Spectrum and Propagation Measurements

The radio spectrum is an enigmatic natural resource that offers immense benefit to industry, government, and private citizens by supporting radio/wireless communications and a wide variety of other systems like radar and remote sensing. It is non-depleting and exists everywhere, but it is finite and can be rendered less useful by noise and interference. Until recently, traditional methods of allocating spectrum and assigning channels have ensured effective and efficient use of the spectrum. Today, the rapidly expanding competition for spectrum use and the plethora of new signal types and applications have created an apparent shortage of radio spectrum. While new spectrum management methods will alleviate this problem, they cannot do so without increasingly more complex knowledge of the existing signals and noise environment and better understanding of how systems that share spectrum affect each other.

The Spectrum and Propagation Measurements Division provides the technical information needed to enable more effective and efficient use of the spectrum, thus enabling spectrum allocation and sharing regulations and policies that are effective, reliable, and enduring. To do so, the division performs analyses and measurements of the effects of radio signals on the spectrum and on other systems. Measurements and assessments of spectrum occupancy can be accomplished at any location using the mobile Radio Spectrum Measurement Science system. New measurement methods are developed and complex testing is accomplished in well-equipped laboratories and at the Table Mountain Field Site.

The following areas of emphasis are indicative of the work done in the Division recently in support of NTIA, other Federal Agencies, academia, and private industry.

Areas of Emphasis

Radio Spectrum Measurement Science (RSMS) Operations
The RSMS is comprised of laboratory, transportable, and mobile facilities. This capability is used to assess spectrum occupancy and usage, electromagnetic compatibility, and to resolve interference problems. This project is funded by NTIA.

RSMS-4 Development
Measurement methods, both established and new, are supported by hardware and software. They are continually being refined and developed. The fourth generation system software is capable of fully autonomous operation and remote monitoring, uniform data recording and storage, and powerful analysis and display routines. This project is funded by NTIA.

Table Mountain Research Program
This field site, protected by state law and federal regulation as a radio quiet zone, is used by many operations and experiments that require both protection from strong, external radio signals, and minimum vibration. Research into new spectrum occupancy measurement methods, including radio noise measurement, new antennas, and complex radar measurements are conducted by ITS at the site. These projects are funded by NTIA.

Spectrum Efficiency Research and Engineering
Investigations of the efficient and effective use of the radio spectrum, including allocation and assignment methods, are pursued. Definitions for spectrum efficiency and effectiveness can be nontrivial and elusive. Actual measurements of band and channel usage are compared with known assignments to determine the merits of new and competing channel assignment schemes. This project is funded by NTIA.

Signal Characteristics, Spectral Emissions, and Interference Analyses
A complex assessment of the interference potential of ultrawideband (UWB) signals was largely completed this past year. This study required the utmost care and thoroughness to determine which characteristics of a variety of UWB signals were best correlated with interference effects observed in a digital television satellite receiver. This project is funded by Freescale, Inc.

Radio Spectrum Measurement Science (RSMS) Operations

Outputs

- Measurements to determine move-times, detection thresholds, and aggregate emission characteristics of dynamic frequency selection (DFS) devices.
- Measurements and report on Land Mobile Radio (LMR) channel occupancy in Federal bands 162-174 MHz and 406-420 MHz.
- Measurements to address compatibility between radiolocation and maritime and aeronautical services in the bands 9000-9200 MHz and 9300-9500 MHz.

The Radio Spectrum Measurement Science (RSMS) Operations project performs critically needed radio signal measurements necessary for making decisions regarding Federal Government spectrum allocations. As stated under Departmental Organization Order 25-7, issued 5 October 1992, and amended December 1993, the NTIA Office of Spectrum Management (OSM) is responsible for identifying and making arrangements for measurements necessary to provide NTIA and the various departments and agencies with information to ensure effective and efficient use of the spectrum. The RSMS resides at ITS and is tasked to perform measurements in support of OSM as required to fulfill their mission. ITS, through the RSMS Operations program, provides OSM and the executive branch with radio spectrum data, data analysis, reports, and summaries. The four basic areas of RSMS are 1) spectrum surveys and channel usage, 2) equipment characteristics and compliance, 3) interference resolution and compatibility and 4) signal coverage and quality. In FY 2005, several different measurements were performed in support of the basic mission.

In August 2005, additional laboratory measurements were conducted to determine move-times and detection thresholds of dynamic frequency selection (DFS) devices. DFS is a method whereby a radio-local-area-network (RLAN) device, using the 5-GHz band for unlicensed operations, will detect the operations of radar and promptly evacuate the channel if the radar is present. Measurements were conducted to determine if current DFS devices comply with specifications given in ITU-R M.1658. In FY 2004, testing was performed to demonstrate DFS proof of concept with a table of radar signals developed in conjunction with the Federal Communications Commission (FCC), industry, the Department of Defense (DoD), and NTIA. In FY 2005, additional testing was performed with a new set of radar signals developed by the DoD and NTIA to ensure radar operations in the 5-GHz band were protected. The test results will help determine whether this technology is able to move forward toward deployment in commercially available RLAN-type communication devices. In preparation for radiated measurements scheduled for FY 2006 to determine degradation of radar capabilities, aggregate radiated emissions of multiple DFS devices were also recorded at the Table Mountain facility located north of Boulder, Colorado, for the purpose of modeling these signals.

In the early part of FY 2005, measurements were conducted in the Washington, DC, area to measure and provide a report on Land Mobile Radio (LMR) channel occupancy in Federal bands 162-174 MHz and 406-420 MHz. This was part of NTIA's effort to improve the spectrum efficiency of Federal radio usage. Specifically, this effort was undertaken to help obtain data required to realistically design future possible shared trunked systems for Federal radio users and determine long-term usage trends by comparing results with previous measurements taken in the same location in 1986 and 1989. The measurements were made using new equipment and techniques developed at ITS that measure large areas of the spectrum and process it to obtain simultaneous signal levels of up to 480 individual LMR channels. These techniques provided faster measurements, but also allowed enhanced post-processing of the data to remove measurement defects.

In support of an agenda item at the International Telecommunication Union - Radiocommunication Sector's (ITU-R) World Radiocommunication Conference (WRC-07) to upgrade the status of the radiolocation service in the bands 9000-9200 MHz and 9300-9500 MHz to primary status, measurements were conducted in April of FY 2005. The

RSMS truck on site for the Land Mobile Radio measurements in Washington D.C. (photograph by I.L. Tobias).

measurements were designed to address compatibility between radiolocation and maritime and aeronautical services in the above mentioned bands. Waveforms of the radiolocation systems were generated and injected into the receiver of an SPS-73 radionavigation system to determine levels of degradation.

In support of a current review by NTIA/OSM of a spectrum support request that is contingent upon the in-band and out-of-band emissions of a Globalstar Mobile Satellite Service, measurements were made in late FY 2005 to characterize the emission levels of these devices. In addition, similar measurements were conducted to characterize emissions of a 1.9-GHz cellular handset. Of particular interest were the out-of-band levels received in the global positioning system (GPS) bands.

To investigate waiver applications to the FCC's ultrawideband Part 15 Rules permitting devices to employ swept frequency techniques, measurements were conducted at the ITS Boulder Labs. The purpose was to provide an understanding of swept signals at the output of various filter bandwidths and to provide information to develop test procedures that could be used in compliance measurements.

In support of the ITU-R Joint Rapporteurs Group 1A/1C/8B regarding the international review of emission limits of radar systems, measurements were conducted in October of FY 2005 on several Japanese radars. The purpose was to collect emission characteristics to help with decisions in the development of the ITU limits which currently are similar to specifications stated in the U.S. Radar Spectrum Engineering Criteria (RSEC).

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Radio Spectrum Measurement Science (RSMS)-4 Development

Outputs

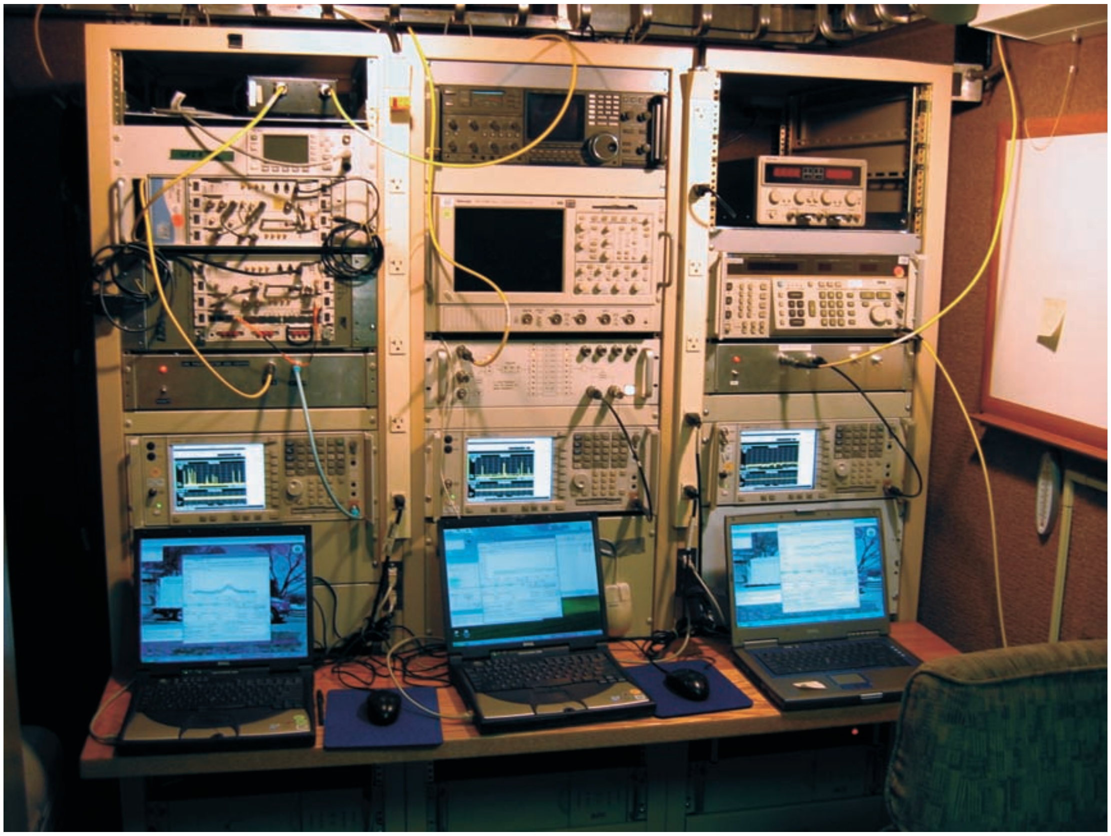
- Two new ITS custom-built preselectors and enhancements of existing preselectors.
- Real-time fully automated direction-finding system that can be used with pulsed signals such as radar.
- Fully automated data acquisition and processing software used for Land Mobile Radio channel occupancy measurements.
- Several new ITS custom-designed software modules for instrument control and measurement.

The 4th generation system for the Radio Spectrum Measurement Science (RSMS) Development project consists of state-of-the-art tools (vehicle, software, and hardware) necessary for making measurements to characterize spectrum occupancy, ensure equipment compliance, determine electromagnetic compatibility, and analyze interference problems. The development of the 4th generation system originated out of the recognized need to upgrade to the latest technology used in RSMS operations. RSMS operations, in turn, directly supports NTIA by providing critical measurement support for determining policies affecting both the public and private sectors. To this end, several new capabilities and improvements have been added to the system in FY 2005.

Integral to the RSMS measurement system has been the development of customized preselector units that filter out unwanted signals and amplify the input to increase system sensitivity. Recently, two new fully functional 4th generation preselectors have been designed and constructed — one for frequencies between 0.5 – 18.0 GHz and the other for frequencies between 18.0 – 26.5 GHz. Both preselectors are protected against strong signals by highly shielded enclosures and are controlled via fiberoptic connections to prevent signals coupling into control lines. In addition to these 4th generation units, several preselectors have been custom-designed specifically for Land Mobile Radio (LMR) measurements. Because the RSMS system has several functional preselectors from previous generations, each of these existing units has also been refurbished and improved upon so as to maintain a large selection of usable devices. Under the development of the 4th generation software, computer automated control of each of the units — new and old — has been integrated into the larger software package. Modularized instrument software units have made it possible to seamlessly swap out preselector units for different applications of the same measurement capabilities.

Currently in progress is the development of real-time "signal direction finding" capabilities. Two student interns, along with ITS engineering staff, have been working together to develop these capabilities through implementation of digital control and processing using Field Programmable Gate Array (FPGA) technology. The system switches through the different antennas of a six-sided array to determine the angle of signal arrival. Using rapid digital processing and a switch control by the FPGA, information is relayed via the Internet to a computer, which can then be used for real-time high-gain antenna positioning toward stationary or moving targets. One of the advantages of this system over most off-the-shelf systems is that it can be used with pulsed signals such as radar. By implementing this system in software as an instrument module, it is easily integrated into the larger RSMS software package for use with a variety of measurement capabilities. Development of this system using FPGA technology will not only provide signal direction finding capabilities but opens up a whole new way of acquiring and processing data using what is essentially a hardware re-programmable instrument that can be used for many different applications.

Recently implemented and used in Washington, DC, and Denver, a fully automated LMR channel occupancy measurement system has been developed by ITS. Using the latest in digital signal processing capabilities, this system simultaneously acquires data on as many as 480 LMR channels, performs processing to remove artifacts, and stores data every second. This new system is an improvement over previous systems in that it can acquire data much more rapidly, and it has enhanced capabilities for removing artifacts such as noise, a wide dynamic



Interior of RSMS 4th generation truck showing setup for LMR measurements taken in the Denver area (photograph by J.R. Hoffman).

range, and because of special processing techniques, a better sensitivity. In addition to the acquisition software, a whole suite of data processing routines have been developed that allow us to look at statistics in ways we have never been able to do before. Because of the versatile nature of the system and the development of a complete set of automated processing routines, application of this system for further measurements in other locations is highly possible and could be implemented efficiently.

Three newly developed additions to the RSMS software include: (1) a rotator instrument control, (2) an azimuth signal search routine, and (3) an enhanced stepped frequency measurement. The rotator instrument control is a software module integrated into the larger RSMS software that allows remote control of an antenna position device. This module can, in turn, be used in combination with a spectrum analyzer control routine for measurements such as the azimuth signal search routine which locates the direction of one or more signal point sources as it sweeps the horizon. The stepped frequency routine is a measurement procedure, used typically for radar measurements, in which the system steps through a narrow bandwidth of frequencies and measures the power. This allows the measurement of signals with a very large dynamic range of power. The FY 2005 enhancement to this routine comprised adding an automated attenuation capability which further increased the capability for measuring wide dynamic ranges.

New features planned for FY 2006 include enhanced data file management, a fully automated swept measurement routine, a swept calibration routine, a yttrium-iron-garnet (YIG) filter calibration routine, a vector signal analyzer instrument control module, two new noise measurement routines, and a scheduler for automated control of multiple measurements.

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Table Mountain Research Program

Outputs

- Measurements of aggregate emissions from dynamic frequency selection (DFS) RLAN-type transmitters.
- A prototype of a 3-axis antenna built to study the total incident field and polarization of radiated signals.
- Signal simulators developed to study the characteristics of complex signals such as UWB and man-made noise.

The Table Mountain Field Site and Radio Quiet Zone supports fundamental research into the nature, interaction, and evaluation of telecommunication devices, systems, and services. To achieve this goal, the Table Mountain Research Project actively solicits research proposals both from inside the Institute and from external agencies.

The results of this work are disseminated to the public via technical reports, journal articles, conference papers, web documents, and computer programs. Some highlights of the program are presented below.

Radar Testing

It was suggested by the International Telecommunication Union - Radiocommunication Sector (ITU-R) Working Party 8B that radar emission spectra might vary as a function of the pointing angle of radar antennas as they turn. If true, it would not be possible to determine a radar's emission spectra by simply measuring at a single location. To assess the possibility that this effect might occur, a maritime radar was set up at the Table Mountain site and its spectrum measured at four different azimuthal locations (see Figure 1). The results, documented in NTIA Technical Memorandum TM-05-430, indicated that no such effect is likely to occur.

Other experiments explored the possibility of antenna pattern variations that occur as a function of frequency.

DFS Testing

In other work, dynamic frequency selection (DFS) radio local area network (RLAN)-type device prototypes operating at 5 GHz were tested at Table Mountain as aggregates of up to ten clients communicating with an access point (see Figure 2). The purpose of the tests was to determine the spectrum and amplitude probability distribution (APD) characteristics of aggregate DFS emissions. The results of the work were forwarded to the NTIA Office of Spectrum Management (OSM), as part of a broader study of the performance and effectiveness of the DFS prototypes.

Land Mobile Radio Occupancy Measurements

In the fall of 2004, measurements were conducted in the Washington, DC, area to measure Land Mobile Radio (LMR) channel occupancy in Federal bands 162-174 MHz and 406-420 MHz. This was part of the NTIA effort to improve the spectrum efficiency of Federal radio usage. The goal was to obtain data needed to design shared communication systems for Federal users, and to determine long-term usage trends by comparing results with previous measurements taken in the same location in 1986 and 1989 (see pp. 6-7 for more information).

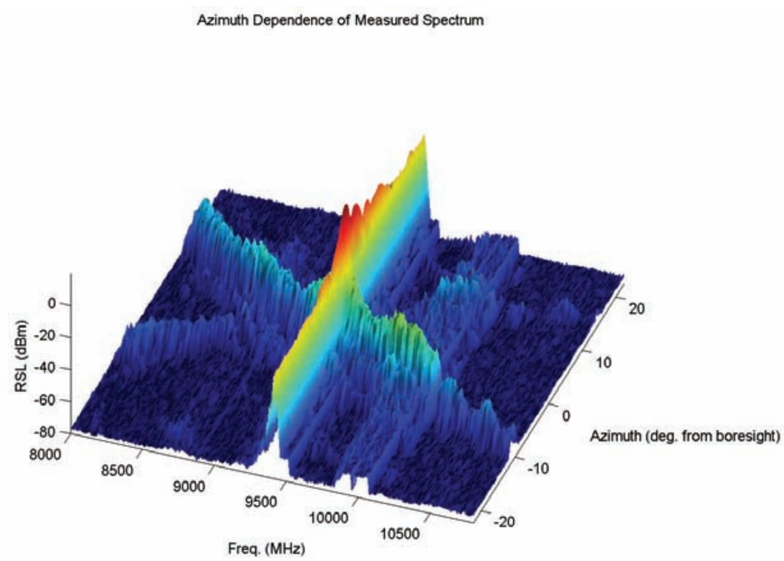

Figure 1. Three-dimensional view of radar azimuthal emission patterns from 8000-10800 MHz, between ±20 degrees of the radar main beam direction. The color is keyed to received signal level (RSL).

Figure 2. DFS testing at Table Mountain (photograph by F.H. Sanders).

During the summer of 2005 the Table Mountain Research project provided the resources needed to improve upon the existing LMR measurement system. This time the system was deployed to the Denver metropolitan area, and in addition to the frequency bands measured in Washington, DC, preparations were made to measure in bands 30-50 MHz, 138-162 MHz, and 420-450 MHz, as well as several bands in the 800 and 900 MHz regions of the spectrum. The Denver measurements will serve two purposes: (1) to check out recent changes to the measurement system and (2) to supplement the Washington, DC, measurements by measuring LMR usage of both Federal and non-Federal bands in a large city where transmissions are less centrally located.

FY 2005 Cooperative Research Programs
(see pp. 50-51 for more information)

- First RF Corporation
- RF Metrics Corporation
- Coherent Technologies
- Deep Space Exploration Society
- University of Colorado

Recent Publications

F. Sanders and B. Ramsey, “Phased array antenna pattern variation with frequency and implications for radar spectrum measurements,” NTIA Report TR-06-436, Dec. 2005.

F. Sanders and B. Ramsey, “Comparison of radar spectra on varying azimuths relative to the base of the antenna rotary joint,” NTIA Technical Memorandum TM-05-430, Aug. 2005.

T. Brown, S. Doshi, S. Jdhav, D. Henkel, and R. Thekkekunnel, “A full scale wireless ad hoc network test bed,” in “Proceedings of the International Symposium on Advanced Radio Technologies: March 1–3, 2005,” J.W. Allen and J. Ratzloff (Eds.), NTIA Special Publication SP-05-418, Mar. 2005, pp. 51-60.

J.W. Allen, “Gain characterization of the RF measurement path,” NTIA Report TR-04-410, Feb. 2004.

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Spectrum Efficiency Research and Engineering

Outputs

- Report on Federal LMR systems in Washington, DC, area.
- Internal papers on spectrum efficiency concepts.
- Consultation with OSM on spectrum efficiency planning.

NTIA is deeply committed to an extensive multi-pronged program to improve the spectrum efficiency of Federal radio systems. This program was given additional importance by the May 2003 announcement of a November 30 Presidential Spectrum Policy Initiative to promote the development and implementation of a U.S. spectrum management policy for the 21st century. More recently, NTIA administrator Michael Gallagher announced a multi-year effort to carry out a series of spectrum efficiency directives contained in a November 2004 Presidential Memorandum to multiple Federal departments. Although most of this work will be accomplished by NTIA/OSM in Washington, ITS is also playing a key role in several aspects of the work.

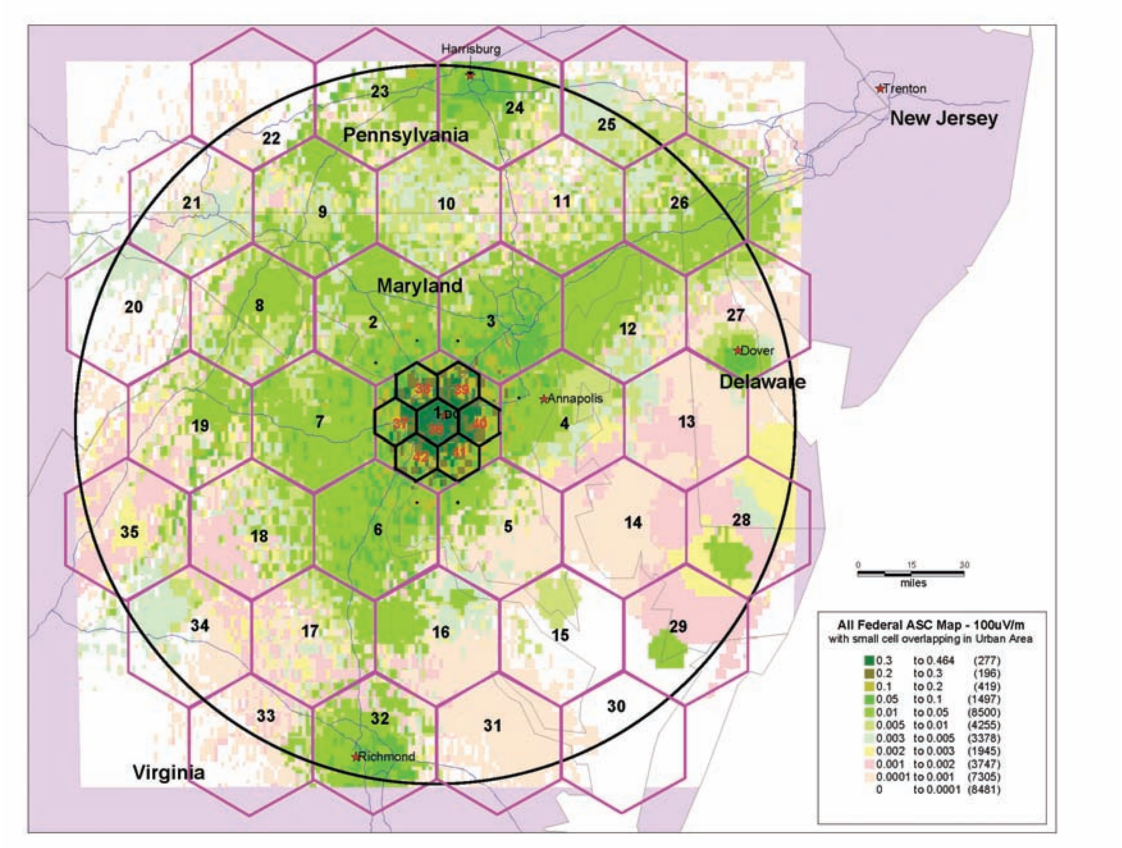
ITS is working with OSM to develop theoretical concepts and practical applications of improved spectrum efficiency. One problem is that "spectrum efficiency" can mean many things — some of them contradictory — and ITS has been active in helping to sort out concepts that will be useful in guiding Federal policies toward more effective use of the radio spectrum. An internal NTIA paper on spectrum efficiency concepts was written to guide discussion on some of the problematic aspects of spectrum efficiency that needed to be resolved to help NTIA develop improved policies and practices.

ITS is currently examining possible categories of definitions (sometimes equations) that describe the spectrum efficiency and effectiveness of several types of radio services. Initial work suggests that there is considerable flexibility in the choice of definitions; the choice will need to match the specific purposes for which the calculations will be performed. These definitions typically differ in the factors selected to represent significant features of the real world. Sometimes it is sufficient to consider only the technical characteristics of the radio equipment; sometimes it is necessary to consider how the equipment characteristics match the operational requirements of the mission. The computation methodologies and the numeric answers for a specific situation can differ considerably, depending on the nature of the definition that is selected.

ITS has been assisting OSM in a modeling effort to see whether the current myriad of single-agency Federal mobile radio systems in the Washington, DC, area could be efficiently replaced by one large shared trunked radio system. The first part of this work was completed in FY 2004, including a draft report "Phase 1 - Study of Federal operations in the 162-174 MHz band in the Washington, DC, area," which is now awaiting final clearance for publication. This work investigated the current Federal land mobile radio (LMR) systems within 100 miles of Washington, DC. This study developed a signal capacity (SC) model that uses Government Master File (GMF) Federal radio license data and terrain-based propagation models to provide a combined geographical coverage "footprint" of the multiple independent existing radio systems now serving Federal Agencies. This model showed that as many as 268 separate LMR radio channels were available to a mobile user in the downtown Washington area in the 162-174 MHz band, as well as summarizing the geographical coverage of current systems.

Another input to a model for the design of future LMR systems was the measurement of actual LMR traffic (Erlangs) in the Washington area, using the ITS Radio Spectrum Measurement Science (RSMS) system, as described on pp. 6-9 of this report. These measurements were completed in early 2005, and the results have been used to describe the total amount of traffic that a possible future shared radio system should be designed to handle. A report on the RSMS measurements should be published soon.

The design of possible future alternative shared LMR systems will be based on the signal capacity geographical coverage data and the RSMS measured traffic data. The figure shows the Average Signal Capacity (ASC) map for Washington, DC, overlaid with a 100-mi radius circle, and idealized hexagonal coverage areas for one of the proposed future



Possible future alternative shared LMR system using large cells overlapped with small urban cells.

systems. The ASC map shows the number of independent radio systems per square mile (actual ASC values are multiplied by 10,000 on the map). This ASC data is summed over the coverage area and multiplied by measured channel occupancy data to get the nominal traffic load in Erlangs that each cell must support. This example uses rural/suburban cells with a 20-mile coverage radius (violet hexagons) overlaid with 7-mile radius cells in the densest urban areas (small black hexagons). Several different architectures have been evaluated using various assumptions about the total number of users participating in the shared system, including traffic loads as large as ten times more than current traffic loads. A report on the completed evaluation will compare the expected costs and number of frequencies needed for the alternative future systems and the current LMR systems.

Recent Publications

J.R. Hoffman and R.J. Matheson, “RSMS measurement and analysis of LMR channel usage,” in “Proceedings of the 2005 International Symposium on Advanced Radio Technologies: March 1-3, 2005,” J.W. Allen and J. Ratzloff (Eds.), NTIA Special Publication SP-05-418, Mar. 2005.

R.J. Matheson, “Flexible-use spectrum rights”. in “Proceedings of the 2005 International Symposium on Advanced Radio Technologies: March 1-3, 2005,” J.W. Allen and J. Ratzloff (Eds.), NTIA Special Publication SP-05-418, Mar. 2005.

G. Patrick, et al., “Phase 1: Study of Federal operations in the 162-174 MHz band in the Washington, DC, area,” NTIA Report in progress.

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Signal Characteristics, Spectral Emissions, and Interference Analyses

Outputs

- Technical publications and presentations demonstrating research results.
- Comparative measurements and analyses of DP-UWB, DS-UWB, and MB-OFDM signals.
- Measurement and analysis of DTV susceptibility to ultrawideband signals.

Since the Federal Communications Commission (FCC) permitted low power ultrawideband (UWB) emissions between 3.1 and 10.6 GHz in February 2003, a number of companies have developed new UWB technologies for application in wireless personal area networking (WPAN) to achieve high data rates at short distances (nominally less than 10 meters). Examples of these developments include Multi-band Orthogonal Frequency-Division Multiplexing (MB-OFDM) and Direct-Sequence Ultrawideband (DS-UWB) technologies. MB-OFDM achieves its ultra-wide bandwidth with a 528-MHz wide OFDM signal that hops between 14 different bands. In contrast, DS-UWB combines conventional spread spectrum techniques and pulse shaping to achieve its ultra-wide bandwidth.

Questions arose regarding how UWB signals interfere with legacy systems such as C-band satellite television, which demodulates signals that lie within the frequency band allocated for UWB operations. On March 22, 2004, ITS entered into a Cooperative Research and Development Agreement with Motorola/Freescale Incorporated to address these questions. We hypothesized that UWB interference potential could be quantified in terms of UWB signal characteristics. To test this hypothesis, a test system was designed and built to inject UWB signals with known characteristics into a C-band satellite digital television (DTV) receiver and quantitatively measure interference susceptibility via signal quality metrics, e.g., segment error rate, pre-Viterbi bit error rate, and modulation error ratio, taken from various points in the receiver signal processing chain. Figure 1 shows the test set-up. Results from the experiment are being published in a three-part NTIA Report Series entitled “Interference Potential of Ultrawideband Signals.” Part 1, released in February 2005, describes the test setup and procedures in detail.

Figure 1. Test set-up (photograph by F.H. Sanders).

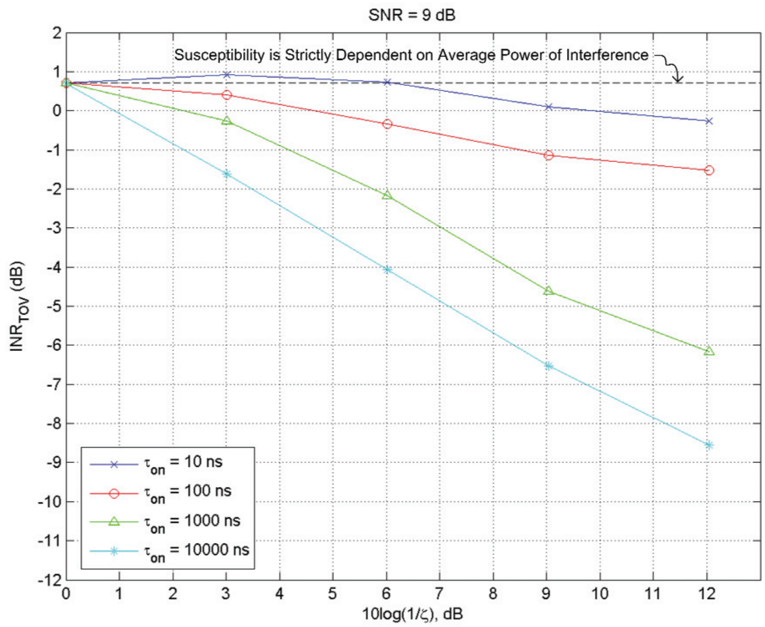

Figure 2. INR_{TOV} *versus 10log(1/ζ) for a DTV receiver operating at* SNR = *9 dB and exposed to gated noise interference.*

Part 2, released in August 2005, provides test results for gated-noise interference to DTV receivers. While continuous- and gated-noise signals are unlikely to be used in communications, their similarities to DS-UWB and MB-OFDM, respectively, are unmistakable and their analytic tractability is profoundly useful. This report demonstrates that DTV susceptibility to gated-noise interference cannot be predicted by interference power characteristics alone. As illustrated in Figure 2, it was found that DTV susceptibility, quantified by the average interference power that caused DTV degradation at the threshold of visibility (INR_{TOV}), is also dependent on temporal characteristics (e.g., τ_{on} and ζ) of the interfering signal and the bandwidth of the DTV receiver. Moreover, high correlation was observed between susceptibility and forward error correction performance of the receiver.

Part 3, *to be released*, will provide results from tests that measured DTV susceptibility to actual UWB signals. In this experiment, a DTV victim receiver was exposed to Dither-Pulse UWB, DS-UWB, and MB-OFDM interference. It was found that categorization of the UWB signals into three regions of common DTV susceptibility could be achieved with a priori knowledge of the temporal structure of the signal and bandwidth of the victim receiver.

Recent Publications

M. Cotton, R. Achatz, J. Wepman, and B. Bedford, “Interference potential of ultrawideband signals, Part 1: Procedures to characterize ultra-wideband emissions and measure interference susceptibility of C-band satellite digital television receivers,” NTIA Report TR-05-419, Feb. 2005.

M. Cotton, R. Achatz, J. Wepman, and P. Runkle, “Interference potential of ultrawideband signals, Part 2: Measurement of gated-noise interference to C-band satellite digital television receivers,” NTIA Report TR-05-429, Aug. 2005.

M. Cotton, R. Achatz, J. Wepman, and R. Dalke, “Interference potential of ultrawideband signals, Part 3: Measurement of ultrawideband interference to C-band satellite digital television receivers,” NTIA Report in progress.

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