Telecommunications Engineering, Analysis, and Modeling

The Telecommunications Engineering, Analysis, and Modeling Division conducts studies in these three areas for wireless and wireless-wireline hybrid 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 national security/emergency preparedness (NS/EP), military, and commercial environments.

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 specialized applications.

Modeling has been one of ITS' greatest strengths for many years. Propagation models are incorporated with various terrain databases and data from other sources, such as the U.S. Census. Adaptations of historic models, and those for more specialized situations have been developed, enhanced, and compared. ITS engineers contribute their propagation modeling expertise to the ITU as well.

The **Wireless Networks Research Center** (WNRC), opened in May 2001, has been home to four projects in its first year. ITS engineers have been able to assist other Federal agencies with emerging technologies in 2.5G and 3G wireless communications. The WNRC was designed to accommodate studies of emerging technologies and PCS, analysis of wireless protocols, and studies of wireless network effects such as congestion and capabilities such as priority access. (See page 75 for more information about the WNRC.)

Areas of Emphasis

ENGINEERING

PCS Applications The Institute helps the Telecommunications Industry Association (TIA) committee TR46.2.1 develop an inter-PCS interference model and handbook. ITS also serves as editor for this committee. The project is funded by NTIA.

Cellular and PCS Network Measurements Analysis of commercial wireless networks is achieved by collecting network protocol messages and physical RF link measurements. To help develop a better understanding of the loading of commercial wireless networks, ITS has conducted a series of IS-95 network code channel occupancy measurements. This work is funded by multiple Department of Defense agencies

Wireless Network Analysis and Forecasting Wireless communication links are used to extend wired networks to solve the first mile/last mile connectivity problem. The Institute is actively investigating wireless networks and services expected to be used in the future, including the interference between wireless network technologies, such as that between 802.11b and Bluetooth. This work is funded by multiple DoD agencies.

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 available to government and non-government customers and 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. In addition, ITS has developed a 3-D fly-through capability. This work was funded by the Dept. of Defense and ARINC.

MODELING

Propagation Model Development & Comparisons The Institute develops enhancements to existing propagation models. This research includes examination of various related databases, such as terrain, and how they interact with the models. Models are also examined using sets of measured data. Some of the technical products from this effort are presented on behalf of the U.S. at the ITU-R. This project is funded by NTIA.

PCS Applications

Outputs

- Technical contributions to an industry-developed inter-PCS interference standard for predicting, identifying, and alleviating interference related problems.
- Interference models for the PCS technologies currently in use, as well as proposed third generation (3G) systems.

Personal Communications Services (PCS) is widely used for mobile voice and data communications and is becoming an important resource for implementing emergency telecommunication services following a natural or man-made disaster. Several factors contribute to diminished channel capacity of a wireless network. A major limiting factor of channel capacity is co-channel interference for channels in the same technology. Another stress on channel capacity occurs from multiple, independent, non-interoperable systems that service the same geographical area, often using the same frequency bands and infrastructure (base station sites and towers). In addition, natural and man-made disasters can damage the terrestrial telecommunication system, forcing users to migrate to cellular resources. This sudden influx of traffic by private, commercial, civil, and Federal users results in wireless system overloads, a decrease in signal quality, 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.

ITS contributes to understanding inter-PCS interference by participating in the Telecommunications Industry Association (TIA) committee TR46.2 (Mobile & Personal Communications 1800-Network Interfaces). Through this committee, ITS helps develop the Technical Service Bulletin "Licensed Band PCS Interference." This bulletin is a first step in characterizing the interfering environment caused by large numbers of active users and competing technologies.

However, this work requires tools to characterize the interference experienced by PCS air-interface signals. PCS interference models are tools that can be used to predict levels of interference and identify sources of interference. Information from simulations or simulators fed by these models can be used to develop methods to alleviate existing interference problems and even avoid future interference problems. Several standard propagation models are accepted by industry members (i.e., Okumura and COST-231/Walfish/Ikegami) but no interference models have been developed or accepted. ITS is developing a series of PCS interference models starting with a model based on the ANSI/TIA/EIA-95B standard (Rusyn 2002, see **Recent Publication** on next page). The model covers system-specific interference modeling to determine co-channel interference from both immediate and adjacent cells.

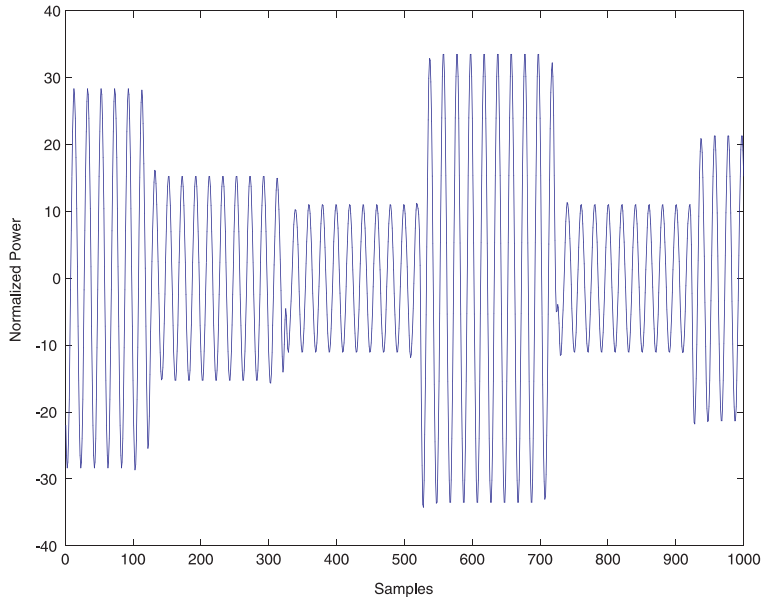

Figure 1. The output of the ITS models can be used in either software- or hardware-based simulations.

The output of the physical model is a sampled modulated signal which is the composite of the signals transmitted from all sources identified in a specified scenario. Software- and hardware-based simulations can use the sampled signal from the model to evaluate system designs (see Figure 1). These simulations can characterize one-on-one, one-on-many, and many-on-one interference. As a result, potential solutions to congestion can be proposed to solve existing problems or to anticipate and avoid potential problems. ITS is currently working on the verification and validation of the first, ANSI 95-B, model. The validation process will include both software and hardware aspects of the model.

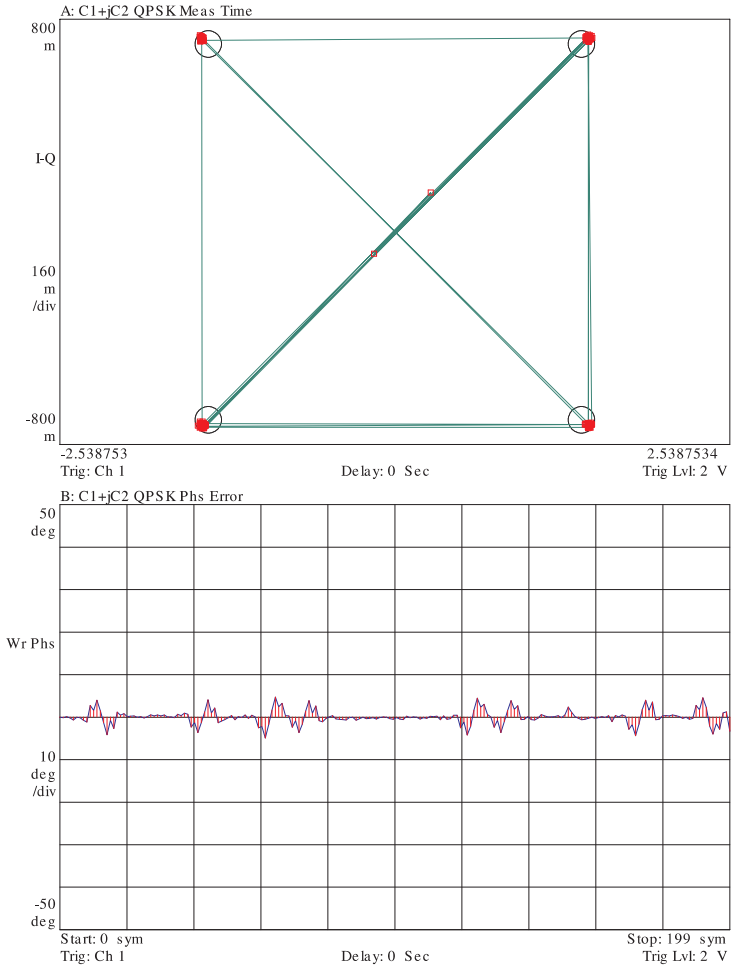

Figure 2. The ITS model can show properties of a PCS signal such as the phase error shown here.

The ANSI 95-B model is the first in a series of models that will include third generation (3G) systems. The communications industry has proposed and developed new technologies to address system limitations such as system capacity, coverage, and data transfer rates. 3G systems have been proposed to support the goals established by the International Telecommunication Union (ITU) with IMT-2000. These systems include cdma2000 and W-CDMA, known as UTRA (Universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access) in Europe. These technologies present new issues for the existing PCS networks. The new 3G systems will need to coexist with current PCS systems for a period of time. The series of ITS models will include cdma2000 and W-CDMA. All of the new models are being developed such that the output data from the models will be compatible with the output data from the other models in the series; this will allow users to characterize potential problems between the different technologies as the 3G systems are implemented as well as characterizing interference problems with the existing PCS networks (see Figure 2).

Recent Publication

T.L. Rusyn, “Co-channel interference modeling of the ANSI/TIA/EIA-95-B Code Division Multiple Access cellular system,” in *Proc. 2002 IEEE EMC Symposium*, Minneapolis, MN, Aug. 2002.

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Cellular and PCS Network Measurements

Outputs

- Network discovery.
- Wireless network capacity and interference measurements.
- Hostile environment characterization.

The Federal Government is relying more heavily on commercial wireless infrastructure to satisfy its communications needs. Consequently, government services are increasingly dependent on commercial wireless infrastructure. In times of national emergency it is imperative to maintain a continuity of government service over these infrastructures so that critical government services are not interrupted. Therefore, it is crucial that the government have an understanding of the commercial networks that it is relying on.

In contrast to wired networks, wireless networks exhibit an ephemeral and dynamic relationship between services and resources. At each transaction, the measurable RF and network parameters will change depending on the demands of that particular transaction. It is essential to investigate both of these domains, radio and network, in order to understand the network behavior, since simple RF power measurements alone are inadequate.

Analysis of commercial wireless networks is achieved by collecting network protocol messages and physical RF link measurements. Both types of data are needed to identify wireless network characteristics such as usage patterns, channel resource allocation and network topology. This multifaceted viewpoint is necessary since many wireless network architectures rely on spread spectrum techniques to increase user density. Without this real time information about the air interface and the network interface, parameters like channel occupancy would not be obtainable. For instance, in IS-95 networks, the paging channel must be decoded to gain access to the Walsh code domain which is required to measure traffic channel activity. A similar problem exists in GSM networks, where frequency hopping sequences and time slot allocations from control channels are needed to identify user activity. These kinds of measurements are not possible without examining the integral connection between network protocols and radio resources. These tools are used to identify the intricacies of wireless infrastructure topologies in real time.

To help develop a better understanding of the loading of commercial wireless networks, ITS has conducted a series of IS-95 network code channel occupancy measurements. The code domain correlation strength data was collected over several time regimes. Both continuous and discrete measurements were made during potential busy hours and busy daytime periods. A statistical analysis of the IS-95 base station code channel occupancy was then conducted. Results of the analysis are shown in Figures 1 and 2, which show the channel occupancy and channel idle time distributions, respectively. The data in Figure 1 are suggestive of a lognormal distribution. Previous investigators have found that call holding distributions exhibit a lognormal

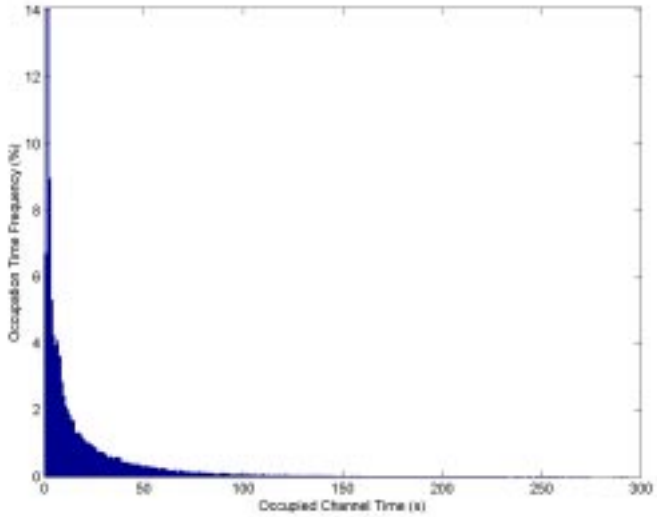

Figure 1. Occupied channel time distribution (discrete case).

characteristic.* This contrasts with the exponential distribution observed in wireline systems.

The second distribution, Figure 2, examines the time between successive uses of a code channel. Essentially, this is a look at the call arrival model, and shows that it too represents the lognormal distribution. In contrast to the occupancy, or channel holding-time model in the previous figure, this result was unexpected since previous investigators had found an exponential distribution for this statistic.* The discrepancy might be due to the abstracted nature of code power measurements versus true user occupancy data.

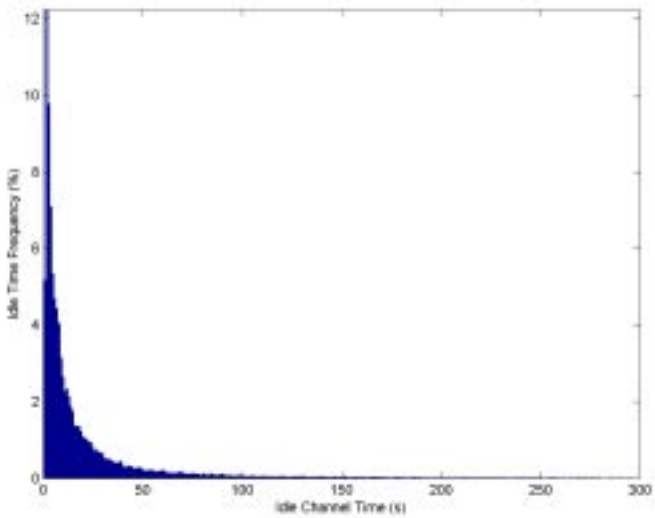

Figure 2. Unoccupied channel time distribution (discrete case).

Since there is very little public domain information available about real time cellular/PCS usage, this work will help in the development of usage pattern models for both commercial and government users. This kind of data has added benefit to Federal network planners in that it is an independent evaluation of commercial providers of government communication services.

Figure 3. Wireless phones used in cellular and PCS network measurements in the ITS Wireless Networks Research Center (photograph by S. Wolf).

ITS has also investigated issues relating to GSM interference. ITS has conducted a series of experiments that explore the behavior of GSM handsets in hostile environments. Such an interference environment would be expected to materialize in times of national emergency. Experiments attempted to identify user recognizable and measurable manifestations of system congestion or other manmade sources of interference. These tests were designed to help quickly identify network overload and vulnerabilities.

* C. Jedrzychi and V.C. M.Leung, "Probability of channel holding time in cellular telephony systems," in *Proc. 46th IEEE Vehicular Technology Conference, Mobile Technology for the Human Race*, Volume 2, 1996, pp 247-251.

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Wireless Network Analysis and Forecasting

Outputs

- Wireless ad hoc network research.
- Forecasting of future wireless technologies.
- Studies of WPAN to WLAN interference.

Wireless communication links are used to extend wired networks to solve the first mile/last mile connectivity problem. The advantages of economy and flexibility are making wireless data links more attractive relative to fixed infrastructure, which is more expensive to upgrade and whose inherent limitations restrict user mobility. Wi-Fi (wireless fidelity) networks essentially extend the range of wired networks, rather than operating as autonomous and/or independent networks. Wired networks are extended via wireless access points, where multiple wireless communication links connect to a central point. The nodes that make up a Wi-Fi network communicate through a wireless access point, rather than peer-to-peer. This topological similarity with wired networks does not exploit the advantages of wireless links, which posess the unique features of mobility and self association. Peer to peer communications, such as those defined in the 802.11 standard and Bluetooth, only partially take advantage of the self association characteristic of wireless communication. Self associating wireless networks are known as ad hoc wireless networks. ITS is examining the use of ad hoc wireless networks for use in Federal communications architectures. Research at the Institute is focusing on how to make these ad hoc wireless networks suitable and secure for Federal wireless users.

The Institute is actively investigating the kinds of wireless networks and services Federal users will be seeing in the future. These networks are being examined for suitability to interface to mobile government security services. In particular, common interfaces are being closely examined since they may aid in the rapid adoption of emerging wireless technologies. ITS is attempting to identify the interfaces, both software and hardware, that will allow a broad range of government wireless communications services to be developed and deployed. Future wireless networks, such as IEEE 802.15 and IEEE 802.16, which are on the verge of being fielded, promise to make broadband services widely available. IEEE 802.15 will support data rates of up to 54 Mbps with a range of tens of meters. This technology will provide the capability to send real-time video over

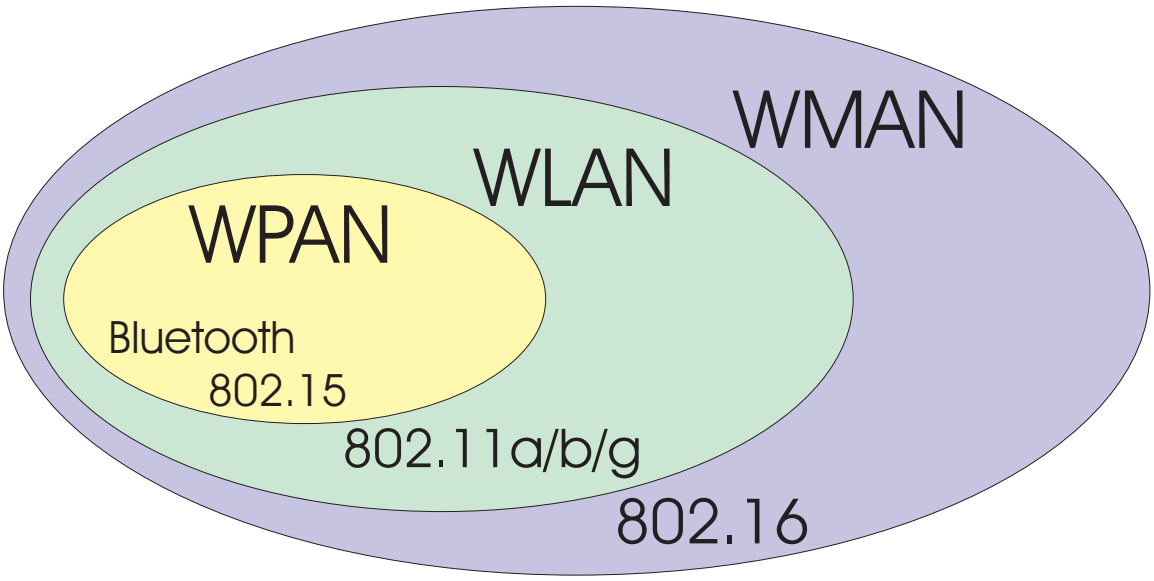

Figure 1. Hierarchical connectivity between wireless network standards

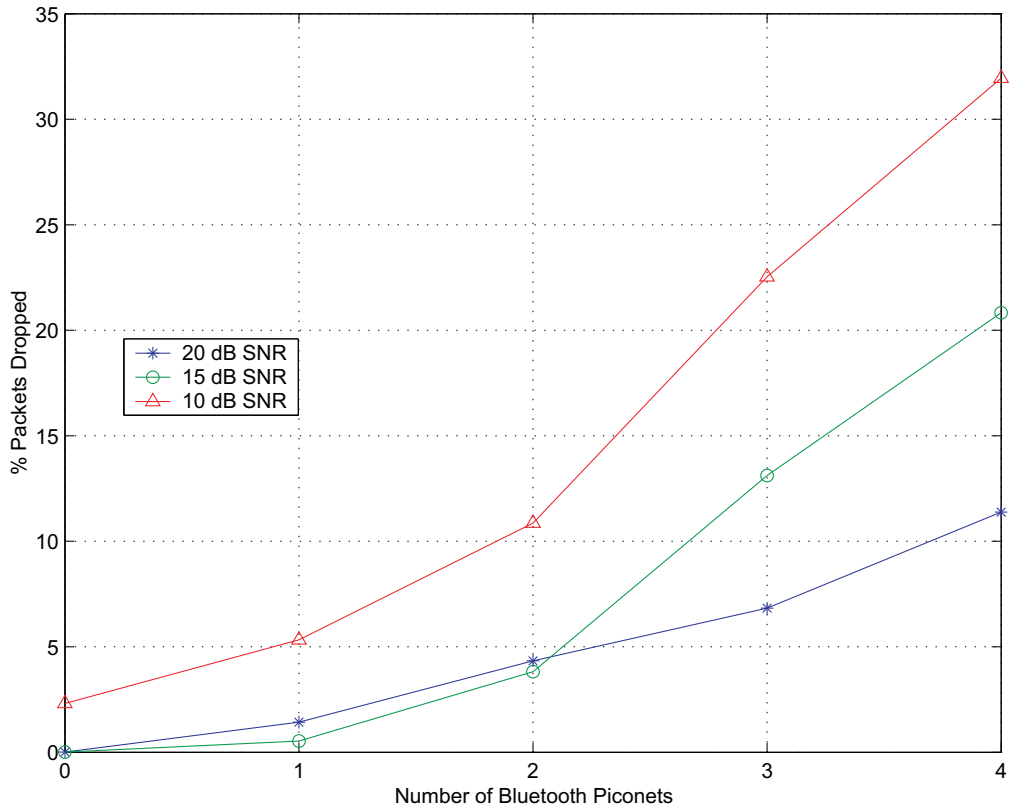

Figure 2. Percent packets dropped vs. active Bluetooth piconets.

piconets (small networks of devices) in the unlicenced 2.4 GHz band. Piconets are also identified as wireless personal area networks (WPAN). IEEE 802.16 is designed for data rates of up to 155 Mbps in a point-to-multipoint metropolitan area network (MAN). A MAN facilitates the connection of multiple wireless LANs over a range of 50 km. A hierarchical connectivity diagram of these networks is shown in Figure 1.

Another area of research centers on the interference between wireless network technologies. The Wi-Fi (IEEE 802.11b) and Bluetooth wireless networking technologies are widely available and are increasingly used in field applications when government data infrastructures do not exist. Unfortunately, interference between these networks can create vulnerabilities for government emergency services, particularly when these networks are used as ad hoc data infrastructures. Wi-Fi operates in the unlicenced 2.4 GHz band, uses direct sequence spread spectrum (DSSS), and supports data rates of up to 11 Mbps. It is typically deployed in networks ranging up to 100 meters in airports, homes and businesses. Bluetooth, which is also in the 2.4 GHz band, uses frequency hop spread spectrum (FHSS), supports data rates up to 1 Mbps, and typically operates in piconets of up to 10 meter range. Bluetooth piconets are used as wireless data cables to connect peripherals such as printers to PDAs or to connect headsets to handsets. Although these networks are designed for somewhat different applications, they are often found in the same area, and consequently may interfere with each other. ITS has been exploring the interference between these wireless networks by conducting a series of measurements. Figure 2 above shows the percentage of dropped Wi-Fi packets versus the number of active Bluetooth piconets. As the figure indicates, there is increasing packet loss on the Wi-Fi link as the number of piconets increases and the Wi-Fi link power decreases.

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Telecommunications Analysis Services

Outputs

- Internet 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, and 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 1-arc-second (30 m) for CONUS and 3-arc-second (90 m) resolution for much of the world and GLOBE (Global One-km Base Elevation) data for the entire world; the US Census data for 2000, 1997 update, and 1990; and Federal Communications Commission (FCC) databases. For more information on available programs see the Tools and Facilities section (pp. 74-75) or call the contact listed below.

TA Services is currently assisting broadcast television providers with their transition to digital

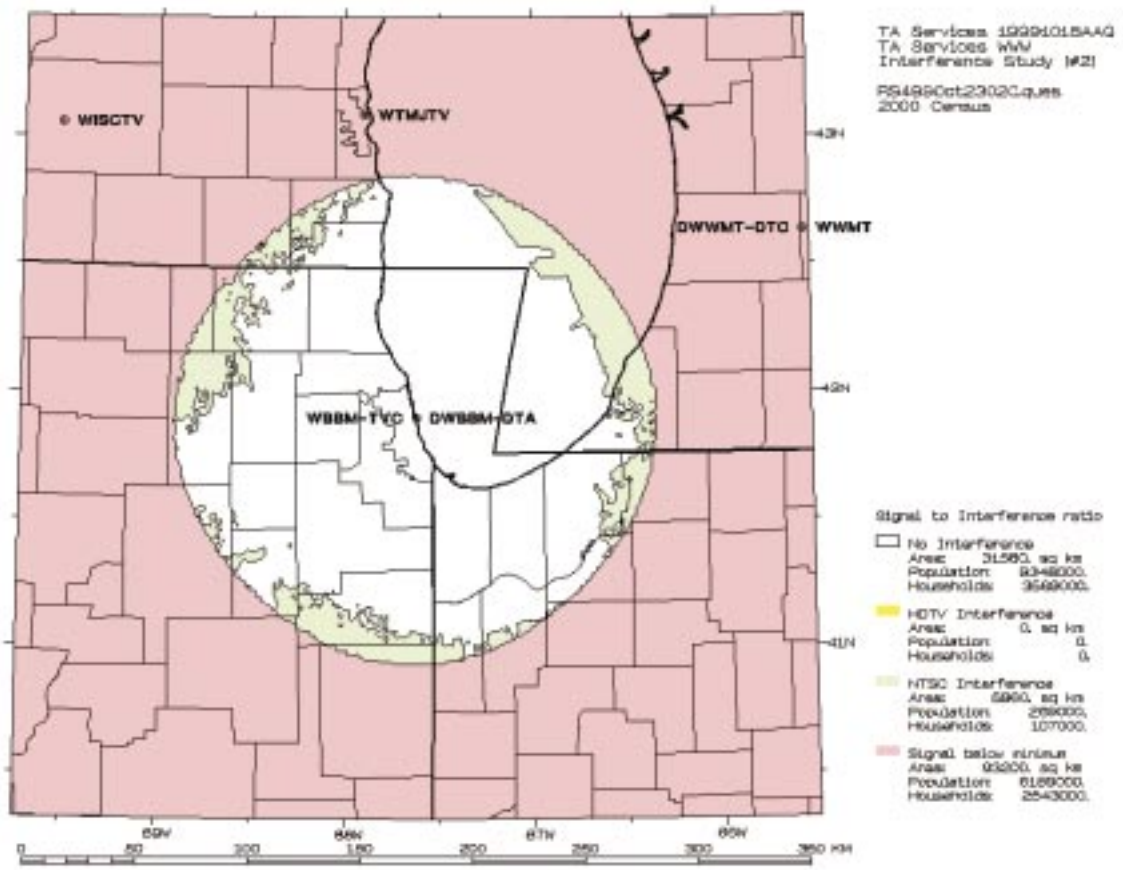

Figure 1. Interference analysis for proposed digital station in Chicago.

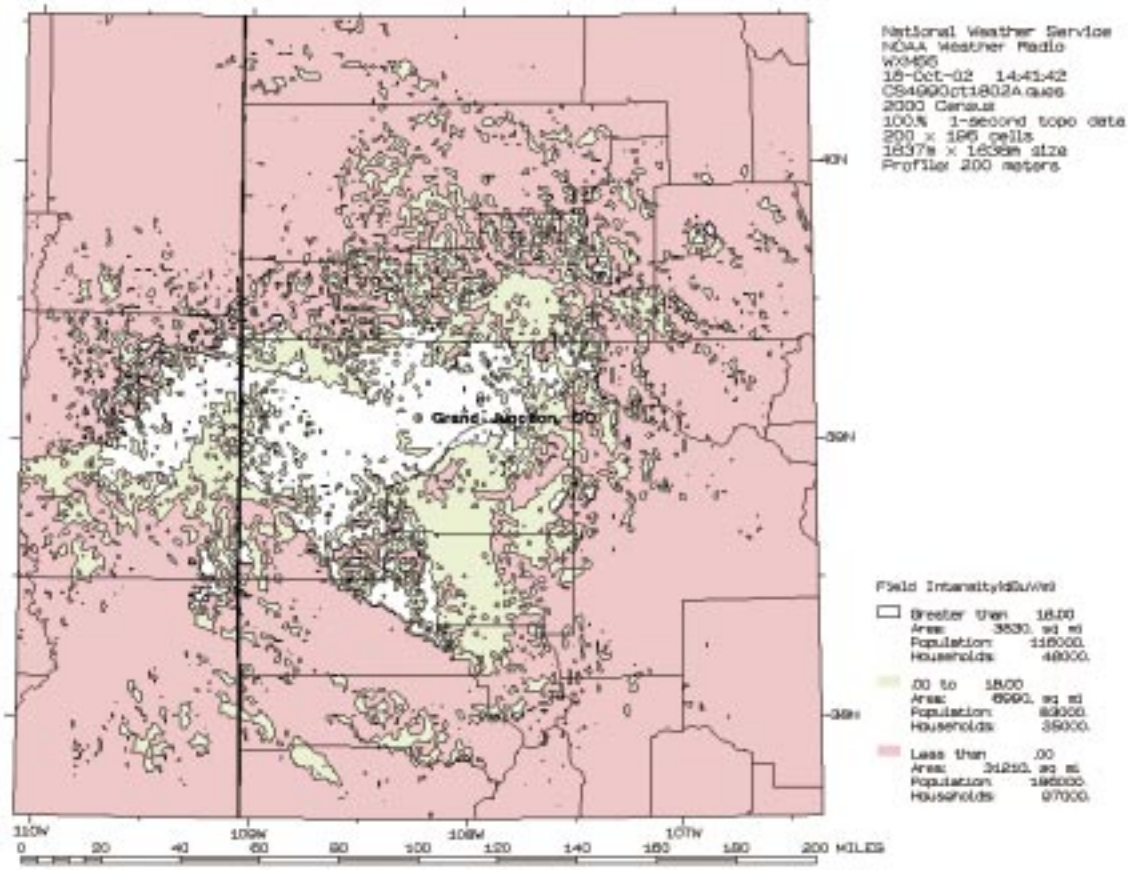

Figure 2. NWS stations coverage for Grand Junction, Colorado.

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 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 number of households within those areas. Figure 1 shows the result of a study done analyzing the predicted interference to a proposed digital TV station in Chicago, Illinois. The model can also determine the amount of interference a selected station gives to other stations. This allows the engineer to make modifications to the station and then determine the effect those 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 tabular output 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.

TA Services is also assisting the National Weather Service (NWS) in locating additional sites to increase its coverage for weather radio reports and emergency warning broadcasts. Recently the whole NWS database was recalculated using the 1-arc-second terrain database. Figure 2 shows the recalculated coverage for Grand Junction, Colorado.

All models in TA Services and their outputs can be accessed via a network browser.

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Geographic Information System Applications

Outputs

- Propagation coverages for one or more transmitters draped over surfaces created by the program or imported by the user.
- Interference and overlap coverages of multiple transmitters.
- 2.5-D or full 3-D coverage predictions with interfaces to 3-D visualization tools.

ITS maintains a suite of Geographic Information System (GIS) based applications which are available to public and private agencies for propagation modeling and performance prediction studies. A GIS efficiently captures, stores, manipulates, analyzes, and displays all forms of geographically referenced information in a user-friendly and flexible manner. Databases for use in GIS systems are becoming more commonly available at affordable prices and include such data as terrain, satellite photo imagery, 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) which can be connected to a GIS. The Institute has modified and distributed this tool to several groups with modifications tailored to a specific application. These groups include government agencies, private cellular companies, paging system providers, public and private television systems, private consultants and transportation companies such as the railroads of the United States.

One form of this GIS tool is called the Communication Systems Planning Tool (CSPT). CSPT is a menu-driven propagation model developed for applications 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 the GIS background. CSPT allows the user to import digital stereo photographs or other remote sensing data which have been 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. New propagation models can easily be connected to the GIS with minimal effort, providing the user with greater flexibility and future growth.

A graphical description of CSPT is shown in Figure 1. The output shows an analysis area of Dupont Circle in Washington, DC, made from an imported digital elevation model and image at 1 meter resolution. The image shows the coverage of a transmitter placed in the center of Dupont Circle.

The general flow of CSPT is as follows. The user defines an area within which a study will be performed. This analysis area can be defined

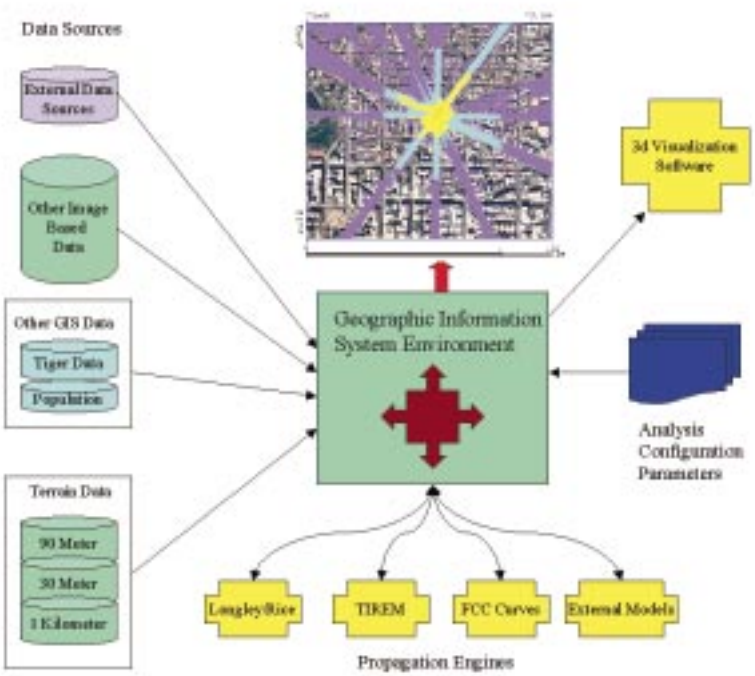

Figure 1. Overview of the CSPT model.

graphically by zooming into a map of the world or of the U.S. or by defining the latitude and longitude of the boundaries of the desired area. The user then imports desired GIS information such as political boundaries, roads, rivers, special imagery, or application specific GIS data. Then the user creates or imports transmitter, receiver, and antenna data. Lastly, the user selects the type of coverage and the propagation model to be used in the analysis.

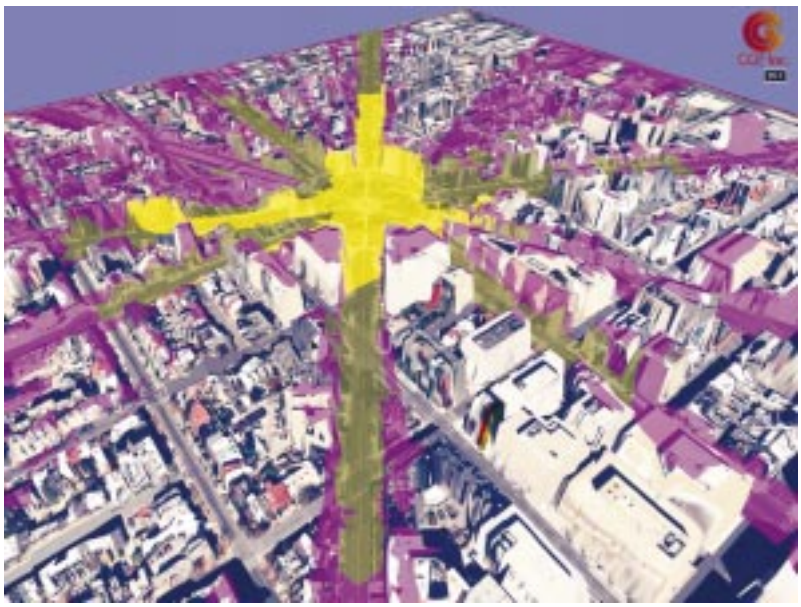

Figure 2. CSPT fly-through analysis showing Dupont Circle in 2.5-D.

The CSPT software can be configured to produce propagation predictions in 2.5-D or full 3-D. A 2.5-D prediction includes the calculation of signal strength at the surface of the analysis area but not above the surface. A full 3-D propagation prediction includes all of the space from the surface to a user specified altitude. This data can then be exported from CSPT into one of two additional tools that permit the user to view the combined imagery and propagation prediction. The first tool, shown in Figure 2, allows the user to fly into the 2.5-D analysis area and view not only the terrain and buildings but also the propagation prediction draped over the image. The second tool, shown in Figure 3, allows the user to fully manipulate the area of interest and the 3-D propagation cloud. This tool is useful only in relatively small regions since the amount of data is extremely high, but it allows for the most visually appealing and accurate results possible.

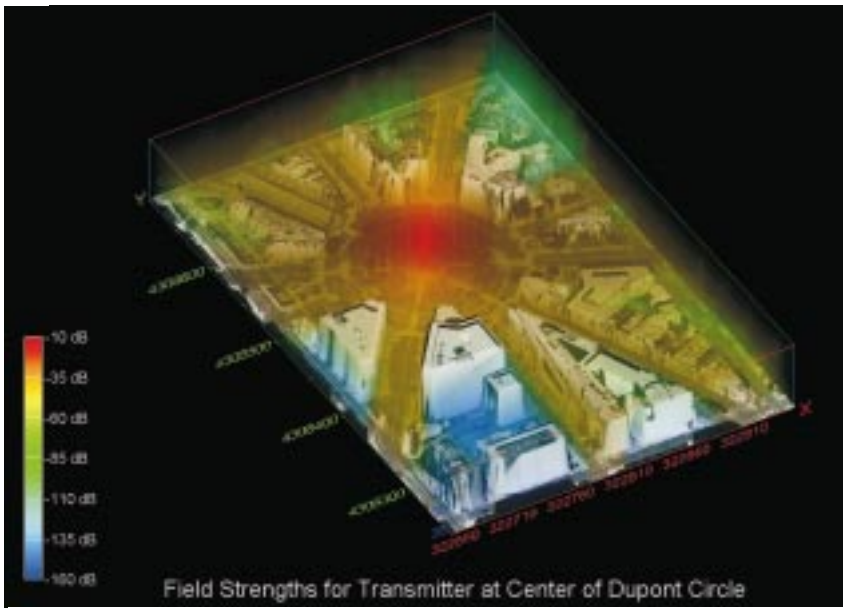

Figure 3. Same area of coverage shown in Figure 2, in full 3-D.

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 available. We suggest that users have an account with ITS on our TA Services computer so that we may provide phone support.

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Propagation Model Development & Comparisons

Outputs

- Comparison of algorithms used in ITM and TIREM models.
- Comparison of ITM and TIREM models to various measurement datasets.

ITS' work on propagation model development in FY 2002 focused on intercomparison and harmonization of the two radio frequency electromagnetic wave propagation models employed by the U.S. Government, 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) and by ITS. Progress in each area for FY2002 is described below.

ITM & TIREM Intercomparison

ITM, developed by ITS, and TIREM, developed by OSM/IITRI, were very similar thirty years ago. Both models are based on NBS Technical Note 101.* ITM has remained virtually unchanged since the early/mid eighties, but TIREM has undergone many significant changes during the same time period.

ITM is an empirical model: its "deterministic" results are modified by comparisons to measured data to account for parameters that the model does not control. The set of measured data consists of over a dozen datasets containing more than 41,000 measurements, which span the frequency range from 20 to 10,000 MHz. Many different types of terrain (plains, hills, mountains, etc.) are included, and a wide variety of antenna heights and polarizations for the transmitter and receiver antennas were used to perform the measurements. If the data used to develop the empirical model cover all possible propagation situations, then the model should apply as a tool to perform radio-wave propagation predictions along any path. However, there are still propagation scenarios not contained in this database.

In FY 2001, ITS began a project to describe and compare the algorithms used in ITM and TIREM. This work continued through FY 2002. Specifically, the algorithms for the line-of-sight (LOS), diffraction, and troposcatter regions are being examined, in addition to how each model utilizes an effective antenna height for these calculations. The final report will contain a summary of the results. It will provide a better understanding of these algorithms, propose explanations for why ITM and TIREM produce different answers, and suggest methods for obtaining the same answers with each model which also agree more closely with measured data.

ITM & TIREM Harmonization

During FY 2000, a study was launched to compare ITM v1.2.2 and TIREM v3.14 predictions to several measured radio propagation datasets. The major goals of this work, which continued throughout FY 2002, are to improve the predictive accuracies of ITM and TIREM, and to reduce or eliminate, where possible, differences between these two models' predictions for circuits with equivalent input values, all while preserving the increased predictive accuracies.

Difficulties arose when the results of two previous comparison studies were examined. The two studies considered data from datasets with substantial commonality and found comparable mean and variance statistics for the models' prediction errors. However, examination of the results for individual paths revealed large differences in the detailed comparisons of the predictions for a given model (TIREM) between the two studies. Furthermore, there was evidence from the data that both the measurements and the predictions, and, hence, the prediction errors, were subject to significant correlation. Computation of meaningful statistics in the presence of correlated data was a major problem encountered in this study.

ITS has proposed a mechanism for the data correlation and tested it on several datasets. Results show substantial correlation in the data and the statistics are affected by this correlation. This data correlation is due to many of the measurements having been made at multiple frequencies and antenna heights on the same path. When propagation conditions for the measurements and hence predictions were found to be good or bad for a particular path, they were good or bad for all frequencies and antenna heights along the path. Univariate statistical analysis of the data

*P.L. Rice, A.G. Longley, K.A. Norton, and A.P. Barsis, "Transmission loss predictions for tropospheric communication circuits," NBS Technical Note 101, vols. 1 & 2, May 1965 (rev. May 1966 and Jan. 1967).

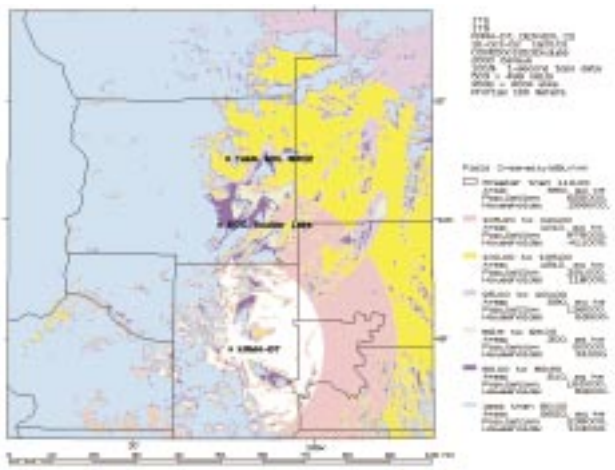
relies on data samples in which the individual measurements have been randomly drawn from a large universe of radio-wave propagation measurements. These samples should be independent and have identical frequency distribution. When the data samples are correlated, this independence assumption is violated.

It is necessary to eliminate this correlation. As our model, the measurements on one path are considered to be independent of measurements taken on another path. The excess loss relative to free space predicted by ITM was compared to the measured data, and the difference was used as the statistical random variable. By segregating the data so that it is taken from different paths, a multivariate statistical analysis can proceed. This enables testing the significance of the distribution of the means, medians, and standard deviations of the difference between model loss predictions and measured data. These results will aid the harmonization effort for the two propagation prediction models.

Effective Antenna Height Study

ITM uses effective antenna heights throughout most of the program (except when computing horizon elevation angles, distances to horizons, and Fresnel zone clearances), while TIREM uses structural heights exclusively. This difference has a significant impact on propagation loss predictions. Thus, the correct value of reference attenuation depends on the values of effective antenna height. Effective antenna height changes the predicted propagation loss by as much as 45 dB relative to predictions using only a structural height. Transmitter and receiver effective antenna heights above the dominant reflecting plane are computed by an algorithm within ITM. The effective antenna heights along the propagation path are determined from the terrain contour, the structural antenna heights above ground level, and the distances to the horizon from each of the antennas.

ITM was used to examine propagation paths found in the measured data. In one case, the ITM effective antenna height algorithm was used to select the effective antenna height. In a second case, the effective antenna height was fixed at the structural height. Propagation loss predictions were made for most propagation paths in the database. The predicted value of propagation loss was compared with the measured value for both cases. The loss deviation is the predicted value of attenuation from the model minus the measured value of attenuation.



Example of the use of ITM to predict electric field strength for a proposed digital television broadcast antenna on Lookout Mountain near Golden, CO. The predictions were made using USGS 1" terrain data.

The comparison of ITM predictions to measured data has generated a number of different behavior characteristics related to the internal computation of effective antenna height being investigated. This investigation will provide guidance in selecting an improved effective antenna height computation. In some cases, ITM computes a large effective antenna height that differs substantially from the structural height, resulting in a large deviation between the value of predicted and measured transmission loss. There are cases where, if the effective antenna height were made equal to the structural height, then the deviation can be reduced, but in just as many cases large deviation occurs. That is, many cases exist where the deviation resulting from measured paths using the structural height is much larger than the deviation for the measured paths using the effective height. There are also many measured paths where the optimum value of effective antenna height is somewhere between the ITM-determined effective antenna height and the actual structural antenna height. The effective antenna height is always greater than or equal to the structural height. Further study of the behavior of ITM in different scenarios will provide information for the development of a new effective antenna height algorithm that minimizes the deviation between predicted and measured propagation loss.

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