Telecommunications Engineering, Analysis, and Modeling

The Telecommunications Engineering, Analysis and Modeling Division conducts studies in these three areas for wireless and wireline applications.

Engineering work includes assessment of the components of telecommunications systems; evaluation of protocol and transport mechanism effects on network survivability and performance; and assessment of the impact of access, interoperability, timing, and synchronization on system effectiveness in a national security/emergency preparedness environment.

Analysis work is often performed in association with Telecommunications Analysis (TA) Services, which offers analysis tools online via the Internet. In addition, ITS can provide custom tools and analyses for larger projects or specific organizations.

Modeling has been one of ITS's greatest strengths for many years. Propagation models include various terrain databases and other data. Adaptations of historic models, and those for more specialized situations have been developed and enhanced.

Areas of Emphasis

ENGINEERING

NS/EP Requirements for Wireless Networks The Institute promotes technology advancement in the telecommunication industry and improvements to the access and interoperability of wireless systems supporting NS/EP needs. Sponsors include the National Communications System (NCS).

Third Generation HF Modem Testing As part of its HF Program, the Institute develops effective ways of evaluating and assessing telecommunications equipment. The project is funded by NCS and NTIA.

Tandem Vocoder Testing The Institute tests the performance of vocoders, both singly and in different combinations of tandem configurations, to evaluate overall voice quality. The project is funded by NCS.

PCS Applications The Institute helps the Telecommunications Industry Association (TIA) committee TR46.2.1 develop an inter-PCS interference model and handbook. The project is funded by NTIA and NCS.

Mobile IP Network Access Technologies The Institute examines the application of Internet protocol (IP) to wireless terrestrial and satellite links, and evaluates the applicability of cellular phone and satellite technologies to mobile computing for NS/EP environments. The project is funded by NCS.

ANALYSIS

Telecommunications Analysis (TA) Services The Institute provides network-based access to its research results, models, and databases supporting applications in wireless telecommunications system design and the evaluation of systems. These services are funded by fee-for-use and fee-for-development charges.

Geographic Information System Applications The Institute has developed a menu-driven propagation model using geographic information system (GIS) formats. This work was funded by DOD and ARINC.

MODELING

Propagation Model Development In coordination with NTIA/OSM, the Institute develops enhancements to existing propagation models and works to harmonize related models. The project is funded by NTIA.

Time-hopped UWB Simulation Analysis for BWCF In coordination with NTIA/OSM, the Institute models and simulates ultrawideband (UWB) systems from an analytic description to determine bandwidth correction factor (BWCF) and the interference effects of these devices on victim receivers. Projects are funded by NTIA.

Jammer Effectiveness Model The Institute assesses the impacts of jamming and interference on communications and radar system performance in electronic warfare scenarios. The project is funded by the U.S. Army.

NS/EP Requirements for Wireless Networks

Outputs

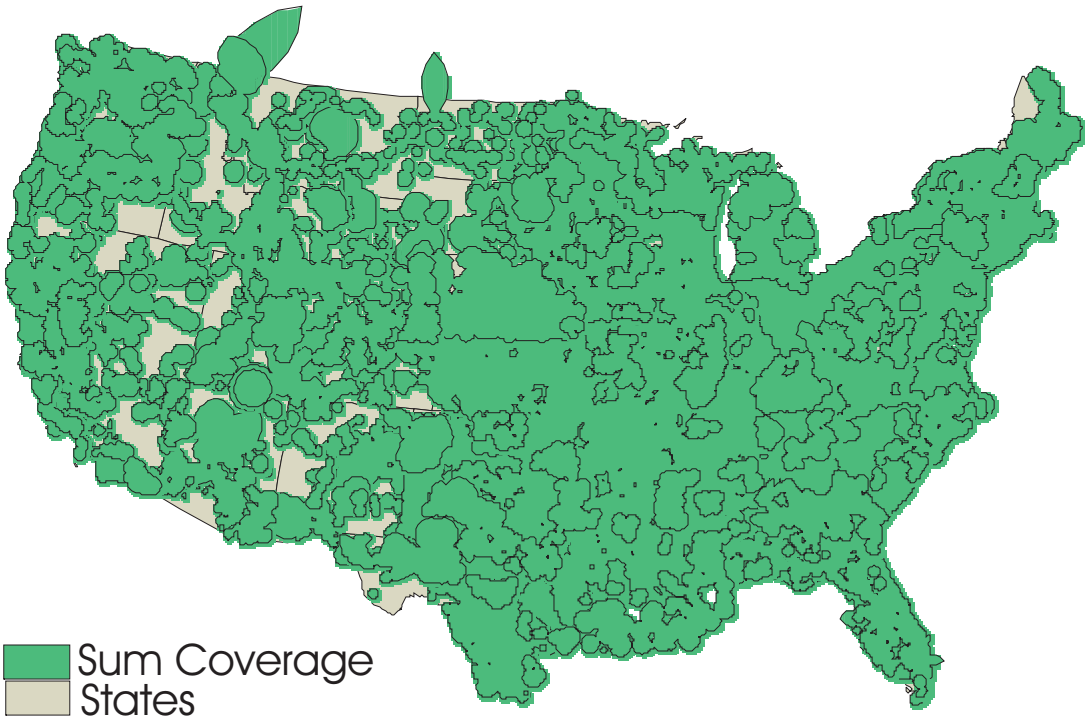
- Technical assessment of wireless priority services for NS/EP users.
- TIA TR45 Standard Requirements Document.

The National Communications System (NCS) is responsible for planning and implementing initiatives to enhance national security and emergency preparedness (NS/EP) telecommunications under a wide range of operational scenarios. To fulfill this responsibility effectively, NCS must have a systematic process for defining comprehensive NS/EP telecommunications needs, evaluating relevant communications technologies, and specifying those technologies that economically meet the defined NS/EP communications requirements. One such requirement is priority access service. Currently, priority access service exists in the wireline public switched telephone network (PSTN) via the Government Emergency Telecommunications Service (GETS) program. The wireless augmentation of priority access service is the objective of the current ITS tasking, which will provide mobile users with the same capability as their wireline counterparts.

During FY 2000, ITS participated in two efforts pertaining to NS/EP requirements for wireless networks. The first effort was to perform a technical assessment of the wireless priority services for NS/EP users. This consisted of researching a wide range of wireless technologies. The report produced from this assessment illustrates both the comprehensive technologies, and the physical system specification of essential NS/EP wireless communications capabilities. The report addresses the technology baseline, the status of the technology, some relevant forecasts, and the issues of priority integration for each of the related wireless technologies.

The report begins by examining several possible disaster scenarios requiring priority access service, and assigns a degree and duration of congestion to each scenario. Each scenario is then related to appropriate technologies that would provide NS/EP communications. Wireless technologies presented include commercial wireless telephony, mobile satellite systems, land mobile radio, personal digital assistants/pagers, high altitude communication technologies, multimode handsets, software-configurable radios, telephony over wireless IP networks, wireless ATM (asynchronous transfer mode), HF radio, and security. The Figure shows a coverage plot for CDMA (code division multiple access), TDMA (time division multiple access), and GSM (global system for mobile) technologies in the contiguous United States. From this plot, NS/EP users can determine areas where wireless coverage exists, as well as areas where other wireless technologies may be needed to augment the commercial wireless network in the aftermath of an NS/EP event.

The report provides advice and guidance for NCS on a strategy for achieving wireless priority access service. ITS concluded that NCS should continue to promote the basic GETS call program in both the wireline and wireless PSTN. For commercial wireless networks, the Wireless Intelligent Network (WIN)-based radio channel access and egress queuing should be pursued, since this is a good tradeoff of increased wireless high probability of connectivity (HPC) call functionality and, potentially, a vendor-independent standard for NS/EP responders. In addition, ITS concluded that the Service Control Point (SCP)-based GETS PIN database can be used to provide HPC functionality for both today's commercial land-based wireless networks and future wireless networks that will interwork with the PSTN. Each of these approaches can help to satisfy a pressing, near-term need for wireless and wireline priority access service.



Total wireless computed coverage (800 MHz) in the contiguous United States.

ITS' second major effort in this area during FY 2000 was to assist NCS in developing a Standard Requirements Document (SRD) for standardizing a priority access service in commercial wireless networks employing a WIN-based approach. This standardization effort will be accomplished through the Telecommunications Industry Association (TIA) TR45 standards committee.

Under TR45, ITS will participate in the TR45.2.5 WIN Working Group to standardize the WIN implementation of priority access service. This group is standardizing the event and trigger detection points at which transfer of control from the mobile switching center (MSC) to a WIN service logic can occur, in the WIN Basic Call State Model (BCSM). The WIN BCSM's provide a high-level vendor independent abstraction of call and connection processing. This, in turn, implies uniform call and connection processing across multiple vendors' implementations of these functions. As such, this group provides a forum for NCS to achieve the goal of providing a uniform wireless priority access service.

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Third Generation HF Modem Testing

Outputs

- Results of modem performance testing published in an industry journal.
- Software system for the automation of multiple repetitive tests.

During national security/emergency preparedness (NS/EP) situations, terrestrial communication systems may be unavailable or inoperable due to damage or overloading. High frequency (HF) systems offer the capability of voice or data communications over long distances without the restrictions of higher frequency systems. Data communication has increased in importance due to the complexity of information and the need for reduced probability of misunderstanding (information corruption). Since the government traditionally has depended on the large reserve of HF operators and systems in emergency situations, a common, efficient, HF data exchange method is needed. The National Communications System (NCS) sponsored ITS to test and compare the newest HF modem protocols. The Federal Emergency Management Agency (FEMA) will use the test results to determine which protocols could be used to serve as a common exchange with the amateur community in the event of a national emergency.

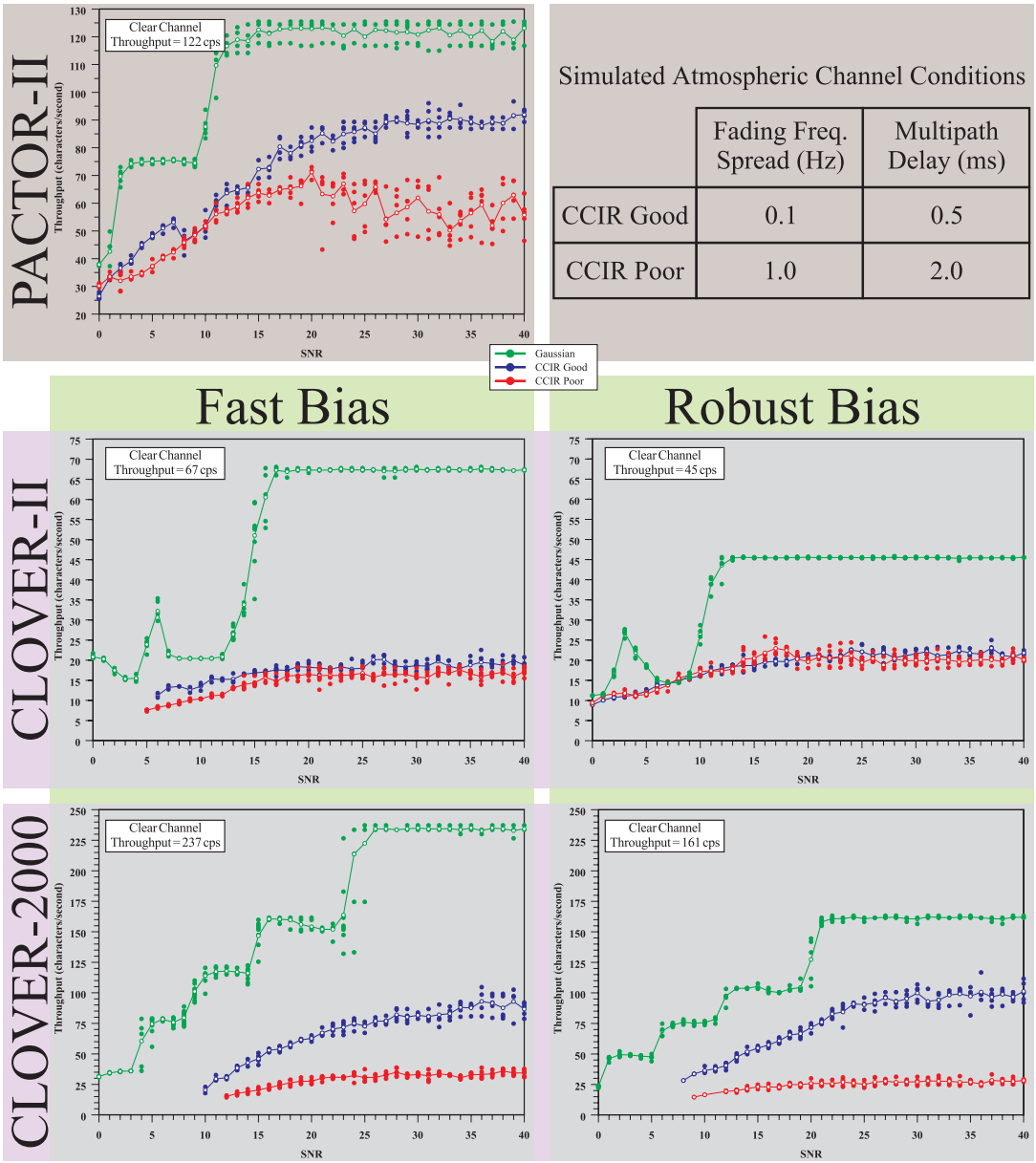
To obtain greater data throughput and higher bandwidth efficiency, HF digital modem protocols have been enhanced with better error correction and more advanced modulation schemes, resulting in reduced data errors and less susceptibility to atmospheric degradation. PACTOR-II improves on the widely used PACTOR protocol, while CLOVER-2000 is the newest generation of the CLOVER family of protocols. In previous testing (Riley et al., 1996; see Publications Cited, p. 102), ITS tested what could be considered the second generation of protocols (PACTOR, AMTOR, G- TOR, and CLOVER-II) as well as the then newly released PACTOR-II.

In the time elapsed since those first tests, much had changed in terms of available computing power and software capabilities. Consequently, the test environment was significantly different than when the first tests were performed. To verify the consistency of results between the two tests, two protocols from the first tests, PACTOR-II and CLOVER-II, were re-tested during the second series of tests. PACTOR-II can be considered a third-generation protocol, comparable to CLOVER-2000. CLOVER-II was re-tested because it was implemented in new hardware.

The test configuration consisted of two modems connected back-to-back through two atmospheric simulator channels. The HF channel simulator consisted of the Watterson channel model implemented in two digital signal processing (DSP) cards plugged into one personal computer. The two modems and the channel simulator all are controlled by a second, test controller, computer. The modems were configured to operate in automatic repeat request (ARQ) mode to assure error-free data transmission and eliminate the need to measure bit-error-rate. A 15,183 byte file was passed between the two modems, under a variety of simulated atmospheric conditions, to calculate throughput. The file was transmitted five times for each channel simulator setting to assure statistical reliability. Clear channel conditions were used to confirm the test setup. Gaussian noise of varying levels (0 to 40 dB in 1 dB steps) was used to confirm the modem's operation, and to enable comparison with other published test results. Finally, CCIR* Good and Poor conditions, with varying levels of Gaussian noise, were used to approximate actual atmospheric conditions.

Unique to the CLOVER protocol was a bias setting. Robust bias implemented 60% data transmission and 40% error correction coding; fast bias implemented 90% data transmission and 10% error correction coding. Fast bias offered the highest raw data throughput, but corrected the fewest errors and required more packet retransmissions during degraded conditions. As a result, the robust bias mode occasionally exhibited higher throughput than the fast bias mode.

*CCIR stands for the International Radio Consultative Committee, now known as the International Telecommunications Union Radio Communications Sector (ITU-R); however, the acronym CCIR is still used in certain situations.



Simulated Atmospheric Channel Conditions

	Fading Freq. Spread (Hz)	Multipath Delay (ms)
CCIR Good	0.1	0.5
CCIR Poor	1.0	2.0

Throughput testing results under varying atmospheric channel conditions

The Figure shows the throughput results of all three protocols under Gaussian noise, CCIR Good, and CCIR Poor channel conditions. All three protocols use multiple modulation schemes which are dynamically selected depending on the detected re-transmission demand. This is exhibited in the Gaussian noise curves. As the channel becomes more degraded, simpler modulation techniques are chosen and lower throughput is measured. Note that, for the sake of readability, a different vertical scale was used for each of the three protocols. In comparing the results, the fact that CLOVER-2000 uses a 2 kHz bandwidth, while CLOVER-II and PACTOR-II both use a 500 Hz bandwidth, should be considered if bandwidth efficiency is a concern.

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Tandem Vocoder Testing

Outputs

- Quality evaluation of widely used vocoder technologies.
- Tandem vocoder test results.

Vocoders are used to minimize transmitted bit rate (and the associated transmission bandwidth) in digital voice communication systems. Bandwidth is an especially precious commodity in wireless communication systems, since wireless service providers must normally accommodate many users within a fixed spectrum allocation. Vocoders allow voice to be transmitted efficiently over circuit-switched or packet-switched digital networks. Vocoders also make spectrum-efficient wireless voice communications possible, and they allow the digitized voice stream to be encrypted. It is a goal of vocoders to transmit the highest quality speech using the least amount of bandwidth. This should be accomplished using the lowest possible complexity to reduce implementation cost and vocoder processing delay.

There are many different types of vocoders, designed to work with the many different types of communication systems. The various types of public safety communication systems require speech decoding and encoding at system interfaces to enable interworking. A vocoder will be required for each digital system; and, in addition, it will be required that the vocoders be connected in various "tandem configurations." Vocoder manufacturers generally focus their testing on individual products, often with little consideration of tandem configurations. The objective of this program, sponsored by the National Communications System (NCS), was to test the voice quality of commonly-used vocoders in different tandem configurations.

Tests were performed first on individual vocoders, and then on pairs of vocoders in tandem. The latter testing allowed the degradation from tandem vocoder combinations to be evaluated. Several commonly used vocoder technologies were investigated during this test. These technologies included: code excited linear prediction (CELP), vector-sum excited linear prediction (VSELP), Qualcomm code excited linear prediction (QCELP), improved multi-band excitation (IMBE), advanced multi-band excitation (AMBE), and algebraic codebook excited linear prediction (ACELP). All of the vocoders tested were hardware implementations with the exception of the ACELP vocoder, which was a software implementation.

Figure 1 shows a block diagram of the test setup used to evaluate the vocoders. A standardized objective voice quality assessment algorithm, developed (and patented) by ITS, was used in this testing. The algorithm was implemented using the ITS-developed Audio Play, Record, and Estimate (APRE) software tool. APRE estimates the voice quality of a device under test (DUT) by playing a digital voice input file to the DUT and recording the DUT input and output signals in digital voice files on a personal computer. It then performs a comparison of the voice files and provides an auditory distance (AD) score that indicates the degradation introduced by the DUT.

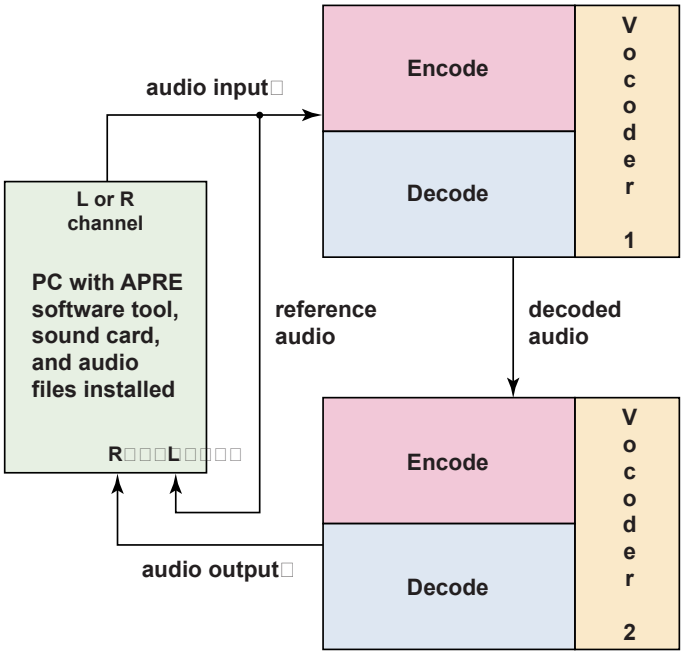

Figure 1. Block diagram of the test setup used to evaluate the vocoders.

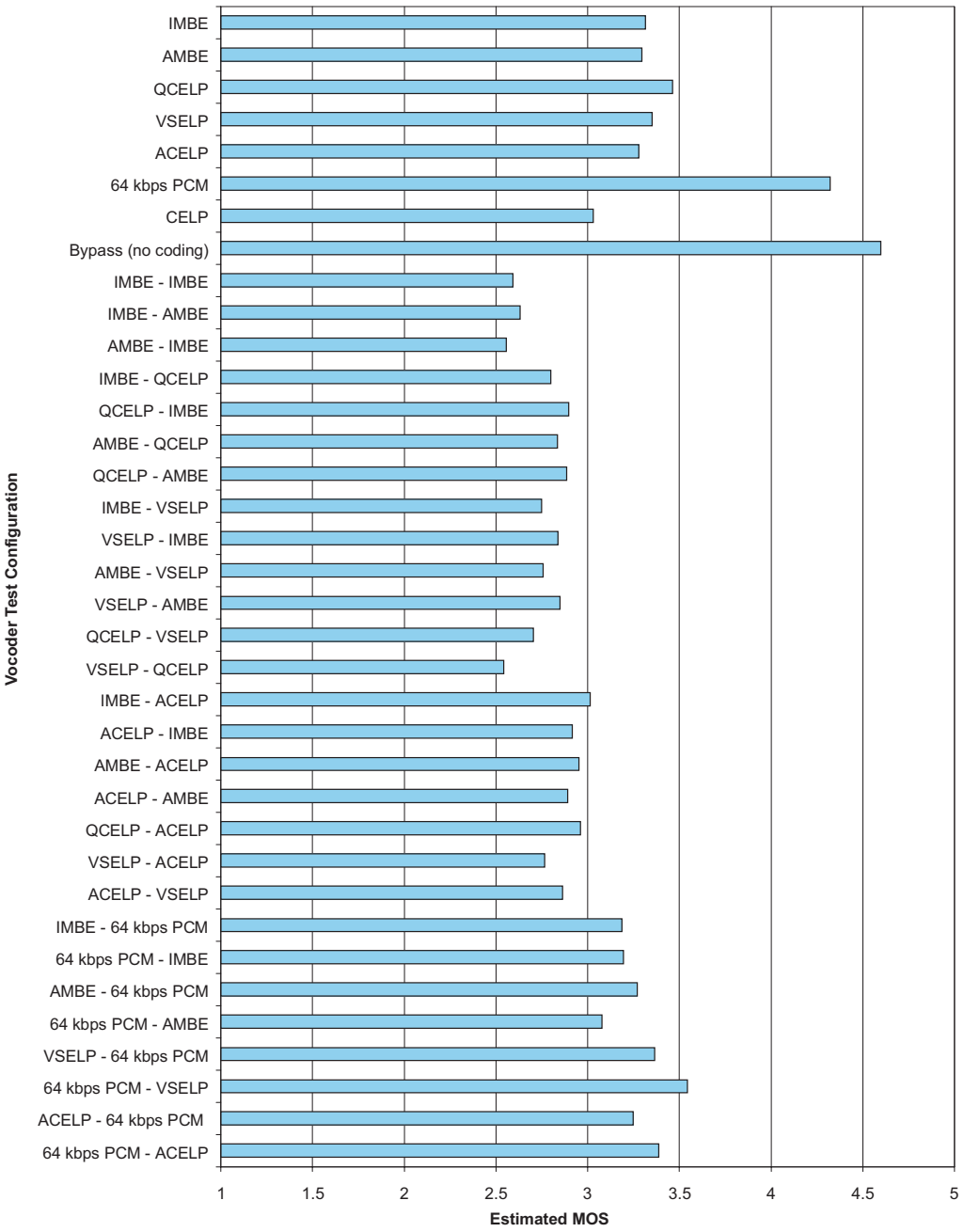

Figure 2. Estimated MOS for tested vocoder configurations.

An APRE parameter called L(AD) was used to compare the various vocoder configurations. L(AD) can be converted to estimated Mean Opinion Score (MOS), which is a common method for subjectively rating vocoder voice quality. It has been demonstrated that MOS estimates developed by APRE correlate well with subjective test results for a wide variety of conditions, although they cannot be considered to be replacements for formal subjective tests. Figure 2 shows the MOS values for the tested vocoder configurations.

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PCS Applications

Outputs

- Interference model for the various PCS technologies currently in use, as well as proposed technologies for two and a half generation (2.5G) and third generation (3G) systems.
- Contributions to industry-developed inter-PCS interference standard for predicting, identifying, and solving interference related problems.

Personal communications services (PCS) has become the choice for mobile voice and data communication and is a significant resource for emergency recovery of telecommunication services following a natural disaster. PCS networks of varying technologies from many providers cover a majority of this nation's area. Most areas are serviced by multiple, non-interoperable systems which function independently but use the same radio frequency bands and infrastructure (base station sites and towers). This joint use of spectrum is one source of interference. When damage occurs to the terrestrial telecommunication system, users tend to migrate to cellular resources, resulting in another source of interference. This sudden influx of traffic by private, commercial, civil, and Federal users results in wireless system overloads, interference, and disruption of service in the affected area. National security/ emergency preparedness (NS/EP) planners and network operators must understand these interference effects to operate effectively in an overloaded environment. To facilitate their understanding, it is necessary to characterize the interfering environment caused by large numbers of active users and competing technologies.

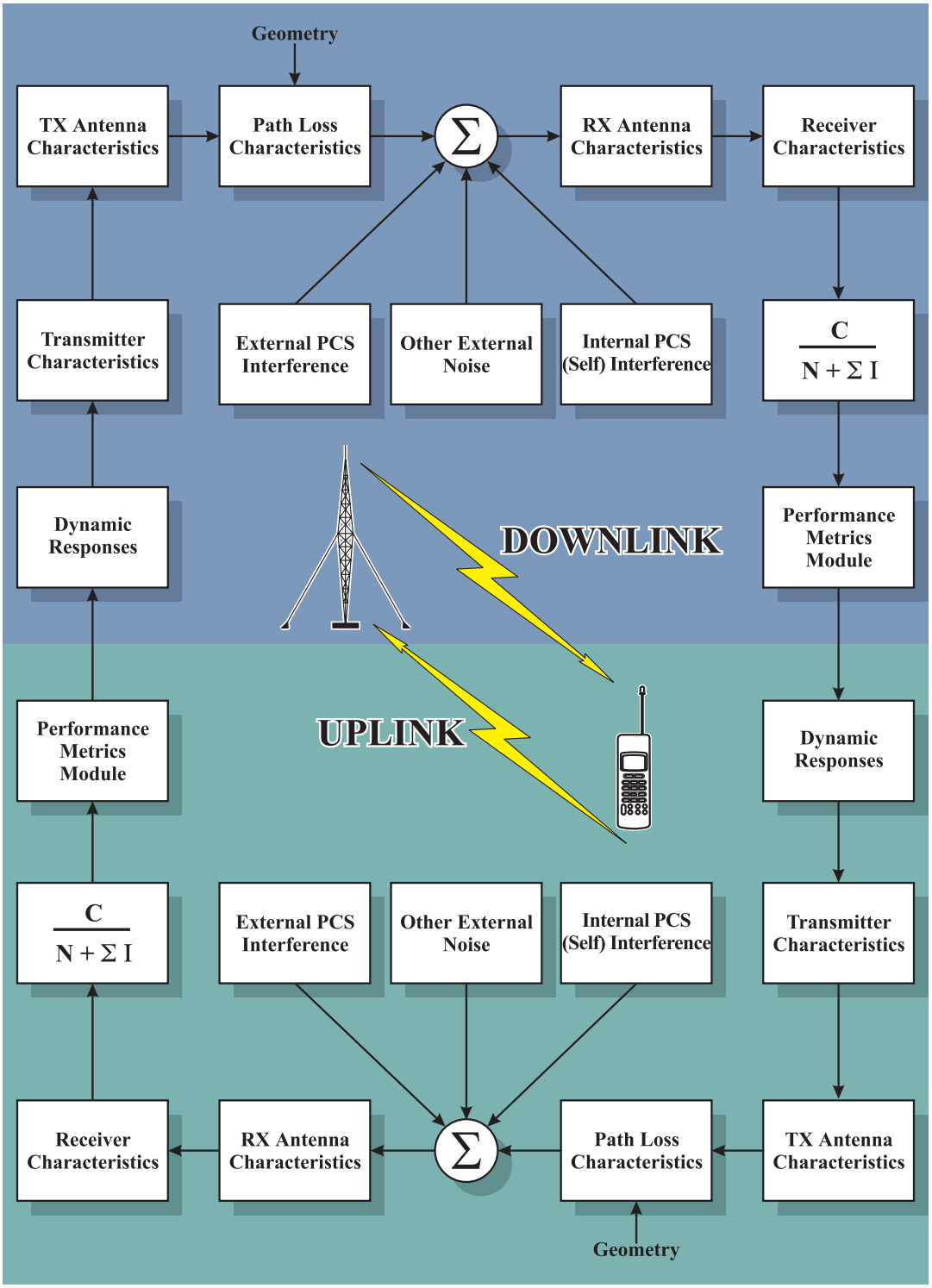
ITS has contributed to inter-PCS interference understanding through its participation in the development of an inter-PCS interference handbook developed by the Telecommunication Industry Association (TIA) committee TR46.2 (Telecommunications Systems Bulletin TSB-84A, *Licensed PCS to PCS Interference*). Since the handbook was released in July of 1999, the communications industry has developed and proposed new technologies to address system limitations such as system capacity and coverage, and data transfer rates.

In the near term, 2.5G systems such as EDGE (Enhanced Data Rates for Global Evolution) and GPRS (General Packet Radio Service) are enhancements to current technologies designed to improve current services without requiring extensive changes to the existing infrastructure. In the long term, 3G systems such as code division multiple access (CDMA) 2000 and wideband CDMA (W-CDMA)* have been proposed to support the goals established by the International Telecommunication Union (ITU) with International Mobile Telecommunications 2000 (IMT-2000). In addition, high-altitude platform systems such as HAPS (high altitude platform station), HALO (high altitude long operation) fixed-wing aircraft, HELIOS (a NASA experimental high altitude long endurance solar-powered aircraft), and other unmanned air vehicles (UAVs) will have an effect on existing systems due to their large signal footprint and effective radiated power.

As a result of these advances, and in an effort to promote higher visibility of the inter-PCS interference problem, TR46.2 has begun work on the next version of the handbook as a draft American National Standard. While the basic interference estimation process (see the Figure) will remain unchanged, it will be expanded to include future technologies.

In support of this work, ITS is enhancing its multi-user, multi-network PCS interference model (described in Ferranto 1997; see Publications Cited, p. 102) to cover 2.5G and 3G PCS. The model currently profiles the signals generated by the base and mobile stations in the cell under study, in addition to the base and mobile stations in adjacent cells. It takes into account system considerations and management functions (such as power control in CDMA) that are affected by the dynamic nature of the interference. To further enhance the model's usefulness, ITS is expanding it to determine the effects that co-located or adjacent PCS systems have on one another.

* W-CDMA is called UTRA (Universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access) in Europe.



Process used to estimate interference between PCS systems (from TSB-84A).

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Mobile IP Network Access Technologies

Outputs

- Wireless laboratory and field testing of PCS data transport mechanisms.
- Tools and techniques to help understand wireless IP access issues.

In times of national emergency, wireless network access is becoming a primary necessity to insure the uninterrupted service of many Government agencies. It is perhaps unknown to the typical Federal wireless data user, but throughput can depend as strongly on the computing platform as it can on the underlying wireless network. The radio and computing hardware elements, in conjunction with the software protocols that make data communication possible, create a multi-dimensional environment. The ITS wireless data test bed facilitates experiments to identify and analyze the effect of wireless propagation characteristics on data access in these diverse networking environments.

Wireless impairments, such as flat fading and cochannel interference, create problems that are not handled well by networks designed for wired transmission. For instance, fading on wireless links can cause the error rate of the data channel to increase momentarily. Algorithms present in TCP interpret this effect as incipient congestion and back off on the data transmission rate. This behavior is correct over short time intervals, but is incorrect over longer time frames because wireless channel impairment can change very rapidly. The net result of this wired network designed protocol behavior, as applied over wireless links, severely decreases the effective throughput of the data channel. Not only are wired protocols inappropriately applied to wireless connections but present generation cellular and PCS networks can act in unexpected ways when propagating data. The PCS networks were designed for voice communication, which demands low latency and can operate tolerably for relatively large error rates. This kind of network may not be applicable for data communication, which is quite tolerant to varying degrees of latency but is very sensitive to bit error rate (BER).

From the point of view of these Federal users, the most salient network parameter is application speed. At the system engineering level a multifaceted measurement is warranted. Throughput measurements exist within a continuum from the session to the individual IP packet. At the user level, gross measurements representing data services of a given session are sufficient. A more detailed look, suitable to the system engineering point of view, involves measurement of transport times on a packet by packet basis. Both measurements are complicated by the wireless user access to only the end points of the linkage. The intermediate portion of the network remains invisible to the user. These intermediate links may encompass base station to PSTN connections. In either event ITS has the ability to examine complexities of wireless data connections from the low level protocol management signaling to the propagation phenomena that impair wireless data communication.

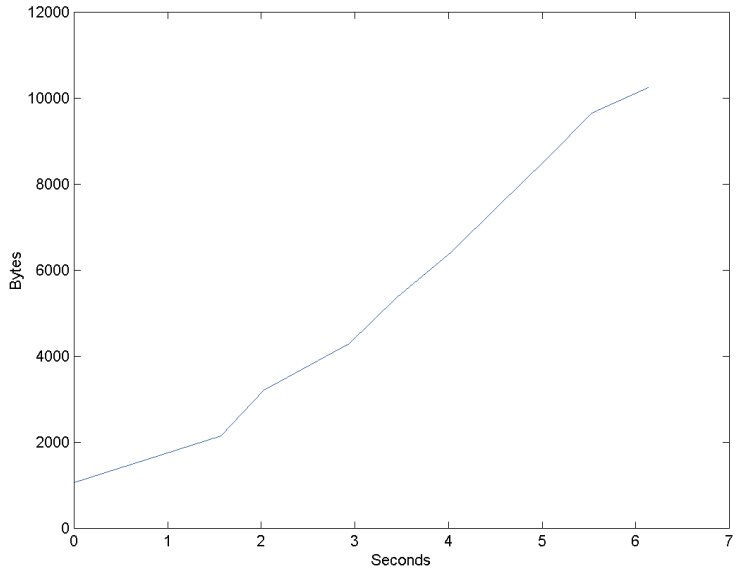

Figure 1. GSM Channel with 10 kB file transfer.

Examples of the capabilities of the ITS wireless data access test bed are displayed in the following Figures. Figure 1 shows a 10 kilobyte file transfer over a GSM channel. In this experiment the maximum transfer rate observed was 19.1 kilobits/sec but the average rate was only 7.2 kilobits/sec. This average data rate is 75% of the 9.6 kilobits/sec expected rate for GSM, whereas the burst rate is almost twice that. Figures 2 and 3 illustrate the effect of different file sizes on the transfer rate over a CDMA channel. In Figure 2, a 10 kilobyte file transfer is measured. Here, the maximum burst rate observed was 16.6 kilobits/sec but the average was 13.5 kilobits/sec. This average data rate is 94% of the 14.4 kilobits/sec expected rate for CDMA, but the burst rate exceeds the expected rate by 15%. Figure 3 shows the result obtained using the same CDMA channel with a larger file, 100 kilobytes in this case. At this larger scale the transfer rate appears much more constant, 8.6 kilobits/sec in this measurement, although we have observed average transfer rates as high as 12 kilobytes/sec over CDMA channels.

As these three graphs indicate, effects due to differences in PCS technologies as well as differing file sizes can be studied using the ITS test bed. Existing tools allow investigation down to the packet level of parameters such as throughput, delay and latency. Future projects include the collection of time statistics for wireless networks, investigation of PCS network discovery tools and verification/validation of propagation models. In addition, the test bed will be augmented with new third and fourth generation technologies as they are brought online.

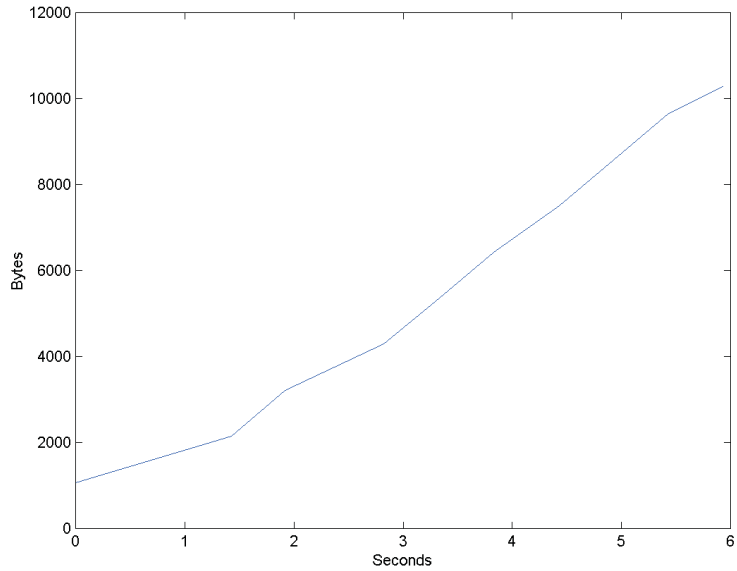

Figure 2. CDMA Channel with 10 kB file transfer.

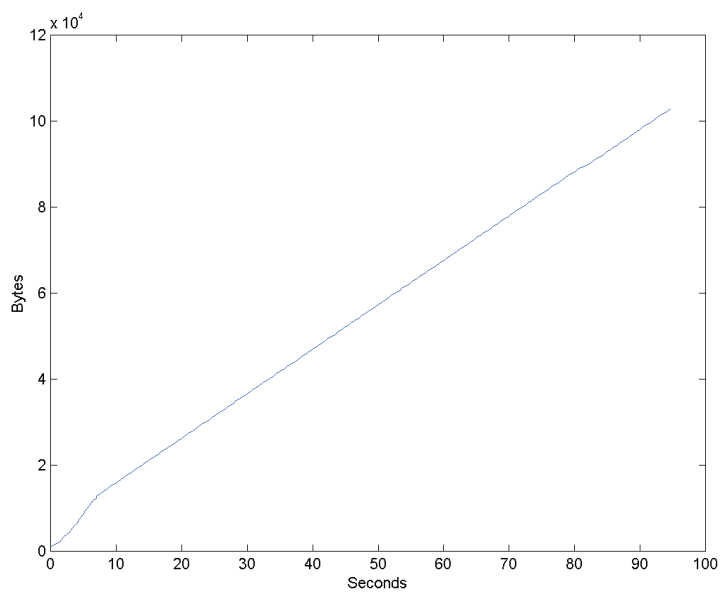

Figure 3. CDMA Channel with 100 kB file transfer.

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Telecommunications Analysis Services

Outputs

- Network access for U.S. industry and Government agencies to the latest ITS engineering models and databases.
- Contributions to the design and evaluation of broadcast, mobile, radar systems, personal communications services (PCS) and local multipoint distribution systems (LMDS).
- Standardized models and methods of system analysis for comparing competing designs for proposed telecommunication services.

Telecommunications Analysis Services (TA Services) gives industry and Government agencies access to the latest ITS research and engineering on a cost reimbursable basis. It uses a series of computer programs designed for users with minimal computer expertise or in-depth knowledge of radio propagation. The services are updated as new data and methodologies are developed by the Institute's engineering and research programs.

Currently available are: on-line terrain data with some 1-arc-second (30 m) and 3-arc-seconds (90 m) resolution for much of the world and GLOBE (Global One-km Base Elevation) data for the entire world; the 1990 census data with the 1997 population updates; Federal Communications Commission (FCC) databases; and geographic information systems (GIS) databases such as the land use/land cover (LULC) database. For more information on available programs see the Tools and Facilities section (p. 85–87) or call the contact listed below.

TA Services is currently assisting broadcast television providers with their transition to digital television (DTV) by providing a model for use in advanced television analysis (high-definition television, advanced television, and digital television). This model allows the user to create scenarios of desired and undesired station mixes. The model

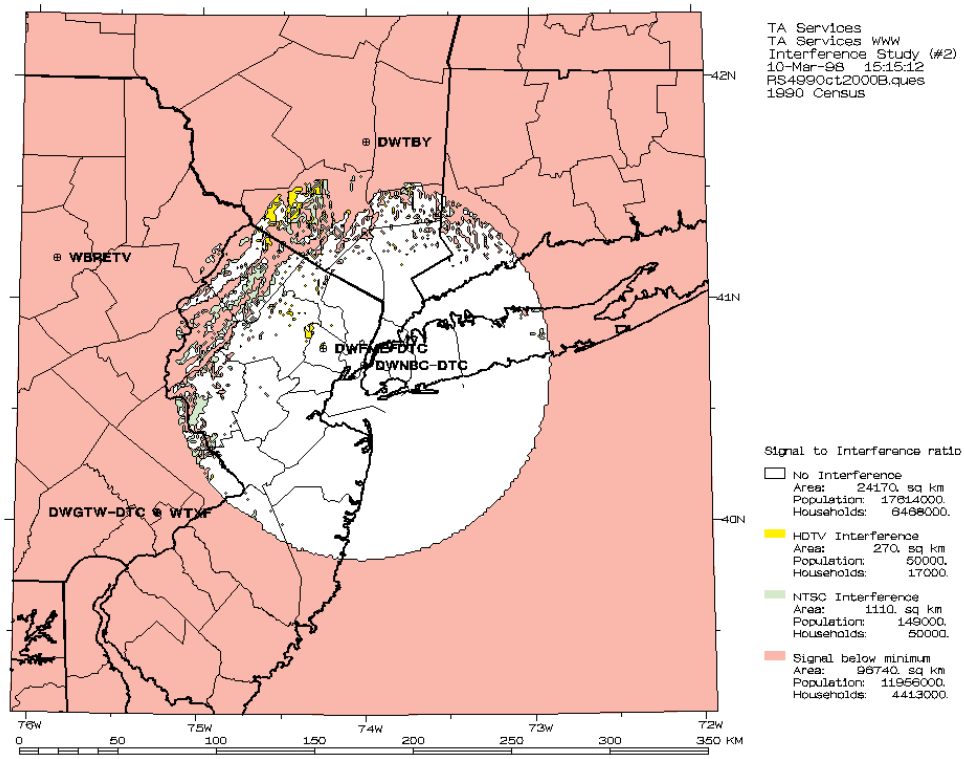

Figure 1. Interference analysis for a proposed digital station in New York.

maintains a catalog of television stations and advanced television stations updated weekly from the FCC from which these scenarios are made. Results of analyses show those areas of new interference and the population and households within those areas. Figure 1 shows the result of a study done for a proposed digital station in New York. In addition to determining the contribution to interference from other stations to a selected station, the model can tell the user the amount of interference a selected station gives to other stations. This allows the engineer to make modifications to the station and determine the effect these modifications have on the interference that station gives other surrounding stations. In addition to creating a plot similar to that shown in Figure 1, the program creates a table which shows the distance and bearing from the selected station to each potential interferer as well as a breakdown of the amount of interference each station generates. This model can be accessed via a network browser.

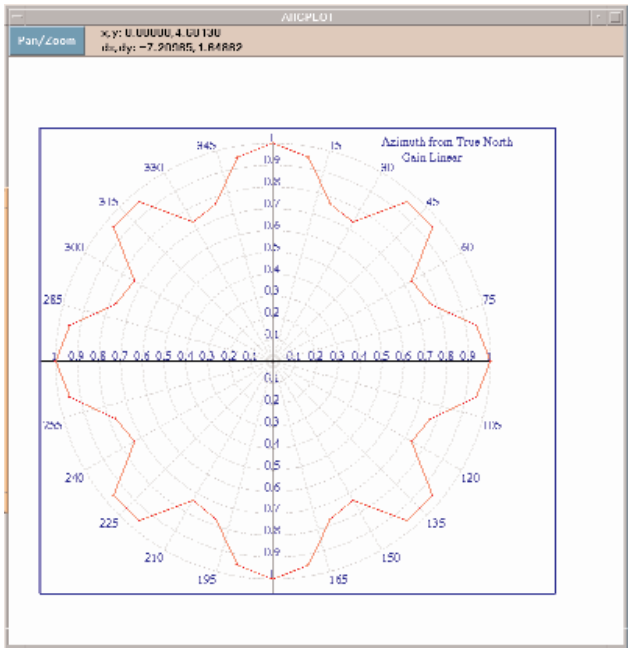

Figure 2. Antenna pattern from the user catalog in the TA Services PCS/LMDS model.

TA Services continues to develop models in the geographic information systems (GIS) environment for personal communications services (PCS) and local multipoint distribution systems (LMDS). A GIS efficiently captures, stores, updates, manipulates, analyzes, and displays all forms of geographically referenced information. The use of GIS has grown substantially over the past several years. As a result, databases necessary for telecommunication system analysis are becoming available in forms easily imported into the GIS environment. These databases, including terrain, roads, communications infrastructure, building locations and footprints, land type and use, and many others, can be maintained in commonly used and available relational database management systems (RDBMS) that can be connected to the GIS or placed into the GIS RDBMS. This greatly reduces the amount of database development necessary in PCS/LMDS modeling.

As the frequency of an application increases, the level of detail required to describe the path also increases. At PCS and LMDS frequencies, we need to know the location of trees and buildings, the kind of vegetation a signal is penetrating, and the shape and materials used in buildings. Software available at ITS allows us to import digital stereo photographs or other remote sensing data taken from aircraft at relatively low altitudes or spacecraft and convert these images to three dimensional models of the region. This highly accurate surface is then imported into the GIS PCS/LMDS model.

The PCS/LMDS model under development at ITS lets a user select a region of interest with a database generated or imported into the model. These environment and analysis results can be displayed in two or three dimensions. A user can create a database of transmitters and antenna patterns from which to create analysis scenarios. The GIS software reads the location of the transmitter from the map and stores it in the transmitter definition table. Antenna patterns can be imported, entered in table form, or drawn on the screen by a user as shown in Figure 2.

Analysis scenarios consist of a set of transmitters, antennas, and models chosen to produce propagation results for a region of interest. Models include a line of sight (LOS) model, a diffraction model, and a ray tracing model under development by two prominent U.S. universities.

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Geographic Information System Applications

Outputs

- Two- and three-dimensional propagation coverages for one or more transmitters.
- Interference and overlap coverages of multiple transmitters.
- Ray tracing analyses for urban environments.

The Communication Systems Planning Tool (CSPT) is a menu driven propagation model developed by ITS to give industry and government agencies access to the latest ITS research and engineering tools at frequencies as high as 50 GHz. The accuracy of the results and the usefulness and flexibility of the presentation of the results are enhanced by the power of a geographic information systems (GIS) background. CSPT allows the user to import digital stereo photographs or other remote sensing data converted to 3-dimensional models of the region. This environment is then taken into consideration as the model calculates the results of the desired analysis. Contained within CSPT are propagation "engines" valid at frequency ranges used by cellular, personal communications services (PCS), radio, TV, pagers, microwave and other communication links. A GIS efficiently captures, stores, manipulates, analyzes, and displays all forms of geographically referenced information in a user-friendly way. Databases include terrain, roads, communications infrastructure, building locations and footprints, land type and use, water bodies, streams, population densities and many others. These are maintained in commonly used relational database management systems (RDBMS).

A graphical description of CSPT is shown in Figure 1. The output shows an analysis area in Washington D.C. made from an imported digital elevation model and color image at 1 meter resolution. There are eight transmitters defined for this particular analysis.

The general flow of CSPT is as follows. The user defines an area, graphically or with latitude/longitude, anywhere in the world, and then imports desired GIS information such as political boundaries, roads, rivers, etc. Then the user creates or imports (from the Federal Communications Commision (FCC) database) transmitter, receiver, and antenna data. Multiple transmitters can be defined for each area. Each transmitter can be made active or inactive for any particular analysis calculation. If the user chooses to perform an interference study (one of the analysis options), then one transmitter must be designated as the "desired" transmitter and others as the interferers. CSPT allows the user a great deal of flexibility in defining antenna patterns. Many vertical and horizontal patterns are included with the software. Their formats include: linear, log relative, log dBi, and log dBd. In addition, the user may create his own pattern using any one of the above formats.

After creating the transmitter database, receivers, and antennas, and after selecting a set of these for a particular study, the user defines the type of analysis to be performed. The analysis can be a propagation prediction of one of the following types:

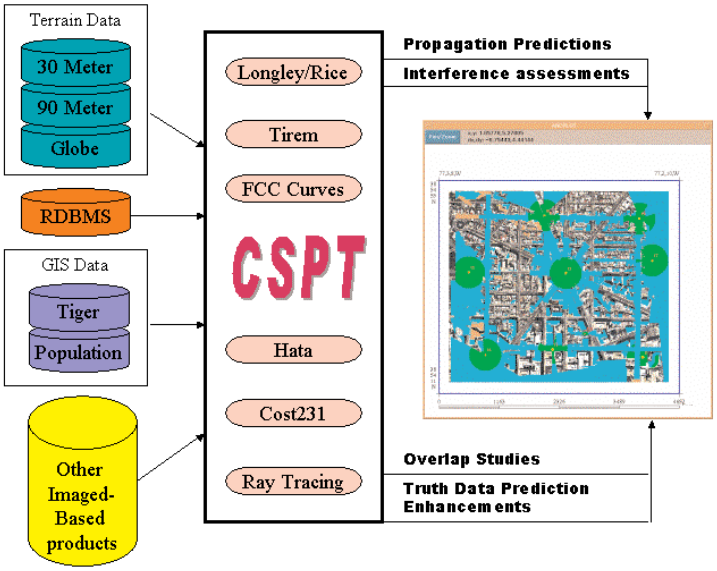

Figure 1. Overview of the CSPT model.

1. Create a line of sight (LOS) coverage only.
2. Calculate signal strength within the LOS region.
3. Calculate signal strength based upon terrain diffraction.
4. Calculate signal strength along a single path.
5. Perform ray tracing analysis (urban environments).
6. Add rain loss to any of the above.

Propagation predictions can be augmented with "truth data" provided by the user, and can be overlayed to determine locations of redundant coverage. The output from a propagation prediction analysis can be displayed in any one of the following forms: field intensity (dBuv/m); available power (dBm); basic transmission loss (dB), or signal/noise power ratio (dB). In addition to running a propagation prediction, the user can select a set of transmitters to use in an interference analysis. Signal strength calculations are performed by one of several prediction models according to the user's choice. The models included are:

- Longley/Rice - for analysis options based upon terrain diffraction.
- Tirem - for analysis options based upon terrain diffraction.
- Hata - for urban or suburban environments without detailed environments.
- Cost231 - for urban/suburban environments without detailed environments.
- Ray Tracing - for detailed urban environments.
- FCC Curves - for areas larger than 5 kilometers.

Analysis results are draped on top of the analysis area image. These results can be shown in two or three dimensions (shown in Figures 2 and 3). Figure 2 shows a single railroad transmitter (white area in upper right) with field strength contours of 50, 60, and 70 dBuV/m. The coverage of the transmitter is good near the transmitter, but not for the railroad tracks (magenta lines) heading south. Figure 3 shows the same analysis as Figure 2 in 3D. Notice that the impact of the mountains on the coverage can be clearly seen. Also, the user can zoom into any region of the analysis area and look at individual cell values of signal strength or interference.

CSPT is available on a UNIX or Windows® NT platform. CSPT contains an extensive help system. Most menus have a "help" button which displays an explanation of the options on that menu. A user's manual is currently being written. We suggest that users have an account with ITS on our TA Services computer so that we may provide phone support.

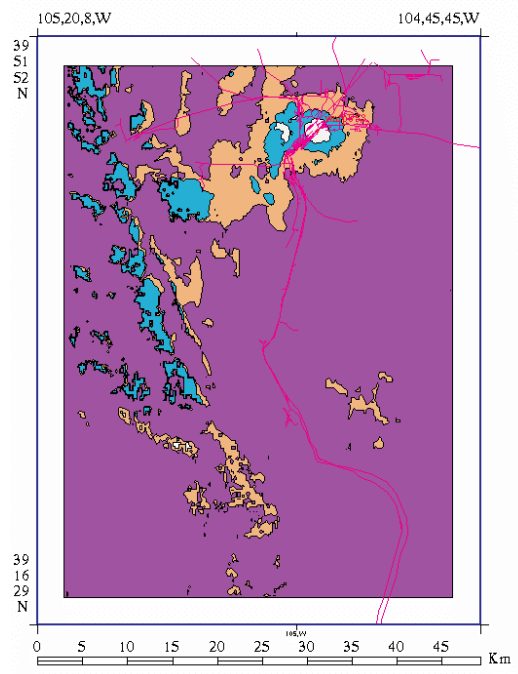

Figure 2. CSPT analysis showing a 3-contour coverage in 2D.

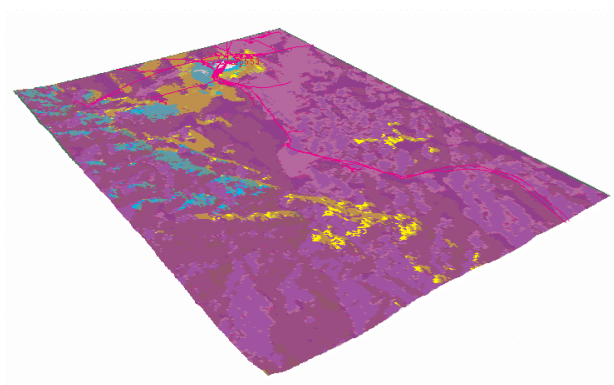

Figure 3. Same coverage shown in Figure 2, in 3D.

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Propagation Model Development

Outputs

- Methodology for prediction of site-specific RF electromagnetic wave propagation.
- Intercomparison/harmonization of ITM and TIREM.

ITS' work on propagation model development focused on two primary areas in FY 2000: enhanced development of a Fresnel-Kirchhoff based methodology for the prediction of site-specific (i.e., point-to-point) radio frequency electromagnetic wave propagation; and intercomparison/harmonization of the two radio frequency electromagnetic wave propagation models employed by NTIA, the Irregular Terrain Model (ITM) and the Terrain Integrated Rough Earth Model (TIREM). This work was sponsored by NTIA's Office of Spectrum Management (OSM). Progress in each area is described below.

Fresnel-Kirchhoff Methodology

The particular attraction of the Fresnel-Kirchhoff methodology is that it provides for the accurate prediction of diffraction by terrain (or other) obstacles with arbitrary shapes and separations, thereby obviating the need to approximate this diffraction as some assumed combination of knife edges, wedges, smooth spheres and/or cylinders. The theoretical basis for the method is Green's Theorem and is, in principle, exact. The development uses approximations, appropriate for the VHF-UHF radio propagation regimes, which are described or implied below. In view of this, we approximate the Green's function for our problem by the free space propagator plus its image in a finitely conducting ground plane. Next, we assume all angles of incidence are nearly grazing. Finally, we assume that variations in the coordinate perpendicular to the plane of incidence are ignorable. Future work in this area will address these limitations.

For a given path's distance, effective earth's curvature and transmit and receive antenna heights above ground, the method proceeds by identifying the sequence of locations on the terrain profile which have direct ray (or its convex hull, in cases where the terrain profile intrudes into the direct ray) clearances less than a specified fraction of a first Fresnel radius, subject to a specified minimum horizontal separation. Horizon points, if present, are always included in the sequence. For each of the locations identified above, consecutively, starting from the location nearest to the transmitter, the total field above the ground, relative to free space, is computed as a function of height. This is done by integration, roughly speaking, from the ground to infinity, over the total field and its image, as a function of height above the ground, at the preceding location. On the first surface, the total field is found by taking the sum of the direct ray from the transmitter and its image into the finitely conducting ground plane presented by the terrain. Currently, the image term is computed using the appropriately polarized plane wave (i.e., Fresnel) reflection coefficient for a finitely conducting ground plane. The last location, corresponding to the receiver, only requires calculation of the total field at a single height, i.e., the receiver's antenna height above ground.

The integrations of the total field and its image over a given height interval are accomplished by piecewise fits, at three discrete heights containing the height interval, of the integrands' amplitudes and phases to quadratic height dependencies. (As a practical matter, it is important to ensure that the phases are on the same Riemann sheet.) However, in some intervals it can happen that one or both of the phase variations under consideration would be better characterized, from a numerical standpoint, as having either linear or constant variation with height. If this occurs, the phase variation is then treated as piecewise linear or constant on the interval in question. For the step to infinity, though, physical considerations require that both integrands' phases vary in height quadratically, with positive second derivatives. This requirement imposes ancillary conditions on the height at which the total field computation can be terminated. That is, the top three heights for which the total field is computed, at a given location, must be great enough to capture a sufficient portion of the contributions to weakly convergent integrands (see below), as well as have the desired phase arrangements amongst the total fields and their corresponding images, for all heights of interest at the next location where the total field as a function of height is to be computed, for the step to infinity.

For quadratic phase variation with height, the integrals thus obtained on a height interval evaluate to a combination of Fresnel integrals and complex exponentials, after a suitable change of variable. For the linear or constant phase variation, the resulting integrals on a height interval are even simpler. The total field at any given height at a new location is then obtained by summation of the results over all height intervals at the preceding location, including the step to infinity. Note, also, that both the amplitude and the phase of the total field strength are available as byproducts of the methodology. (Indeed, both are required at the intermediate steps in the solution.) Phase information can be useful, for example, in propagation predictions for some broadband electromagnetic excitations.

The Fresnel-Kirchhoff prediction methodology has been tested for paths which have analytic solutions. This testing approach was adopted, in part, because it permitted examination of the accuracy of the intermediate results, as well as the final result. Since the accuracy of the final result will depend heavily on the accuracies of the intermediate results, on any given path, it is possible to get information on error propagation due to finite precision arithmetic, horizontal and vertical discretizations, quadratic vs. linear vs. constant phase variation decision conditions and termination conditions. Thus far, indications are that accurate results require double precision arithmetic for paths requiring roughly ten or more intermediate integrations. Given the comments above, accurate results are also strongly dependent on height termination choices and the phase variation choice decision conditions. Current and future work continues on finding robust choices for these for many different path lengths, ray clearances, etc.

ITM & TIREM Intercomparison/Harmonization

During FY 2000, a study was launched to assess the comparison of ITM v1.2.2 and TIREM v3.14 predictions to several measured radio propagation datasets. TIREM v3.14 is the most recent version of that model, containing several bug fixes and improvements over earlier versions that had been used in the past. In all, the measured data considered in the study numbered over 41,000 measurements. The datasets contained results for a wide range of frequencies (approximately 20 MHz - 10 GHz), antenna heights, path lengths and terrain. Ostensibly, the goal of the study is to attempt to make some quantitative statement concerning the relative quality of the prediction error of ITM as compared to TIREM. However, this task is complicated by the fact that a great deal of the measurements and, hence, the predictions, within each individual dataset considered in the study are correlated. Given this, current and future work will focus on methods of removing the effects of the correlations from the measurements and predictions. Preliminary results of the study are shown in the Table below. However, due to strong correlations within each dataset, the reader is cautioned against imputing great significance to these statistics.

Comparison of the Overall Dataset Prediction Errors' Statistics for ITM and TIREM

Dataset	No. of meas.	ITM mean (dB)	TIREM mean (dB)	ITM std. dev. (dB)	TIREM std. dev. (dB)
CO. MTNS.	550	-17.1 +/- .7	-4.4 +/- .6	16.2 +/- .5	13.7 +/- .4
CO. PLNS.	1983	-14.9 +/- .2	-4.4 +/- .2	10.2 +/- .2	9.9 +/- .2
NE OH.	1787	-10.1 +/- .2	0.0 +/- .2	9.2 +/- .2	9.6 +/- .2
R-1	6780	2.0 +/- .2	1.2 +/- .1	13.9 +/- .2	12.0 +/- .1
R-2	2458	-7.5 +/- .5	-18.4 +/- .4	25.7 +/- .3	20.8 +/- .3
R-3	5149	1.9 +/- .2	2.8 +/- .2	11.6 +/- .2	11.4 +/- .1
R-4	9498	-12.8 +/- .2	-14.1 +/- .2	16.6 +/- .2	16.6 +/- .1
VA.	1655	-.9 +/- .3	-.2 +/- .4	13.2 +/- .3	15.6 +/- .3
ID.	435	-17.5 +/- .7	-10.9 +/- .6	14.5 +/- .4	11.9 +/- .4
WA.	892	-2.4 +/- .4	5.1 +/- .4	12.8 +/- .3	12.0 +/- .3
WY.	704	-11.9 +/- .6	-6.8 +/- .5	14.6 +/- .4	12.5 +/- .3
Ft. Hua.	372	-3.0 +/- .6	11.4 +/- .3	11.5 +/- .3	6.0 +/- .2
TASO	8865	-3.2 +/- .1	-1.2 +/- .1	12.5 +/- .1	14.0 +/- .1

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Time-hopped UWB Simulation Analysis for Bandwidth Correction Factor

Outputs

- Peak and average power as a function of victim receiver IF bandwidth from 0.3 to 100 MHz for time-hopped or pulse-position-modulated (PPM) ultrawideband (UWB) systems.
- Transmitter block diagram, simulation and power calculation process for time-hopped UWB systems.
- Received UWB spectra, time waveform, and envelope for no dither and 50% dither in victim receiver narrow IF bandwidth of 3 MHz.

Interest by the Government and private sector in the potential application of ultrawideband (UWB) devices has stimulated a measurement and analysis program to determine the interference effect of these devices on victim receivers. Results are shown for a class of time-hopped (time-dithered) UWB systems modeled and simulated from an analytic description of the system. These simulated time waveforms and Fourier spectrum results are analyzed to show the effect of a receiver intermediate frequency (IF) bandwidth (BW) on peak and average power. These peak and average power curves provide the basis for establishing a normalized bandwidth correction factor (BWCF) curve and equation. The BWCF is used to estimate peak power over a range of BWs from average power measurements made in a 1-MHz BW. This BW is prescribed by the Federal Communications Commission for Part 15 devices. Simulation of the UWB devices complements measurements and other analytic model results for these devices.

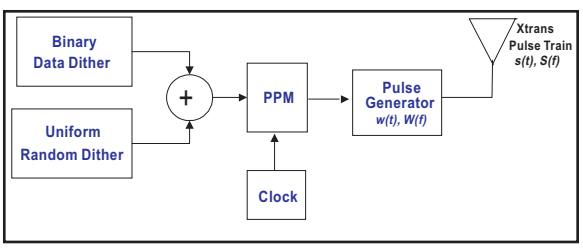

Figure 1. PPM ultrawideband system model.

The simulated time-hopped UWB system block diagram is shown in Figure 1. The system transmits a quasi-periodic, very low duty cycle, dithered pulse train s(t) where delta functions are shaped with a Gaussian 2nd derivative filter. The shaping filter for a specific hardware configuration depends on the transmit and receive antennas, and may deviate somewhat from this model. The specific pulse shape is probably not as important a factor in determining a receiver's narrow IF BW response as the pulse width and corresponding BW. The receiver IF filtering will remove pulse shape details if the pulse is sufficiently narrow and corresponding BW sufficiently wide, compared to the receiver IF BW. In this system the dither consists of two components: a pseudo-random time-hopping dither and a data dither. Usually the time-hopping dither is large compared to the data dither. In our case the time-hopping dither was uniformly distributed between 0 and 0.5T (50% dither); whereas the data dither represented binary 0s and 1s with 0 or 0.045T (4.5% dither). The time-hopping dither values are commonly generated from a pseudo-noise sequence. An undithered pulse repetition frequency (PRF) of 10 MHz was used which made the nominal pulse train period T= 100 ns. Simulation results were also obtained for the non-dithered case where the waveforms are periodic with a period T=100 ns and corresponding line spectra with a fundamental frequency equal to the PRF.

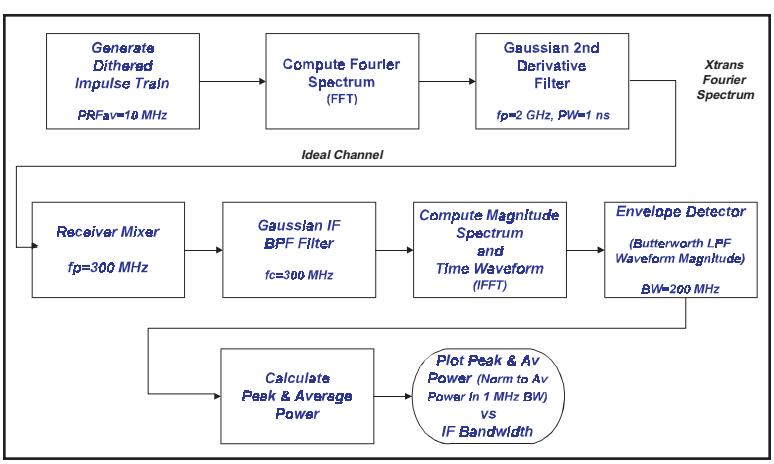

Figure 2. Simulation and power calculation process.

The simulation and power calculation process are shown in the flow diagram of Figure 2. A periodic impulse train is dithered by the combined amount of dither and then Fourier transformed. Then the spectrum is shaped using the Gaussian 2nd derivative filter transfer function W(f). The receiver mixer and IF filter are simulated next, followed by an envelope detector used in a spectrum analyzer. The final step calculates and displays peak and average power.

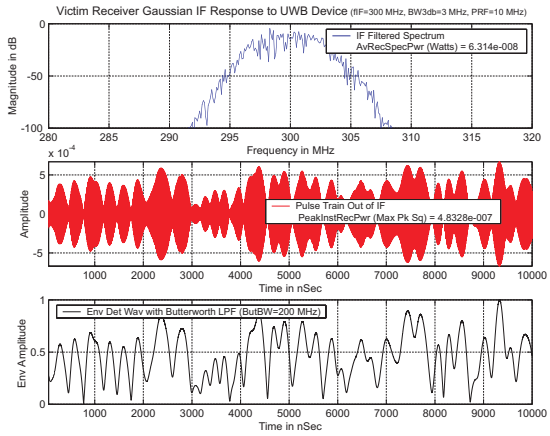

Figure 3. Receiver 3 MHz IF BW output spectrum, pulsetrain, and envelope detected pulsetrain (50% dither).

Figure 3 shows an example received output for a 3 MHz IF filter at the receiver. This case is particularly interesting since output pulses (IF - middle and envelope - bottom) are smeared together for this narrow BW. At a BW of 30 MHz the pulses out of the IF just touch each other. For wider BWs they are completely separated and for narrower BWs they are overlapped, causing peaking in the envelope. It is particularly interesting to compare the 50% and 0 dither cases. With the periodic (no dither) pulse train, the IF filter gets pinged by pulses at a regular interval and just provides periodic pulses out of the detector without peaking. At a BW of 3 MHz the 50% randomly dithered pulse train creates significant peaks and valleys (1 down to 0), whereas the periodic pulse train has a constant envelope coming out of the IF filter.

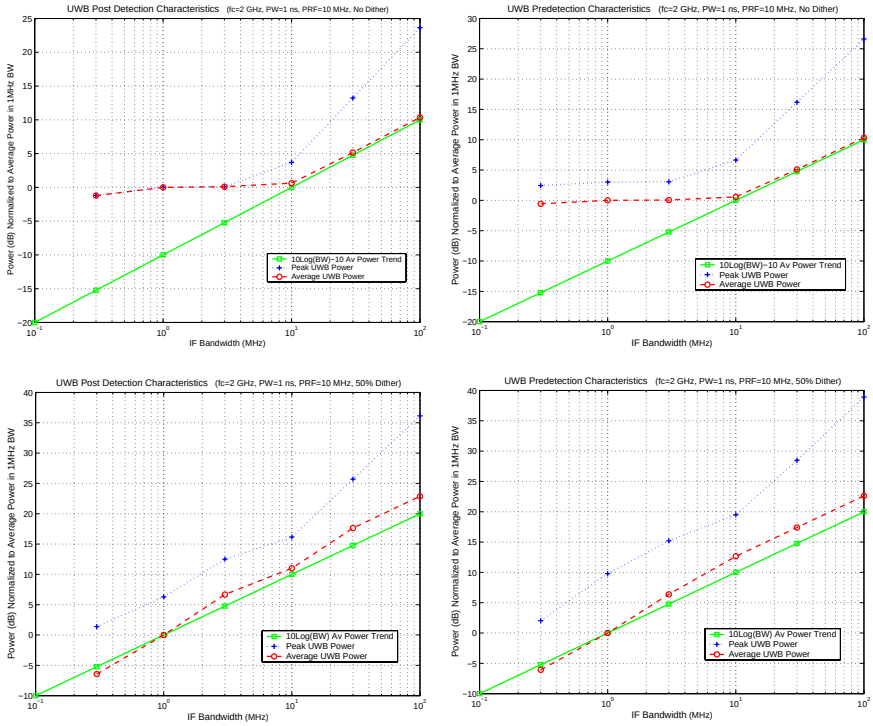

Figure 4. Receiver peak and average power dependence on IF bandwidth (Top no dither: Left— postdetection; Right—predetection; Bottom 50% dither: Left— postdetection; Right—predetection).

Figure 4 shows the received instantaneous peak and average power computed from the simulated time waveforms for receiver IF BWs ranging from 0.3 MHz to 100 MHz. These powers were normalized to the average power in a BW of 1 MHz. Consequently, the average power curves all go through 0 dB at 1 MHz. These curves provide the basis for which to develop BWCFs. The BWCFs are used to estimate the amount of peak power at a given BW from measuring the average power in this 1-MHz BW. In addition to peak and average power curves, a third guideline is provided. This straight line on a log-log plot is the 10 log (BW) average power trend. It follows the average power quite well for 50% dither (both pre- and post-detection); however, for the non-dithered case it follows only for BWs greater than or equal to the PRF.

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Jammer Effectiveness Model

Outputs

- Windows® 95/98/NT version of Jammer Effectiveness Model for communications and radar systems analysis in use by the U.S. Army and other Federal agencies.
- Multiple jammer and interferer analysis capability on a wireless network for use in performance evaluation in an electronic warfare or interference electromagnetic environment.

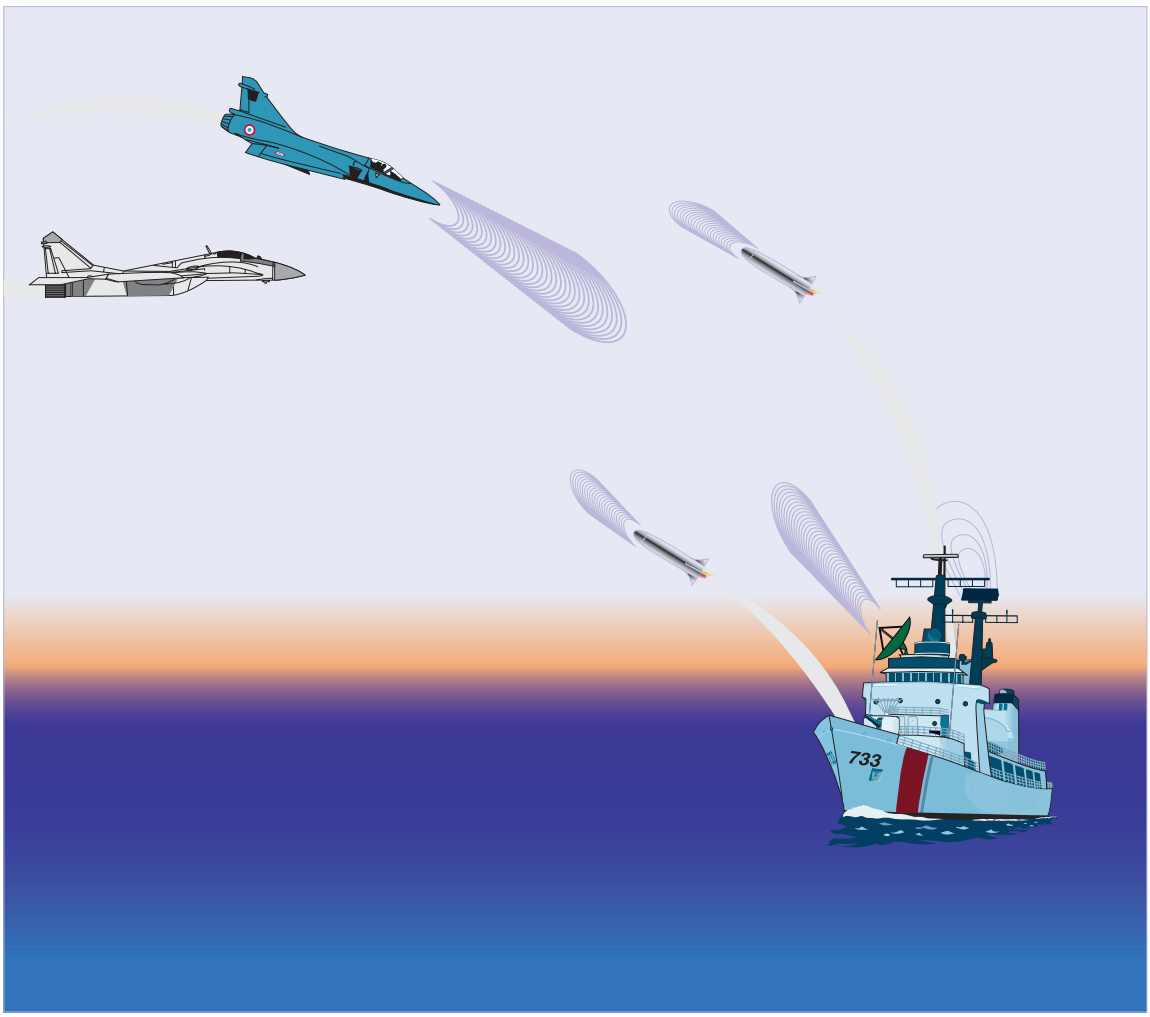
In FY 2000, ITS completed the conversion of the Jammer Effectiveness Model (JEM) to operation in the Windows® 95/98/NT environment. JEM was developed by ITS for the U.S. Army in order to evaluate electronic warfare scenarios on a personal computer. Other programs with similar capabilities require mainframe computers. This model is a very flexible analysis tool and can be used to perform many different types of analysis, because it is highly structured and modular in design. ITS has developed two versions of JEM for systems performance evaluation in an electronic warfare environment: one for communications analysis and the other for radar analysis. Each version of JEM includes a user-created catalog of equipment, ground stations, aircraft and satellite platforms; the software for creating and maintaining this catalog; a climatological database for much of the world; a library of propagation subroutines; and the analysis software. The JEM propagation library includes subroutines for use in calculating clear-air attenuation, rain attenuation, multipath attenuation, diffraction losses, and troposcatter losses. The valid frequency range of the communication version of JEM is currently 2 MHz to 300 GHz, while that of the radar version is currently 30 MHz to 20 GHz.

JEM uses scenario descriptions to completely characterize a communication link or radar configuration with or without a jamming situation. Data entry to create a scenario description is simplified by the use of user-friendly menus and options. Each scenario description is saved in a database, and includes: ground or airborne station location, three-dimensional geometry description, equipment characteristics, and physical factors such as climate and terrain. JEM contains an inventory of specific analyses that can be performed on the physical configurations represented by the scenario description data.

The communications analysis version of JEM is primarily used to model communication systems in electronic warfare scenarios where these systems are being jammed or interfered with. This version of JEM is organized into six scenarios, each of which represents either a communication path geometry description or a jamming geometry description. The four scenario types in the communication geometry description are: ground-to-ground, ground-to-satellite, ground-to-aircraft, and aircraft-to-satellite. The two scenario types in the jamming geometry description are jamming and jammer versus network. The jamming scenario analyzes: received jammer power versus distance, received transmitter power versus distance, jammer footprint, and isopower contours. The jammer versus network scenario analyzes and evaluates the effects of up to three jammers on up to five communications nodes. For the jamming geometry description, the receiver, transmitter, and jammer platforms can be on the ground or airborne.

The jamming and jammer versus network scenarios are the major features of JEM for electronic warfare and interference analysis. The other four scenario types are used to help evaluate and design microwave communication systems. They allow the user to simulate a wide variety of propagation effects on the system that occur in the higher frequency ranges by including clear-air absorption losses and losses due to rain attenuation. In FY 2000, three-dimensional antenna pattern capability was added to JEM.

The radar version of JEM allows radar analysis for different combinations of radars and jammers that are on the ground or carried by airborne stations. The radar scenario analyses consist of evaluating the performance of a radar trying to detect and track a target. The analyses can be performed both with and without the presence of a jammer. A scenario includes the jamming of an airborne radar by a ground-based or airborne jammer to protect potential targets that can either be collocated with the jammer or separated from the jammer. The three-dimensional geometry of these radar scenarios requires three-dimensional antenna patterns, included in the analysis models.



Aircraft with standoff and self-screening jammers avoiding detection by a shipboard fire-control radar and radar-guided missiles (illustration by A. Romero).

There are three analysis modes available in the radar jamming scenario: a radar jammer footprint, a radar isopower contour, and a radar burn-through range. For the radar jammer footprint analysis a jammer is able to jam a radar that is on or within a contour of distance to jammer versus azimuth angle, and prevent it from detecting a target. The isopower contour analysis is a plot of signal power density about the radar or jammer versus distance and azimuth angle about the radar or jammer. The radar burn-through range analysis is the minimum range to the target versus azimuth angle at which the target is obscured by jamming. It is also the maximum range versus azimuth angle at which the radar detects the target.

The Figure illustrates two aircraft, a stand-off jammer and a self-screening jammer, attempting to avoid detection by a shipboard fire-control radar and a radar located in the guided missiles. The shipboard fire-control radar will detect the aircraft and inform the missiles of its location. The radar guidance systems on the missiles will provide terminal guidance to the missiles to destroy the aircraft targets. The stand-off jammer is protecting other airborne targets by jamming both the shipboard and missile radars. The self-screening jammer is protecting itself from detection by the shipboard radar and the missile radar guidance systems. The JEM software allows performance prediction of the jammers' ability to avoid detection in this scenario.

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