues to support Proximity Services (Release 13) V13.0.0 (2017-01); V2.0.0 (2016-12); V1.8.0 (2016-11); V1.7.0 (2016-02)
- 3GPP TR 33.879 Study on Security Enhancements for Mission Critical Push To Talk (MCPTT) over LTE (Release 13) V13.1.0 (2016-06); V13.0.0 (2016-03); V2.0.0 (2016-03); V1.1.0 (2016-02)
- 3GPP TR 33.897 Study on isolated E-UTRAN operation for public safety; Security aspects (Release 13) V13.1.0 (2016-03); V13.0.0 (2015-12)
- 3GPP TS 33.303 Proximity-based Services (ProSe); Security aspects (Release 13) V13.4.0 (2016-06); V13.3.0 (2016-03)
- 3GPP TS 33.179 Security of Mission Critical Push To Talk over LTE (Release 13) V13.3.0 (2016-12); V13.2.0 (2016-09); V13.1.0 (2016-06); V13.0.0 (2016-03); V2.0.0 (2016-03); V1.1.0 (2016-02)
- 3GPP TR 33.885 Study on security aspects for LTE support of V2X services (Release 14) V1.0.0 (2016-12); V0.5.0 (2016-11); V0.4.0 (2016-08); V0.3.0 (2016-07); V0.2.0 (2016-02); V0.1.0 (2016-02)
- 3GPP TR 33.899 Study on security aspects of the next generation system (Release 14) V0.6.0 (2016-11); V0.5.0 (2016-10); V0.4.1 (2016-08); V0.4.0 (2016-08); V0.3.0 (2016-07); V0.2.0 (2016-06); V0.1.0 (2016-06)
- 3GPP TR 33.880 Study on Mission Critical Security Enhancements (Release 14) V0.3.0 (2016-11); V0.2.0 (2016-08); V0.1.0 (2016-08)
- 3GPP TS 33.107 3G security; Lawful interception architecture and functions (Release 14) V14.0.0 (2016-12); (Release 13) V13.5.0 (2016-12); (V13.4.0 (2016-09); V13.3.0 (2016-06); V13.2.0 (2016-03); (See Clause 16 and 17)
- 3GPP TS 33.106 3G security; Lawful interception requirements (Release 13) V13.4.0 (2016-06); V13.3.0 (2016-03)
- 3GPP TS 33.246 Security of Multimedia Broadcast/Multicast Service (MBMS) (Release 14) V14.0.0 (2016-12) (See Annex N)

3GPP SA4 WG

- 3GPP TS 26.179 Mission Critical Push To Talk; Codecs and media handling (Release 13) V13.2.0 (2016-09); V13.1.0 (2016-06); V13.0.0 (2016-03); V1.0.0 (2016-03); V0.2.0 (2016-03); V0.1.2 (2016-03); V0.1.1 (2016-03)

3GPP RAN 1 WG, RAN 2 WG

- 3GPP TR 36.746 Study on further enhancements to LTE Device to Device (D2D), UE to network relays for IoT (Internet of Things) and wearables (Release 14) V0.3.0 (2016-10); V0.2.1 (2016-10); V0.2.0 (2016-10); V0.1.1 (2016-10); V0.1.0 (2016-09); V0.0.1 (2016-09)
- 3GPP TR 36.750 Study on Voice and Video Enhancement for LTE (Release 14) V14.0.0 (2016-10); V1.0.0 (2016-09); V0.4.0 (2016-09); V0.3.1 (2016-09); V0.2.1 (2016-09); V0.2.0 (2016-06); V0.1.1 (2016-06); V0.1.0 (2016-06); V0.0.2 (2016-06); V0.0.1 (2016-06)
- 3GPP TR 36.785 Vehicle to Vehicle (V2V) services based on LTE sidelink; User Equipment (UE) radio transmission and reception (Release 14) V14.0.0 (2016-10); V1.0.0 (2016-09); V0.2.0 (2016-09); V0.0.1 (2016-09)
- 3GPP TR 36.786 V2X Services based on LTE; User Equipment (UE) radio transmission and reception (Release 14) V0.1.0 (2016-11)

- 3GPP TR 36.885 Study on LTE-based V2X Services (Release 14) V14.0.0 (2016-07); V2.0.0 (2016-06); V1.0.0 (2016-03); V0.5.0 (2016-03)
- 3GPP TS 36.300 Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (Release 14) V14.1.0 (2016-12); V14.0.0 (2016-09); (Release 13) V13.6.0 (2016-12); V13.5.0 (2016-09); V13.4.0 (2016-07); V13.3.0 (2016-04);
- V13.2.0 (2016-01);
- 3GPP TS 36.331 Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification (Release 14) V14.1.0 (2016-12); V14.0.0 (2016-10); (Release 13) V13.3.0 (2016-10); V13.2.0 (2016-07); V13.1.0 (2016-04); V13.0.0 (2016-01)
- 3GPP TR 36.881 Study on latency reduction techniques for LTE (Release 14) V14.0.0 (2016-07); V0.8.0 (2016-06); V0.7.1 (2016-06); V.7.0 (2016-06); V0.6.1 (2016-06); V0.6.0 (2016-03); V0.5.2 (2016-03); V0.5.1(2016-03)
- 3GPP TR 38.801 Study on New Radio Access Technology: Radio Access Architecture and Interfaces V1.0.0 (2016-12); V.7.0 (2016-12); V0.6.1 (2016-12); V0.6.0 (2016-12); V0.5.0 (2016-12); V0.4.0 (2016-09); V0.3.0 (2016-09)
- 3GPP TR 38.802 Study on New Radio Access Technology Physical Layer Aspects (Release 14) V1.0.0 (2016-11); V0.3.2-V0.2.0 (2016-11); V0.1.0-V0.0.1 (2016-09)
- 3GPP TR 38.803 TR for Study on New Radio Access Technology RF and co-existence aspects (Release 14) V1.0.0 (2016-12); V0.0.1 (2016-12)
- 3GPP TR 38.804 TR for Study on New Radio Access Technology Radio Interface Protocol Aspects (Release 14) V0.4.0, V0.3.1 (2016-12); V0.3.0, V0.2.1 (2016-09); V0.2.0-V0.0.1 (2016-09)
- 3GPP TR 38.912 TR Study on New Radio (NR) Access Technology (Release 14) V0.0.2 (2016-09); V0.0.1, (2016-06)
- 3GPP TS 36.302 Evolved Universal Terrestrial Radio Access (E-UTRA); Services provided by the physical layer (Release 14) V14.1.0 (2016-12); V14.0.0 (2016-09); (Release 13) V13.4.0 (2016-12); V13.3.0 (2016-09)

3GPP CT1 WG

- 3GPP TS 24.301 Non-Access-Stratum (NAS) protocol for Evolved Packet System (EPS); Stage 3 (Release 14) V14.2.0 (2016-12); V14.1.0 (2016-09); V14.0.1, V14.0.0 (2016-06); (Release 13) V13.8.0 (2016-12); V13.7.0 (2016-09); V13.6.1, V13.6.0 (2016-06); V13.5.0 (2016-03)
- 3GPP TR 24.980 Recommended Minimum Requirements for support of MCPTT Service over the Gm reference point (Release 13) V13.2.0 (2016-09): V13.1.0 (2016-06); V13.0.1 (2016-03); V13.0.0 (2016-03)
- 3GPP TS 24.333 Proximity-services (ProSe) Management Objects (MO) (Release 13) V13.4.0 (2016-09): V13.3.0 (2016-06); V13.2.0 (2016-03)
- 3GPP TS 24.334 Proximity-services (ProSe) User Equipment (UE) to ProSe function protocol aspects; Stage 3 (Release 14) V14.0.0 (2016-12) (Release 13) V13.6.1 (2016-12); V13.6.0 (2016-09); V13.4.1, V13.4.0 (2016-06); V13.3.1 (2016-03); V13.3.0 (2016-03)
- 3GPP TS 24.379 Mission Critical Push To Talk (MCPTT) call control protocol specification (Release 14) V14.0.0 (2016-12); (Release 13) V13.3.0 (2016-12): V13.2.1 (2016-09): V13.2.0, V13.1.0 (2016-06); V13.0.1 (2016-03); V13.0.0 (2016-03)
- 3GPP TS 24.380 Mission Critical Push To Talk (MCPTT) floor control protocol specification (Release 14) V14.1.0 (2016-12), V14.0.0 (2016-09); (Release 13) V13.3.0 (2016-12); V13.2.0 (2016-09); V13.1.0 (2016-06); V13.0.2 (2016-03); V13.0.1 (2016-03); V13.0.0 (2016-03)
- 3GPP TS 24.381 Mission Critical Push To Talk (MCPTT) group management protocol specification (Release 13) V13.3.0 (2016-12): V13.2.0 (2016-09): V13.1.0 (2016-06); V13.0.1 (2016-03); V13.0.0 (2016-03)
- 3GPP TS 24.382 Mission Critical Push To Talk (MCPTT) identity management protocol specification (Release 13) V13.2.0 (2016-12); V13.1.0 (2016-06); V13.0.1 (2016-03); V13.0.0 (2016-03)
- 3GPP TS 24.383 Mission Critical Push To Talk (MCPTT) Management Object (MO) (Release 13) V13.3.0 (2016-12): V13.2.0 (2016-10); V13.1.0 (2016-06); V13.0.0 (2016-03)
- 3GPP TS 24.385 V2X services Management Object (MO)(Release 14) V1.0.0 (2017-01): V0.2.0 (2016-11); V0.1.0 (2016-10)
- 3GPP TS 24.386 User Equipment (UE) to V2X control function; protocol aspects; Stage 3 (Release 14) V1.0.0 (2017-01); V0.2.1, V0.2.0, V0.1.1 (2016-11); V0.1.0 (2016-10)

International Telecommunication Union (ITU)

ITU Radiocommunication Sector (ITU-R)

The ITU-R has been called the single most important international telecommunications and regulatory standardization body. Governments, businesses, and academia rely on ITU-R internationally vetted recommendations to plan, study, and design radio communication systems. ITS has a decades-long history of representing technical RF propagation issues that are critical to U.S. spectrum policy before ITU-R Study Group 3 "Radiowave Propagation." In the technical community, it is well known that ITS propagation work underlies a plurality of the propagation (P series) Recommendations—recommendations that guide the design and operation of radiocommunication systems and services and inform assessments of spectrum sharing worldwide.

ITU-R Study Group 3 (SG 3) drafts recommendations, reports, and handbooks that are reviewed and proposed for adoption as part of the international spectrum policy process. The output documents from ITU-R SG 3 form the technical bases for international spectrum policy decisions made at the World Radio Conference (WRC). ITS efforts within ITU-R SG 3 serve as a clear technical voice for U.S. federal and commercial spectrum interests before international spectrum policy is determined. After international spectrum policy is determined, ITS efforts within ITU-R SG 3 can provide the critical technical context and expertise to U.S. system designers adapting to the new spectrum environments.

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 submission to the State Department. ITS provided leadership to all four Working Parties at the 2016 ITU-R SG 3 meetings and authored four of the consensus contributions on the subjects of air-to-ground propagation, world refractivity mapping, and the effects of sunspot number recalculation. In 2016, ITS also led correspondence groups on building penetration loss and earth-to-air-to-space propagation.

ITS propagation models have been developed and standardized for the unique characteristics of different RF bands and electromagnetic environments. Elements of ITS-developed propagation models are found throughout the ITU-R SG 3 P series recommendations. The ITS IF-77 model, discussed on page 27, for instance, uniquely characterizes Earth-to-air, Earth-to-space, and air-to-space RF transmission.

Earth-to-Air-to-Space Propagation Modeling

IF-77 includes many of the radio wave phenomena that are unique to high-altitude conditions and are consequently required to predict the transmission losses and interference levels over Earth-to-air-to-space communication links. Few propagation models are appropriate for modeling propagation above 1000 m, such as propagation of aeronautical and satellite communication links. A simplified implementation of IF-77 appears as Recommendation ITU-R P.528, "Propagation curves for aeronautical mobile and radio-navigation services using the VHF, UHF, and SHF band." The high-altitude component of models such as IF-77 and P.528 is increasingly critical for spectrum sharing studies among satellite services and terrestrial broadband services.

For example, the recent AWS-3 auction in the U.S. was designed to promote sharing between incumbent federal satellite systems and new entrant broadband services. 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. Preliminary engineering sharing studies leading up to the auction contributed to development of the rules that will govern access to the band. ITU-R models provide a critical tool to determine interference potential and access protection strategies for incumbent satellite ground stations. In this regard, ITS is working within ITU-R SG 3 toward a more comprehensive high-altitude propagation model based on IF-77 and superseding the simple methods outlined in P.528. ITS spearheaded the adoption of Report P.2345 "Propagation model for Recommendation ITU-R P.528-3" and subsequent ITS draft revisions will serve to promote a more contemporary and accurate high-altitude propagation model for future international sharing studies. This effort will assure that the U.S. has the technical expertise to aid U.S. spectrum policy makers and that technical issues relating to new U.S. commercial shared spectrum services are addressed and resolved.

ITU Telecommunication Standardization Sector (ITU-T)

The ITU-T is preeminent in the small, but important area of standards for quality assessment in video and multimedia communications. ITS began contributing to ITU-T work on video quality measurement methods in 1994, expanding on a decade of contributions focused on voice quality and network performance. From 1994 to 2016, ITS engineers held leadership positions in the ITU-T including Rapporteur, Associate Rapporteur, Vice-Chairman, and Chairman. An ITS engineer also served as head of the U.S. Delegation to ITU-T Study Group 9 (SG9) for many of those years.

During that period, ITS was a major contributor to 45 ITU-T Recommendations on video/multimedia quality, six of them in FY 2016. In particular, Recommendation P.913, "Methods for the subjective assessment of video quality, audio quality and audiovisual quality of Internet video and distribution quality television in any environment" (2016) brought video subjective testing into the 21st century. Also of note, Recommendation J.144, "Objective perceptual video quality measurement techniques for digital cable television in the presence of a full reference "(2004) was the first international standard for objective measurement of video quality, and the ITS objective model in that standard (VQM) is still used today and is freely available from the ITS web site at https://www.its.bldrdoc.gov/resources/video-quality-research/software.aspx.

Arthur Webster of ITS (left) chairs a meeting of ITU-T SG9 alongside Vice-Chairmen Satoshi Miyaji of Japan and Wang Dong of China. Photo courtesy ITU.

Video Quality Experts Group (VQEG)

The Video Quality Experts Group (VQEG) performs technical validation that is a prerequisite to standardization. VQEG activities such as validation tests are documented in reports and submitted to relevant ITU Study Groups (.e.g., ITU-T SG9, ITU-T SG12, ITU-R WP6C), and other SDOs as appropriate. Several VQEG studies have resulted in ITU Recommendations.

VQEG brings together international experts from industry, academia, governments, and SDOs to develop improved methods to assess human perception of video quality. This means either human testing (subjective experiments) or computer algorithms (objective metrics). This field of study bridges the gap between the electronics of a video service and the end-user's opinions. ITS has provided substantial leadership to this collaborative effort for 20 years and continues to sponsor VQEG through leadership, e-mail reflectors, and web presence.

With the rapid advances in video technologies, VQEG has become an important venue for keeping abreast of the most current R&D related to video quality assessment. Similarly to other the NTIA-convened multistakeholder processes, VQEG provides an international forum for industry experts and researchers to share state-of-the art knowledge and collaborate to develop solutions. Interactive discussions and open collaborations are encouraged so that the final solutions meet all industry needs.

In FY 2016, ITS led an important shift within VQEG to focus more on technical presentations and collaborative research. This allows people to combine state-of-the-art research and understand emerging video technologies like immersive media (e.g., virtual reality, augmented reality), high dynamic range (HDR) video, ultra-high definition video (e.g., 4K, 8K), and Advanced Display Stream Compression (Adv-DSC). For example, high resolution mobile devices will soon implement visually lossless transmission between the processor and display. The goal is an industry-wide standard that reduces the power envelope, meets severe EMI constraints, provides low latency, and ensures visually lossless transmissions. The discussions within VQEG centered on how to assess whether proposed algorithms are actually visually lossless.

VQEG is conducting a joint project with ITU Study Group 12 to validate and standardize objective models for adaptive bit rate streaming services like YouTube, Vimeo, Amazon Video, and Netflix. For adaptive streaming, the quality experienced by the end user is affected by a network feedback loop. The video provider adaptively changes the video bit rate, resolution, and frame rate in response to network conditions. The networking challenge is to understand in real-time the quality impact of that adaptation, expressed in terms of the user's experience.

Margaret Pinson (third from left, front row) and Arthur Webster of ITS co-chair VQEG along with Kjell Brunnström (third from left, back row) of RISE Acreo. This group photo was taken at the VQEG Meeting in San Diego, CA, February 29 to March 4, 2016, which was hosted by Qualcomm. Photo courtesy VQEG.

ITS Staff Participation in Standards Bodies in FY 2016

At a Glance: FY 2016 ITS SDO Participation
38 positions on 30 different bodies in 7 SDOs,
including 14 Chair/Co-chair/Vice Chair positions

- **Kenneth Baker:** Member, IEEE Standards Association WG802.22 - Wireless Regional Area Networks Working Group, Project P802.22.3 - Standard for Spectrum Characterization and Occupancy Sensing
- **Christopher J. Behm:** U.S. Chair of International Telecommunication Union Radiocommunication Sector (ITU-R) Study Group 3 (SG 3, Radio wave 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) .
- **John E. Carroll:** U.S. 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).
- **Michael Cotton:** Member, IEEE Standards Association WG802.22 - Wireless Regional Area Networks Working Group, Project P802.22.3 - Standard for Spectrum Characterization and Occupancy Sensing
- **George Engelbrecht:** U.S. Chair ITU-R SG 3 WP 3J (Propagation Fundamentals)
- **Paul M. McKenna:** International Chair and U.S. Chair of ITU-R SG 3 WP 3K (Point-To-Area Propagation). International Vice-Chair ITU-R SG 3.
- **Margaret H. Pinson:** U.S. Representative to ITU-T SG 9 (Broadband Cable and TV), ITU-R SG6 WP 6C. Member of ITU-T SG9 Intersector Rapporteur Group Audiovisual Media Accessibility (IRG-AVA). Associate Rapporteur 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). Co-chair of the Video Quality Experts Group (VQEG) and of VQEG's Independent Lab Group (ILG) and Audiovisual HD Quality (AVHD) group.
- **Patricia J. Raush:** U.S. Co-chair of ITU-R SG 3 WP 3J.
- **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 Group 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.
- **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. Co-chair of VQEG. Member of the U.S. Delegations to the ITU-T Study Group 16 (Multimedia), 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 Standardization Committee for Vocabulary (SCV).

Conferences, Workshops, and Symposia

ISART 2016

A record turnout of about 160 scientists, engineers, mathematicians, policy experts and other participants representing government agencies, academic institutions, and industry gathered in Westminster, Colorado, August 1-3, 2016, for the 15th International Symposium on Advanced Radio Technologies (ISART). The topic of ISART 2016 was Spectrum Forensics, an exciting new field of spectrum research aimed at providing novel insights on ways to address radio signal interference. As more and more spectrum users are pressed to operate in shared bands, effective spectrum sharing will require an entirely new legal and regulatory environment, as well as sophisticated technologies that can reliably 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. Spectrum forensics will help build and maintain good fences to make good neighbors. Advances in this area promise to bring improvements to how spectrum is managed, in particular supporting efforts to efficiently and effectively accommodate the constantly increasing demand for use of this critical, limited, and already congested resource.

ISART 2016 was sponsored by the Center for Advanced Communications, a joint effort between NTIA's Institute for Telecommunication Sciences (ITS) and the NIST's Communications Technology Laboratory (CTL), and pre-symposium tours of both labs were well-attended. A tutorial on civil and criminal spectrum interference investigations and enforcement actions kicked off the Symposium discussions. Former and current Federal Communications Commission staffers discussed the technical aspects of identifying sources of interference and the policy and legal challenges of enforcement. They emphasized the value of technical cooperation between users sharing spectrum to rapidly mitigate interference.

In his keynote address, Dr. Greg Shannon, assistant director of cybersecurity for the White House Office of Science and Technology Policy (OSTP) and Chief Scientist at the CERT Division at Carnegie Mellon University's Software Engineering Institute, spoke of the challenges of cybersecurity and the Federal Cybersecurity R&D Strategic Plan released in February of 2016.[1] The Plan specifically called out the need to address the cybersecurity of emerging wireless technologies, including the Internet of Things (IoT) and mobile devices.

Panelists also discussed legal and policy issues, spectrum monitoring, applicable technologies and standards, digital forensics, and data analytics. One of the biggest themes to emerge from the discussions was the inevitable rise in the "noise floor" (the measure of the unwanted signals) with so many more wireless devices in use. In the past, spectrum users have focused on trying to eliminate such interference. Julius Knapp, chief of the FCC's Office of Engineering and Technology, however, spoke of moving from the idea that interference can be eliminated to an understanding that receivers will have to begin to bear some responsibility for robustness and the management of noise in their environment.

Another theme was the need for rapid and reliable investigation into the impact of the proliferation of devices attempting to operate simultaneously in the same or adjacent bands, from both a scientific and a policy perspective. Panelists discussed not only how to predict aggregate interference from many devices and protect against it, but also who bears responsibility for it when it occurs. There was clear agreement on the need to move forward collaboratively in order to keep up with the pace of technical evolution. Transparency, trust, honest brokers, and clear rules are prerequisites to real-time interference mitigation.

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1 Executive Office of the President, National Science and Technology Council, Networking and Information Technology Research and Development Program, *Federal Cybersecurity Research and Development Strategic Plan*, Feb. 2016. Accessed https://www.nitrd.gov/cybersecurity/publications/2016_Federal_Cybersecurity_Research_and_Development_Strategic_Plan.pdf June 30, 2017

At ISART 2016, (left to right) Rebecca Dorch led the opening tutorial on August 1, Ken Baker moderated the panel on Spectrum Monitoring on August 2, and Keith Gremban delivered the closing address on August 3. Photos by Shelby Tisinai and Lilli Segre.

By the end of the symposium, it was clear that spectrum forensics is a broad, deep area that requires contributions from many different disciplines. While forensic science has a legal definition, specific courses of study, and certifications in many physical science disciplines, there is as yet no such structural framework for spectrum forensics—though ISART 2016 moved us a step closer to defining one. Many of the panelists and speakers presented maturing technologies that are important components of the spectrum forensics space. The challenge to the community for the future will be to integrate all the pieces into end-to-end systems that support spectrum monitoring, investigation, and enforcement.

Propagation Measurement Workshop Webinars

On July 7, 14, and 28 and August 11, 2016 ITS hosted a series of Propagation Measurement Workshop Webinars to explore the development of draft best practices for propagation measurements to assess the impact of losses caused by clutter on estimates of aggregate interference to incumbent systems in the 3.5 GHz band. The need for such best practices surfaced as a number of different organizations began executing propagation loss measurements in the band to assess the impact of clutter (man-made structures and foliage) on estimates of pathloss for use in aggregate interference models in preparation for FCC rulemaking to open the 3.5 GHz band to sharing. This is a new research question and no standardized best practices exist for this type of measurement. The objective of these initial virtual meetings was to bring together researchers from government, academia, and industry to discuss key requirements for measurement system design and validation. ITS hosted a series of four Webinars, sponsored by WInnForum, which included a kick-off meeting, a system architecture meeting, a propagation modelling meeting, and an uncertainty/current best practices meeting.

2016 IEEE Military Communications Conference (MILCOM)

Reprising a tradition that had lapsed for a decade, ITS hosted an NTIA booth at MILCOM 2016 November 1-3, 2016. ITS engineer Chriss Hammerschmidt presented a paper on “Extracting Clutter Metrics From Mobile Propagation Measurements in the 1755-1780 MHz Band” that describes spectrum measurements ITS took during 2015 to inform and validate new radio wave propagation prediction models (see page 32). ITS has been working to better understand how to factor in the effects of clutter (man-made structures and vegetation) when analyzing and predicting the behavior of radio waves (see story on *Integrated Terrain plus Clutter Propagation Modeling* on page 27).

The topic is of special interest to military communications professionals because frequency bands where they operate many critical communications systems are now being opened to sharing, and MILCOM is the premier international conference for military communications. ITS Director Dr. Keith Gremban moderated a Technical Panel on *Spectrum Sharing—Issues and Approaches*, where some of the challenges of federal/non-federal spectrum sharing were discussed. Dr. Gremban also chaired a Technical Paper Session on November 1 on *MIMO and Directional Networking*, techniques that can help prevent interference among communications services sharing spectrum.

Publications and Presentations

NTIA Publications

Frank H. Sanders, Edward F. Drocella Jr., Robert L. Sole, "Using On-Shore Detected Radar Signal Power for Interference Protection of Off Shore Radar Receivers," NTIA Technical Report TR-16-521, March 2016. Available http://www.its.bldrdoc.gov/publications/2828.aspx.

A spectrum sharing scheme is considered in which ship-based radar stations are operating in the same spectrum band as on-shore communication transmitters, and in which the communication transmitters will cause interference to the radar receivers when interference, I, to noise, N, ratios in the radar receivers exceed a given level (e.g., I/N >= -6 dB). The problem is that on-shore environmental sensing capability (ESC) monitors need to determine whether interference is occurring at off-shore radar receivers based only on information from the radars' transmitters, with no information available from the victim radar receivers themselves. We describe an on-shore monitoring approach in which the principle of reciprocal propagation between the directions of radar-to-ESC and ESC-to-radar provides a simple go/no-go (single-bit) output from the ESCs to an associated Spectrum Access System (SAS) controlling the communication network, to perform on-shore channel changes for protection of the off-shore radar receivers. The ESC station outputs are based on a power-detection threshold of radar signals at the ESCs (e.g., -64 dBm peak-detected power in 1 MHz bandwidth). Examples are provided in which ship-based radar receivers are protected by a simple algorithm applied to a group of on-shore ESCs and a SAS controller for the terrestrial communication network channel frequencies.

> *"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]

Outside Publications

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.

The new video coding standard, MPEG-H Part 2 High Efficiency Video Coding (HEVC) or H.265, was developed to be roughly twice as efficient as H.264/AVC—meaning H.265/HEVC could deliver the same quality as H.264/AVC using roughly half the bitrate. In this paper we describe a subjective experiment designed to test this claim. We present an experiment using 20 different 1080p 29.97 fps scenes and 12 impairment levels spanning MPEG-2, H.264/AVC and H.265/HEVC. Additionally we compare the results obtained from the subjective assessment to quality estimates from two objective metrics: VQM and PSNR. Our subjective results show that H.265/HEVC can deliver the same quality at half the bitrate compared

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

to H.264/AVC and can perform better at one quarter the bitrate compared to MPEG-2 in many, but not all, situations. For all 20 scenes coded with H.265/HEVC at 4 Mbps mean opinion scores span 38% of the subjective scale, which indicates the importance of scene selection. Objective quality estimations of HEVC have a low correlation with subjective results (0.60 for VQM, 0.64 for PSNR).

Stephen 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, October 19, 2015. Available http://www.its.bldrdoc.gov/publications/2813.aspx.**

The separation of acoustic signals is often accomplished through subtractive decompositions of frequency-domain representations. This is typically enabled by the zero phase approximation or the uncorrelated signals approximation but both of these are very coarse approximations in the mathematical sense. We investigate this disconnect between what works in practice and what is mathematically correct. We conduct a broad search for a domain where the additivity of spectral magnitudes is best satisfied. We apply objective estimators to time-domain reconstructions to characterize the true auditory impact of the magnitude additivity approximation. Our results show the auditory impacts of additivity approximations and allow comparison with the impact of using mixture phase and exact magnitudes in the time-domain reconstruction.

Lucjan Janowski and Margaret H. Pinson, "The Accuracy of Subjects in a Quality Experiment: A Theoretical Subject Model," ***IEEE Transactions on Multimedia,*** **vol. 17, no. 12, December 2015, pp 2210-2224. Available http://www.its.bldrdoc.gov/publications/2814.aspx.**

How accurately are people able to use the absolute category rating (ACR) 5-level scale? Put another way, how repeatable are an individual subject's scores? Several subjective experiments have asked subjects to rate the same sequences a couple of times. Analyses indicate that none of the subjects exactly repeated their prior scores for these sequences. We would like to better understand this imperfection. This paper uses ACR subjective video quality tests to explore the precision of subjective ratings. To make formal measurements possible, we propose a theoretical subject model that is the main contribution of this paper. The proposed subject model indicates three major factors that 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. There are three key consequences. First, subject scoring behavior includes a random component that spans approximately half of the rating scale. Second, the sensitivity and accuracy of most subjective analyses can be improved if the subject scores are normalized by removing subject bias. Third, to some extent, multiple subjects can be replaced with a single subject who rates each sequence multiple times.

Presentations

- Stephen D. Voran, "Exploration of the Additivity Approximation for Spectral Magnitudes," Poster Session 1: Audio Models, Music, Classification, Source Separation, IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA), New Paltz, NY, October 19, 2015.
- Keith Gremban, Technical Program Session Chair, Multicast and Software Defined Networking, IEEE Military Communications Conference (MILCOM 2015), October 26, 2015, Tampa, FL.
- Keith Gremban, Technical Program Session Chair, Channel Modeling and Measurement, IEEE Military Communications Conference (MILCOM 2015), October 27, 2015, Tampa, FL.
- Andrew Catellier, Using U.S. DoC Speech Intelligibility Testing Data to Make Accurate Codec Performance Comparisons, 3GPP TSG SA4#86 meeting, October 26–30, 2015, San Jose del Cabo, Mexico.
- Robert T Johnk, Invited Panelist, "In-Building, HetNets and Towers: How Do They All Fit Together?" IWCE's Urgent Communications Webinar, November 4, 2015.

- Mark McFarland, Co-chair, Propagation Modeling and Measurements Session, International Union of Radio Science (URSI) National Radio Science Meeting (NRSM), Boulder, CO, January 6-9, 2016.
- Mark McFarland, Bob Johnk, and Jaydee Griffith, "In-Building Path Loss Model Analysis: Testing Assumptions and Identifying Outliers in Propagation Models." International Union of Radio Science (URSI) National Radio Science Meeting (NRSM), Boulder, CO, January 6-9, 2016.
- Teresa Rusyn and Linh Vu presented "GPS Signal Strength Measurements," International Union of Radio Science (URSI) National Radio Science Meeting (NRSM), Boulder, CO, January 6-9, 2016.
- Joel Dumke, Nicholas Kent, and Dylan Hicks, "Modeling Aggregate Interference from LTE Systems," International Union of Radio Science (URSI) National Radio Science Meeting (NRSM), Boulder, CO, January 6-9, 2016.
- Nicholas DeMinco "A Generalized Method for Evaluating Interference in Spectrum Sharing and Management Applications," International Union of Radio Science (URSI) National Radio Science Meeting (NRSM), Boulder, CO, January 6-9, 2016.
- Michael Cotton, On-line presentation to engineers from Google on 3.5 GHz maritime radar occupancy data acquired in Virginia Beach (9/2014–8/2015) and San Diego (7/2015–8/2015), January 20, 2016.
- Michael Cotton, "3.5 GHz Maritime Radar Occupancy Data Acquired in Virginia Beach (9/2014–8/2015) and San Diego (7/2015–8/2015)," Wireless Innovation Forum, Spectrum Sharing Face-to-Face Meeting, January 28, 2016, Washington, D.C.
- Andrew Thiessen, with Dean Prochaska of FirstNet, "3GPP Mission-Critical Push-to-Talk Standards Update," International Wireless Communications Expo (IWCE), Las Vegas, NV, March 22, 2016
- Eric Nelson, "Spectrum Sharing: System Lifecycle Engineering Considerations," Dynamic Spectrum Sharing Summit International Wireless Communications Expo (IWCE), Las Vegas, NV, March 22, 2016.
- Michael Cotton, "An Overview of the NTIA/NIST Spectrum Monitoring Pilot Program," Key Projects Panel, National Science Foundation Workshop on Spectrum Measurements Infrastructure, Illinois Institute of Technology, Chicago, IL, April 6–7, 2016.
- Michael Cotton, Focus Group Co-moderator, "Define and prioritize requirements for future measurements systems and architectures," National Science Foundation Workshop on Spectrum Measurements Infrastructure, Illinois Institute of Technology, Chicago, IL, April 6–7, 2016.
- Rebecca Dorch and Michael Cotton, Invited Participants, Wireless Spectrum Research and Development (WSRD) Workshop VIII: Wireless Spectrum Sharing: Enforcement Frameworks, Technology, and R&D, Washington DC, May 5, 2016.
- Kristen Davis, "1695-1710 MHz Radio Frequency Coordination Portal," presentation via teleconference, AWS-3 Transition Planning Working Group (TWPG), May 26, 2016.
- Keith Gremban, "Strategic Planning for Wireless Innovation," National Science Foundation Radio Frequency Spectrum Management Workshop, Department of Electrical and Computer Engineering, College of Engineering, University of Puerto Rico at Mayagüez (UPRM), Mayaguez, Puerto Rico, May 26, 2016.
- Andrew Thiessen, Panelist: "Mission Critical Voice: Bridging the Gap and Advancing the Future," 2016 Public Safety Broadband Stakeholder Meeting, San Diego, CA, June 7, 2016.
- Stephen D. Voran, "Snapshot: Public Safety Audio Quality Research—Assessing Codecs for Mission Critical Voice," 2016 Public Safety Broadband Stakeholder Meeting, San Diego, CA, June 7, 2016.
- Andrew Thiessen, "Snapshot: LMR to LTE Standards Update," 2016 Public Safety Broadband Stakeholder Meeting, San Diego, CA, June 8, 2016.
- Robert T. Johnk, "In-building Coverage Measurements Snapshot: Practical Techniques for Public Safety," 2016 Public Safety Broadband Stakeholder Meeting, San Diego, CA, June 9, 2016.
- Andrew Catellier and Rebecca Dorch, Panelists "Policy and Infrastructure Enablers for Smart Cities," Global City Teams Challenge Expo, to Austin, TX, June 12-15, 2016.

- Chriss Hammerschmidt, Eric Nelson, Paul McKenna, a series of four Workshop Webinars on Propagation Measurements Overview, Design of a Measurement System, Propagation Models, and Uncertainties and Guidelines, July 7, 14 and 28 and August 11, 2016.
- Rebecca Dorch, Moderator, Tutorial on the Legal Process of Spectrum Forensics: Civil & Criminal Case Studies, International Symposium on Advanced Radio Technologies (ISART), Boulder, CO, August 1, 2016.
- Patricia J. Raush, Welcome Address, International Symposium on Advanced Radio Technologies (ISART), Boulder, CO, August 2, 2016.
- Eric Nelson, Moderator, Panel: Policy Considerations, International Symposium on Advanced Radio Technologies (ISART), Boulder, CO, August 2, 2016.
- Michael Cotton, with Mudumbai Ranganathan of NIST, "CAC Spectrum Monitoring," International Symposium on Advanced Radio Technologies (ISART), Boulder, CO, August 2, 2016.
- Kenneth Baker, Moderator, Panel: Spectrum Monitoring – Purposeful Data Collection, International Symposium on Advanced Radio Technologies (ISART), Boulder, CO, August 2, 2016.
- Keith Gremban, Closing Address, International Symposium on Advanced Radio Technologies (ISART), Boulder, CO, August 3, 2016.
- Julie Kub and Billy Kozma, IF-77 Propagation Model Refresh Project, Interdepartment Radio Advisory Committee (IRAC), Washington DC, August 9, 2016.
- Douglas J. Anderson, "A Cost-Efficient, Field-Ready Sensor to Detect and Decode LTE FDD Downlink at Low Signal Levels," GNU Radio Conference (GRCon) 2016, Boulder, CO, on September 14, 2016.
- Frank H. Sanders, "Radio Spectrum Monitoring Techniques and Procedures," United States Telecommunications Training Institute (USTTI), Washington DC, September 23, 2016.
- Andrew Thiessen, "3GPP International Standards Update," National Public Safety Telecommunications Council (NPSTC) Full Meeting, Washington, D.C., September 28, 2016.

Software and Data

ITS makes several software and data tools available via open-source download from its public web site.

Propagation Prediction: The majority of software/data downloads (about 800 each year) from the ITS web site are for propagation prediction tools. The DoC labs have long been world leaders in the development of models and methods for accurate prediction of radio propagation. Propagation prediction algorithms are freely shared through publication, and ITS's predecessor, the Central Radio Propagation Laboratory (CRPL) was one of the first laboratories in the world to develop software to predict propagation for planned communications systems through input of specific parameters to these algorithms. ITS continues to make those software implementations available and to develop new implementations that take advantage of advances in computing. Several standard data sets that can be used to test and validate propagation prediction models are also available.

Audio Quality Testing: In FY 2013, ITS developed an 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 (Pearson correlations of .95–.99). ABC-MRT tools and MRT databases are available for download through the ITS web site, as well as a variety of other sample clips for audio quality testing.

Video Quality Measurement Software: 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 In FY 2016, 496 users downloaded the VQM software. The Web-Enabled Subjective Test (WEST) software package facilitates gathering subjective testing data from multiple locations and multiple portable or computing devices. This software is also freely available for download.

ITS Projects in FY 2016

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. Fifty-four 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 2016.

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,jallen@ntia.doc.gov

Ball Aerospace

Use the Table Mountain Field Site as a field location to safely test and demonstrate the functionality of new lidar systems during product development.

Project Leader: J. Wayde Allen, (303) 497 5871, jallen@ntia.doc.gov

E&S International

Test the responses of new NOAA Weather Radio (NWR) receivers under development to determine whether the receivers comply with the standards set down in CEA 2009.

Project Leader: Raian F. Kaiser (303) 497 5491, rkaiser@ntia.doc.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, jallen@ntia.doc.gov

Halo Smart Labs

Test the responses of new NOAA Weather Radio (NWR) receivers under development to determine whether the receivers comply with the standards set down in CEA 2009.

Project Leader: Raian F. Kaiser (303) 497 5491, rkaiser@ntia.doc.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, jallen@ntia.doc.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, jallen@ntia.doc.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@ntia.doc.gov

Government Projects

NTIA/ITS 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@ntia.doc.gov

Aggregate Emission Modeling

Accurately predict the distribution of interference power generated by an entire LTE network using open-source Monte Carlo simulation software. The simulations should produce CDFs that are useful for planning and in good agreement with measured data.

Project Leader: Joel Dumke, (303) 497 4418, jdumke@ntia.doc.gov

IPC Simulation

Develop new methods for determining receiver IPC by replacing and enhancing IPC measurements with computer simulation. Verify the simulation by comparison to measurements.

Project Leader: Robert J. Achatz, (303) 497 3498, rachatz@ntia.doc.gov

Open Propagation Architecture Toolkit

Develop an open standard for a modular propagation modeling toolkit.

Project Leader: Kristen Davis, (303) 497-4619, kdavis@ntia.doc.gov

Spectrum Measurement System Analysis

Using statistical quality control techniques, determine the amount of variability in a given measurement that is due to the measurement system itself.

Project Leader: Mark McFarland, (303) 497 4132, mmcfarland@ntia.doc.gov

GPS Propagation Measurements

Measure signal strength of a single GPS satellite link at the Table Mountain Radio Quiet Zone Facility. Collect weather and space weather data correlating to the times of the signal data collection.

Project Leader: J. Wayde Allen, (303) 497 5871, jallen@ntia.doc.gov

CMMI

Achieve Level 2 Capability Maturity Model Integration (CMMI) to improve project management practices and standardize business processes using a continuous integration approach and regularly soliciting employee feedback for process improvement.

Project Leader: Kristen Davis, (303) 497-4619, kdavis@ntia.doc.gov

Direction Finding (DF)

Investigate DF techniques to support geolocation efforts in spectrum enforcement, including time-difference of arrival (TDOA), received signal strength, and Watson-Watt Adcock, and Correlative Interferometry.

Project Leader: Heather Ottke, (303) 497-6753, hottke@ntia.doc.gov

Propagation Modeling Upgrade & Validation

Develop enhanced propagation measurements, modeling, and large-scale computational capabilities.

Project Leader: Robert T. Johnk, (303) 497 3737, rjohnk@ntia.doc.gov

ITU 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@ntia.doc.gov

Video Quality Characterization

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@ntia.doc.gov

IoT Laboratory Development

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: Andrew A. Catellier, (303) 497 4951, acatellier@ntia.doc.gov

Systems Modeling and Simulation

Investigate advancing Institute capabilities for systems modeling and simulation.

Project Leader: Randall S. Bloomfield, (303) 497 5489, rbloomfield@ntia.doc.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@ntia.doc.gov

RSMS Modernization

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, gesanders@ntia.doc.gov

Precision Geolocation

Upgrade geolocation information in spectrum measurement systems to increase positional accuracy to within 5 cm.

Project Leader: Anna Paulson, (303) 497 7891, apaulson@ntia.doc.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, jallen@ntia.doc.gov

Spectrum Monitoring

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@ntia.doc.gov

NTIA/OSM Support Projects

5 GHz Case Study to Support CSMAC

Explore potential DFS issues in new bands at 5 GHz that are being considered for expanded sharing.

Project Leader: Frank H. Sanders, (303) 497-7600, fsanders@ntia.doc.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@ntia.doc.gov

IF-77 Propagation Model Updates, Phase I

"Wrap" the ITS IF-77 air-to-ground propagation model's legacy Fortran code in a container that will run in a modern computing environment so that OSM can to interoperate and integrate the model into their current software solutions for air-to-ground propagation modeling.

Project Leader: William Kozma, (303) 497 6082, wkozma@ntia.doc.gov

Interference Protection Criteria Simulation

Develop new methods for determining receiver IPC by replacing and enhancing IPC measurements with computer simulation. Verify the simulation by comparison to measurements.

Project Leader: Robert J. Achatz, (303) 497 3498, rachatz@ntia.doc.gov

Propagation Modeling Support

Assist OSM in achieving the President's 500 MHz goal through sharing/compatibility analyses, exercising or developing propagation models as needed.

Project Leader: Paul M. McKenna, (303) 497-3474, pmckenna@ntia.doc.gov

Propagation Engineering Support

Provide propagation engineering technical support to NTIA/OSM in response to propagation questions and inputs from NTIA/OSM, the IRAC, the FCC, other federal agencies, and the private sector.

Project Leader: Paul M. McKenna, (303) 497-3474, pmckenna@ntia.doc.gov

Radar Engineering Support

Provide engineering support to NTIA/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@ntia.doc.gov

Radio Frequency Spectrum Coordination Portal

Support NTIA/OSM in developing and deploying the Radio Frequency Coordination Portal (RFCP) to coordinate the use of the 1695-1710 MHz band between federal and non-federal users.

Project Leader: Kristen Davis, (303) 497-4619, kdavis@ntia.doc.gov

Spectrum Sharing System Simulation Development

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

Project Leader: Robert J. Achatz, (303) 497 3498, rachatz@ntia.doc.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@ntia.doc.gov

Other Agency Projects

Department of Commerce (DoC)

DoC / 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@ntia.doc.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@ntia.doc.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@ntia.doc.gov

DoC / National Institute of Standards and Technology / Communications Technology Laboratory

AWS-3 Out-of-Band Emissions Measurements

Use the core hardware and software of the RSMS-4 to perform emission spectrum measurements on LTE emitters as part of an electromagnetic compatibility study for future band sharing at 1.7 GHz between government telemetry links and new AWS-3 transmitters.

Project Leader: Brent L. Bedford, (303) 497-5288, bbedford@ntia.doc.gov

FirstNet 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@ntia.doc.gov

Public Safety Communications Research

Provide applied science and engineering expertise to advance telecommunications interoperability and information sharing among local, state, federal, tribal, and international Justice, Public Safety, Homeland Security agencies.

Project Leader: Andrew P. Thiessen, (303) 497-4427, athiessen@ntia.doc.gov

Millimeter Wave Channel Sounder Measurements

Assist in the configuration and verification of a millimeter wave radio propagation measurement system for both indoor and outdoor environments operating at 28, 60, 71-76, 81-86 GHz.

Project Leader: Yeh Lo, (303) 497-3393, ylo@ntia.doc.gov

DoC / National Oceanic and Atmospheric Administration

Radio Frequency Spectrum Coordination Portal

Support NOAA in developing and deploying the Radio Frequency Coordination Portal (RFCP) to coordinate the use of the 1695-1710 MHz band between federal and non-federal users.

Project Leader: Kristen Davis, (303) 497-4619, kdavis@ntia.doc.gov

DoC / National Oceanic and Atmospheric Administration / National Weather Service

National Weather Services Propagation Modeling Website (NWS PMW)

Develop and enhance the Propagation Modeling Website, a web-based multipurpose GIS propagation modeling tool, used 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: Mike Chang, (303) 497-4220, mchang@ntia.doc.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@ntia.doc.gov

Department of Defense (DoD)

DoD / Defense Advanced Research Projects Agency (DARPA)

Tactical Encryption & Key Management Workshop

Organize a stakeholder workshop to explore solutions to the problem of how to dynamically key and re-key different groups with varying levels of access and for varying lengths of time using existing infrastructure or over an ad hoc network which is reliable and user-friendly.

Project Leader: Joseph Parks, (303) 497-5865, jparks@ntia.doc.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.

Project Leader: Chriss Hammerschmidt, (303) 497 5958, chammerschmidt@ntia.doc.gov

DoD / Joint Warfare Analysis Center (JWAC)

Propagation Modeling Website (JWAC PMW)

Expand the current Propagation Modeling Website, a web-based multipurpose GIS propagation modeling tool, by enhancing the current capability, adding in new features, and incorporating new cutting-edge ITS propagation models.

Project Leader: Doug Boulware, (303) 497-4417, dboulware@ntia.doc.gov

DoD / U.S. Air Force

Radio Frequency Spectrum Coordination Portal

Support the U.S. Air Force in developing and deploying the Radio Frequency Coordination Portal (RFCP) to coordinate the use of the 1695-1710 MHz band between federal and non-federal users.

Project Leader: Kristen Davis, (303) 497-4619, kdavis@ntia.doc.gov

DoD / U.S. Army

Propagation Modeling Website (U.S. Army First IO Command PMW)

Enhance the GIS functionality of PMW to include color-coding of radio transmitters on a map based on frequency range, geographic selection of an analysis area, and pin clustering to improve map display.

Project Leader: Kristen Davis, (303) 497-4619, kdavis@ntia.doc.gov

Radio Frequency Spectrum Coordination Portal

Support the U.S. Army in developing and deploying the Radio Frequency Coordination Portal (RFCP) to coordinate the use of the 1695-1710 MHz band between federal and non-federal users.

Project Leader: Kristen Davis, (303) 497-4619, kdavis@ntia.doc.gov

DoD / U.S. Navy

Radio Frequency Spectrum Coordination Portal

Support the U.S. Navy in developing and deploying the Radio Frequency Coordination Portal (RFCP) to coordinate the use of the 1695-1710 MHz band between federal and non-federal users.

Project Leader: Kristen Davis, (303) 497-4619, kdavis@ntia.doc.gov

Department of Energy (DoE)

DoE / Sandia National Laboratories

ACES RSEC Measurements

Perform measurements of emissions from new radars under development to demonstrate compliance with the Radar Spectrum Emission Criteria (RSEC).

Project Leader: Frank H. Sanders, (303) 497-7600, fsanders@ntia.doc.gov

Department of Homeland Security (DHS)

DHS / Office for Interoperability and Compatibility

P25 CAP Test and Evaluation

Conduct scientific analyses, laboratory and field measurements, and test and evaluation activities to evaluate emerging public safety communications technologies, including in-building propagation and P25 CAP support.

Project Leader: Andrew P. Thiessen, (303) 497-4427, athiessen@ntia.doc.gov

Public Safety Audio and Video Quality

Conduct scientific analyses, laboratory and field measurements, and test and evaluation activities to evaluate emerging public safety communications technologies including voice and video information transfers.

Project Leader: Andrew P. Thiessen, (303) 497-4427, athiessen@ntia.doc.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@ntia.doc.gov

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@ntia.doc.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@ntia.doc.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@ntia.doc.gov

DHS / U.S. Coast Guard

Radar-to-Radar Interference Analysis

Perform EMC analyses and parametric studies of potential interference among marine radars operating in the same or adjacent bands. Develop recommended marine radar receiver selectivity standards to minimize interference from and define reasonable adjacent band/out-of-band emissions (OOBE) limits.

Project Leader: Robert J. Achatz, (303) 497 3498, rachatz@ntia.doc.gov

Department of the Interior

Radio Frequency Spectrum Coordination Portal

Support the Department of the Interior in developing and deploying the Radio Frequency Coordination Portal (RFCP) to coordinate the use of the 1695-1710 MHz band between federal and non-federal users.

Project Leader: Kristen Davis, (303) 497-4619, kdavis@ntia.doc.gov

Department of Transportation (DoT)

DoT / 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@ntia.doc.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.

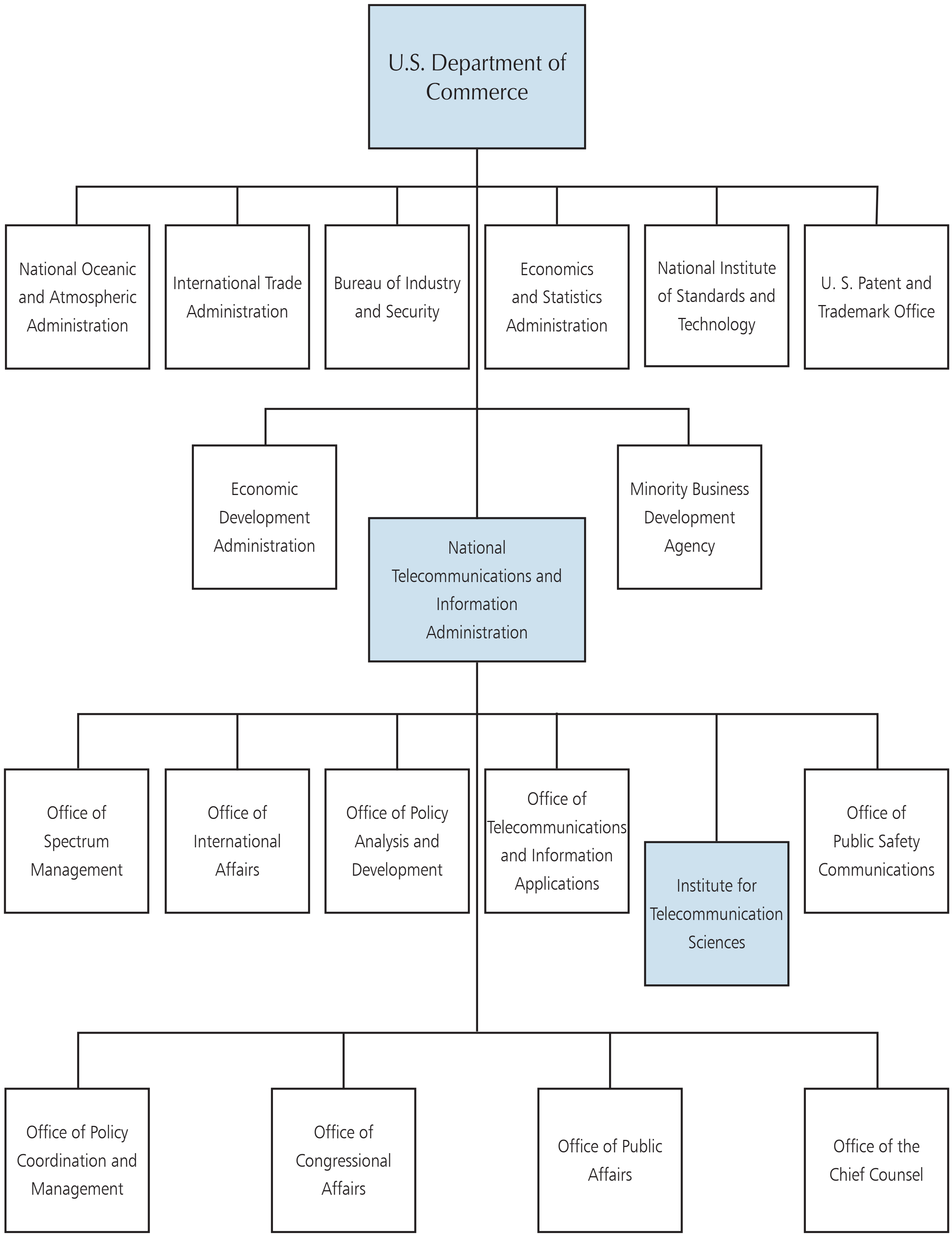
Project Leader: Nicholas DeMinco, (303) 497-3660, ndeminco@ntia.doc.gov

Abbreviations/Acronyms

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
AELTE	Aggregate Emissions from LTE
AMT	aeronautical mobile telemetry
ANSI	American National Standards Institute
ATIS	Alliance for Telecommunications Industry Solutions
AWS	Advanced Wireless Service
BRS	broadband radio service
CAC	Center for Advanced Communications
CDVL	Consumer Digital Video Library
CEA	Consumer Electronics Association
CMRT	crowdsourced MRT
CTL	Communications Technology Laboratory
CRADA	cooperative research and development agreement
CSMAC	Commerce Spectrum Management Advisory Committee
COW	cell-on-wheels
CW	continuous wave
dB	decibel
dBm	decibel-milliwatts
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
EMI	electromagnetic interference
eNB	eNodeB
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FFI	foreign function interface
FHWA	Federal Highway Administration
FirstNet	First Responder Network Authority
FLC	Federal Laboratory Consortium
FM	frequency modulation
FY	fiscal year
GETS	Government Emergency Telecommunications Service
GHz	gigahertz
GIS	geographic information system
GPS	global positioning system
HATS	head and torso simulator
HD	high definition
HF	high frequency
IAA	interagency agreement
IEEE	Institute of Electrical and Electronics Engineers
IF-77	ITS-FAA 1977 propagation model
IMU	inertial measurement unit
INR	interference power to noise power ratio
IoT	Internet of Things
IP	Internet protocol
IPC	interference protection criteria
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
LIDAR	light detection and ranging
LMR	land mobile radio
LMRT	lab MRT
LNA	low noise amplifier
LTE	Long Term Evolution
MF	medium frequency
MHz	megahertz
MoM	Method-of-Moments
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
NTIA	National Telecommunications and Information Administration
NWR	NOAA Weather Radio
NWS	National Weather Service
OATS	open-area test site
OEC	Office for Emergency Communications
OIC	Office of Interoperability and Compatibility
OOB	out-of-band
OPA	Open Propagation Architecture
OSM	Office of Spectrum Management
OTA	over-the-air
P25	Project 25
PMW	Propagation Modeling Website
PSCR	Public Safety Communications Research

PSD	power spectral density
QoE	quality of experience
QoS	quality of service
RAN	radio access networks
RF	radio frequency
RFCP	Radio Frequency Coordination Portal
RFIMS	Radio Frequency Interference Monitoring System
RSEC	Radar Spectrum Engineering Criteria
RSMS	Radio Spectrum Measurement System
SCTE	Society of Cable Telecommunications Engineers
SDO	standards development organization
SDR	software defined radio
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
U.S.	United States
UAV	unmanned aerial vehicle
UE	user equipment
UHF	ultra high frequency
U-NII	Unlicensed National Information Infrastructure
USGS	U.S. Geological Survey
VHF	very high frequency
VNA	vector network analyzer
VNB	very narrow band
VoLTE	voice over Long Term Evolution
VQEG	Video Quality Experts Group
VQM	Video Quality Model
VSA	vector signal analyzer
VSG	vector signal generator
W	watt
WG	Working Group
WInnForum	Wireless Innovation Forum
WP	Working Party
WPS	Wireless Priority Service
WRC	World Radiocommunication Conference

DOC/NTIA Organization Chart



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