Digital Communications Systems: Propagation Effects, Technical Solutions, Systems Design

(Systèmes de propagation numériques: effets de la propagation, solutions techniques, conception des systèmes)


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UHF and Microwave Propagation Prediction in an Urban Environment

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1. SUMMARY
This paper discusses ongoing work by AT&T Bell Laboratories, Pennsylvania State University, Polytechnic University and Virginia Polytechnic University in developing site specific urban propagation computer models. Both two and three dimensional ray tracing algorithms have been developed by the different organizations and applied in the Rosslyn VA area at 900 and 1900 MHz. After the models have predicted the propagation loss from specific transmitter sites to receiver locations, measurements have been taken to determine the actual values. This paper presents some comparisons of the different models and measurements. Where the computer models have worked well, they are typically within about 7 dB of measurements. In some areas of Rosslyn there are known problems with the building data base where predictions differ from measurements, however work is continuing to improve the models in other problem areas. This will be accomplished by comparing the different models to one another and the measurements and then refining the models.

2. INTRODUCTION
Before deploying a cellular or micro-cellular type microwave communication system, it is usually necessary to understand the propagation conditions in the intended service area in order to select antenna sites and set system design parameters to obtain the required coverage. Often design tools using statistical propagation models are used for this purpose. However, these tools are usually not accurate enough for urban environments and extensive on-site measurements are required before the design can be finalized. These measurements add to the time and expense of the system design and may not be practical in many scenarios.

An alternate approach is to use site-specific tools that model microwave propagation by including actual local environmental elements such as buildings, other objects, vegetation and terrain. These tools can be expected to provide better accuracy than can be obtained with statistical models and with less time, expense and intrusion than required for measurements.

Many such models and tools have been proposed in the scientific and engineering literature. To evaluate some of the more promising of these and encourage their further development into a complete urban propagation tool incorporating the best features of each, the United States government is sponsoring a project involving AT&T Bell Laboratories, Pennsylvania State University, Polytechnic University and Virginia Polytechnic University. This project includes a series of propagation predictions from each of the four groups which are then compared with actual measurements made independently. These comparisons are used to evaluate the accuracy of the predictions, identify the relative strengths of each model and refine the modeling techniques in areas where the measurements and predictions differ significantly.

The site selected for the study was about one square km area of Rosslyn, Virginia, USA. Rosslyn is an urban area lying across the Potomac River from Washington, DC which offers an irregular street plan with a variety of building types, building heights and street widths. There are residential areas with light vegetation in the western area of the study with high-rise, commercial buildings with an average height of about 10 stories in the east. The commercial area also includes some open areas and many elevated pedestrian cross-walks over the streets. In addition, terrain elevation varied from 15 to 55 meters over the
study area. These factors allowed a number of environmental variables to be addressed in the study.

3. BUILDING DATA BASE

Another major factor in selecting the Rosslyn site for this study was the existence of extensive photographic data obtained during aerial overflights. From the photographs, the major buildings and other structures were identified and the external surfaces of the buildings were digitally encoded into a set of three dimensional, convex polyhedra using a wire-grid structure. Additional post-processing of this data was performed to remove some of the detail which could greatly lengthen the calculation time without contributing significantly to the accuracy of the predictions. The final data base was generated in the standard DXF format used by many architectural and other CAD programs. The use of this standard format for interfacing all of the propagation prediction tools allowed easy interchange of building data between the four study groups and future flexibility with other data bases and tools. Figure 1 is a perspective view of this data base for a part of the city.

4. MODEL DESCRIPTIONS

4.1 AT&T Model

The computer tool developed by AT&T Bell Laboratories to predict outdoor electro-magnetic propagation currently supports two different ray tracing methodologies. The first is a two dimensional ray tracing technique while the second is a full three dimensional model. This computer tool was developed from an earlier tool designed to predict propagation inside of buildings that is discussed in papers by R. A. Valenzuela et. al.\textsuperscript{[1]} \textsuperscript{[2]}. The two dimensional technique has the advantage of being much faster to calculate than the three dimensional method, however it is only valid when the transmitter and receiver locations are significantly below the tops of the buildings in the area. This technique is sometimes referred to as the infinite canyon model. Both ray tracing techniques determine specular reflections off building surfaces and diffractions at vertical edges of buildings. The three dimensional model also uses specular reflections from horizontal building roofs and the ground and diffractions from horizontal edges.

The propagation tool requires as inputs the locations, orientations and antenna patterns of all transmitter sites and locations of all receivers. It also requires the transmitted power levels of all the transmitters. Finally a description of all the planar surfaces of the buildings is required as input. This surface description file must indicate the position and shape of every building surface as well as what type of surface it is. The user of the tool may select the building wall type from a list of typical building materials such as concrete, glass, wood, sheetrock, etc.

Once the tool has read the input data, it attempts to find all ray paths from a transmitter to a receiver location. These rays may find their way to the receive location by reflecting off building surfaces or diffracting around building corners formed by two building surfaces. The user of the tool may specify the maximum number of reflections and diffractions to consider in finding these ray paths. Once all the rays desired have been found, the electric field each ray provides at the receive location is calculated. The predicted power at the receive location is then calculated from these fields and may be performed coherently adding fields or incoherently adding power contributions.

The field from each ray is calculated by determining the strength of the radiated ray and the loss that ray undergoes. The radiated power is calculated from the transmit power and antenna pattern. The loss has two components, a free space loss and an additional scattering loss. The free space loss is simply the amount of loss due to the radiation of energy out into open space and is inversely proportional to the distance traveled by the ray squared. In addition to this loss, some energy is lost from the ray during each reflection or diffraction it undergoes. To compute the amount of energy lost in a reflection, the building surfaces are modeled as multilayered planar homogeneous lossy dielectric slabs with a plane wave impinging upon them. Good choices for the number, thickness, permittivities and conductivities of these dielectric layers is still an area of research. To date, values have been chosen to try and represent actual building construction and materials. Good agreements with measurements for the outside two dimensional model have been reported by Erceg, Rustako and Roman\textsuperscript{[3]} using material parameters for concrete. To compute the amount of energy lost in a diffraction, the Geometric Theory of Diffraction (GTD) for an infinite lossy dielectric wedge, as reported by Luebbers\textsuperscript{[4]}, has been used.

4.2 Penn State Model

The Penn State propagation model is a hybrid of Shooting and Bouncing Rays (SBR)\textsuperscript{[5]} and the Geometrical Theory of Diffraction (GTD)\textsuperscript{[6]} \textsuperscript{[4]} \textsuperscript{[7]}. Both two-dimensional (2D) and three-dimensional (3D) versions have been developed. The 2D version assumes that the transmitter and receiver are located below the building roof level. The 3D model assumes that either the transmitter or receiver (or both) are located at a height above some of the buildings so that propagation over buildings must be included. The 2D version is therefore a "canyon" model. For the 2D model the ground is approximated as a flat surface which can be slanted. The 3D version is fully three-dimensional, with full polarization dependence
included in the reflection and diffraction coefficients. For the 3D version the building surfaces can be convex flat polygons of arbitrary shape, including slanted edges. The 3D version ground is modeled as connected polygonal plates, so it can be irregular. Diffractions from the ground plate edges are not included in these calculations, but could be added.

When making propagation calculations the SBR method is applied twice. For the first application many rays are shot from the transmitter location, reflecting off buildings and ground. For the 2D model these are disks, but for the 3D model the rays shoot out through a spherical area. The purpose of this "shooting" is to find the diffracting edges for a given transmitter location (and ray direction for the 3D model). This "shooting" is done regardless of the receiver locations. As the rays are "bouncing" off the buildings, the rays closest to building edges are determined. These rays are sorted, and each diffracting edge is identified. If double diffraction is to be applied, additional cones of rays (disks for 2D) are "shot" from the diffracting edges and bounced through the buildings. Once this is completed all the diffracting edges are known. For 3D the diffraction points on each diffracting edge for each ray incident on the edge are known.

Now the rays are all shot again. Each receiver point has a collection aperture surrounding it, typically several meters on a side. For each ray shot from the transmitter, including any subsequent diffracted rays, all rays collected in a receiving aperture are saved. For each ray shot from the transmitter all receiver points are considered. Then the next ray is shot and all receivers are again considered. As the rays are being shot, the rays received by each receiver aperture are sorted and one ray for each unique path is selected. For multiple rays following the same path the ray closest to the center of the receiver aperture is kept. The ray amplitudes are evaluated using reflection coefficients for a plane wave incident on a dielectric half-space. Thus the reflection coefficients are a function of incidence angle. The diffracted rays are evaluated using UTD wedge diffraction. Diffracted rays are combined coherently with the corresponding reflection and shadow boundary rays for each building surface. Rays from different building surfaces are combined incoherently. The ground reflected rays are combined coherently with the corresponding non-ground-reflected ray for the 2D model. In the 3D model the ground reflections are included but are not combined coherently with the corresponding non-reflected ray.

4.3 Polytechnic Model

Instead of a full three dimensional ray trace, the Polytechnic approach uses several simpler two dimensional ray traces to approximate the actual three dimensional rays that give the primary contributions to the received signal. To this end, we identify a hierarchy of ray classes that can be systematically searched by the program to find the primary contributors in each class. For each class, the program consists of a sub program that interrogates the building data base for relevant building information. A second sub program then calculates the ray contributions to the total signal. These individual programs are modular, and reused at later stages in the hierarchy.

In order to describe this hierarchy, we define for each receiver point a Vertical Planes (VP) [6], and a Slant Planes (SP) as shown in Figure 1. The VP’s are defined as containing: 1) the receiver and the transmitter; 2) the receiver and an equivalent source point such as an image of the transmitter in a nearby building, or a diffracting edge; 3) an equivalent receiver point, such as the image of the receiver in a nearby building or an edge near it, and the transmitter; or 4) an equivalent receiver point and equivalent transmitter point. For each VP, there is an SP [9], which is perpendicular to the VP and containing the actual or equivalent transmitter and receiver points.

Within the VP or SP there are classes of rays that must be considered in order to account for the significant paths between the transmitter and receiver. In the VP the ray paths that must be considered include a direct path between the transmitter and receiver via diffraction over the tops of the buildings [10] and reflection near the transmitter prior and/or near the receiver subsequent to the diffraction over the top of the buildings. In the SP the significant ray paths can be considered to be three sub-classes [11] and includes: those rays that reach the receiver by multiple reflections at the sides of the buildings, rays that are multiply reflected at the building sides and undergo one diffraction at a vertical corner and rays that involves two diffractions at vertical building corners and multiple reflections before, between and after the two diffractions. Finally the LOS ray, if it exist will be determined in both the VP and SP, therefore it should be included in the SP and neglected in the VP.

4.4 Virginia Tech Model

A brute force recursive technique is used to trace rays launched from the transmitter in three dimensions. Geometrical optics is used to trace the propagation of direct, reflected, and scattered fields. The transmitter is modeled as a point source generating rays uniformly in all directions. Constant angular separation between the rays is achieved by launching the rays through the vertices of an icosahedron inscribed in an unit sphere, with each of its triangular faces subdivided into smaller triangles. This method of launching rays provides wavefronts of equal shape and area that can
be easily subdivided. While this method is more computationally intensive than those based on image theory, it is much more flexible since different propagation models can be easily incorporated. The computational demands are drastically reduced by using bounding volume hierarchies for buildings and exploiting the parallelism of a network of workstations, the computation time can be further reduced.

The energy at a receiver location is determined by performing a non-coherent superposition of the contributions due to line of sight, reflected, and scattered fields. The contribution from the LOS path is calculated using the two ray model. The reflected ray follows a $1/D^4$ dependence according to the Friis free space formula where $D$ is the total ray path length. The reflection coefficients are varied based on the angle of incidence and this appears to give better predictions over using constant values. A reception sphere is used to determine the reception of a specular reflected ray at a receiver location. Rough surface scattering is taken into account by subdividing the surface into several small facets (so the receiver is in the far field), applying the bistatic RCS to each, and then doing a non-coherent summation of the contribution from each facet. In heavily shadowed regions, diffraction is dominant and is taken into account with wedge diffraction.

5. MEASUREMENTS

5.1 Equipment Description

AT&T owns and operates two test vans equipped with electronic equipment for collecting propagation data in any frequency range up through the microwave region. One van is used for transmitting, while the other for receiving RF energy. The propagation loss measurements are performed by locating a transmitter at the top of a mast on the street level parked transmitting van or on a building roof at specific sites in Rosslyn. Then measurements are collected by the receiving van driving down a particular street or parked at a specific site.

The transmit van has various synthesized signal generators, 4 independent "pods" for leveling capability to keep the antennas vertical, and a 10 meter pneumatic mast upon which the transmitting antennas are placed. The receive van houses a Data Acquisition System (DAS) for collecting, storing and analyzing receive signals, a Positional Acquisition System (PAS) to determine the van's location, and other miscellaneous equipment. Both vans operate off of 10 kwatt gas generators. A block diagram of the receive van is shown in Figure 3, and a brief description of the major components is discussed below.

The DAS consists of 4 spectrum analyzers, signal generators for calibrations, antennas, LNAs, cabling, and a Data Acquisition Computer (DAC). There are two operating modes available from the AT&T DAS: high and low resolution. During high resolution data collecting, the DAC samples the receive power form the spectrum analyzers at 10,000 times per second and stores this data on a Bernoulli floppy disk in the DAC. During low resolution data collecting, the receive power is sampled at 10,000 samples per second, then power averaged and the average recorded. While the van is moving, the data is averaged over each 1 meter of travel. When the van is moving less than 1 meter per second, averaging is done over a 1 second interval. The DAS appends a time stamp on each data record it stores on the Bernoulli floppy disk in the DAC.

The PAS consists of a Trimble Differential GPS system, a Loran-C and a dead reckoning system. If there is no differential solution to the van's position, standard GPS is used. If the GPS signal is insufficient, then either Loran-C or the dead reckoning system is used. The dead reckoning system estimates the position of the van by a magnetic compass, a speed sensor on the van's drive shaft, and knowledge of the van's last position. About every 5 seconds, the location of the van is placed into a file with a time stamp on the Bernoulli floppy disk in the DAC.

5.2 The Measurement Program

In our measurement program there were two types of antenna heights and two types of measurements made. Ground level (from 2 to 10 meters) and rooftop level antenna heights were selected to test the two and three dimensional models' prediction capability, while van receive measurements were performed as either a continuous drive (excluding traffic conditions), or a stationary measurement. Prior to data collection, FCC permissions were obtained, and area surveys were completed to ascertain the best locations for transmitting antennas and optimum drive routes for collecting data. Optimum antenna positions were decided as a compromise between the available locations, limitations on where the vans could be placed, and what immediate environment would best exercise the reflection, diffraction and refraction capabilities of the researcher's modeling programs.

Once specific locations for the transmit and receive (in the case of stationary measurements) antennas, were established, position measurements referenced to the database were made to place the antennas at the intended locations to within about 1 meter. The procedure for data acquisition was simply to place the transmitting antenna at the intended location, perform calibrations to assure full dynamic range of the DAS, and collect data by either driving the receive van along the streets of Rosslyn, or placing the van at the specified locations for the stationary measurements. Unfortunately for the data collected while driving, the
6. COMPARISON OF MEASUREMENTS AND PREDICTIONS

Figures 4-8 display a comparison of a small sample of the model predictions and measured data for a transmitter site and receiver locations down a particular street in Rosslyn. These plots show the measurement data as small dots. The solid line depicts a 5 meter local average of the measurements. The various predictions are displayed as marks on the plots; AT&T as a cross, Penn State as a plus sign, Polytechnic as a diamond and Virginia Tech as a circle. Figure 4 shows a comparison of the two dimensional models for transmitter 2b down Moore St. Transmitter 2b used omni-directional antennas at an elevation of 10 meters two blocks east of Moore St. Except at the intersection of 19th St. near the north end of Moore, it is shadowed from this transmitter site by buildings.

Figures 5-8 display comparisons of the three dimensional models and measurements. Figure 5 shows Moore St. predictions and measurements for transmitter 5. Transmitter 5 used directional antennas pointing down Moore St. from the roof of a 40 meter high building. This transmitter had a clear line of sight to all of Moore St. Figure 6 shows Lynn St. for transmitter 5. Lynn is one block to the east of Moore and is mostly blocked by buildings from transmitter 5. Figure 7 depicts transmitter 6 for Nash and 19th St. Transmitter 6 used directional antennas aimed to the north-east on top of a 45 meter high building. Nash is to the west of transmitter 6 while 19th St. is to the north. These streets have both line of sight and blocked regions to transmitter 6. Figure 8 shows Colonial Terrace for transmitter 7. Colonial Terrace loops through a condominium complex of two to three story brick buildings surrounded by many trees. Transmitter 7 used omni-directional antennas at a 10 meter elevation on the south side of the complex. Colonial Terrace has a clear line of sight back to transmitter 7 at the beginning, end and peak in the middle of the plot. Other areas are blocked by the condominium buildings.

ACKNOWLEDGEMENTS

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REFERENCES


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**Figure 1 - Rosslyn Building Data**
Figure 2 - Vertical and Slant Planes as They Intersect the Building Database

Figure 3 - Receive Van Measurement Equipment
South Moore TX 2b 911 MHz

Figure 4 - Predicted and Measured Propagation Loss

South Moore TX 5 1900 MHz

Figure 5 - Predicted and Measured Propagation Loss
Figure 6 - Predicted and Measured Propagation Loss

Figure 7 - Predicted and Measured Propagation Loss
Colonial Terrace loop TX 7 908 MHz

Figure 8 - Predicted and Measured Propagation Loss
DISCUSSION

Discussor's name: S. Karp

Comment/Question:

Was delay spread measured?

Author/Presenter's reply:

No.

Discussor's name: A. Altintas

Comment/Question:

1. Did you compare 2-D vs. 3-D models for the same transmitter position? If so, do you think that a 3-D model is necessary in general?
2. Did you compare your results with the Okumura-Hata model?

Author/Presenter's reply:

1. In our experience, a 3-D model is necessary for roof-top antennas, but not necessary if both antennas are lower than the roof tops.
2. We have not done so, but believe we are more accurate.

Discussor's name: C. Rigal

Comment/Question:

What would happen to the model for a transmitter placed on a satellite?

Author/Presenter's reply:

For transmitters placed on top of buildings, few rays are involved but they change rapidly when the receiver is moving. For that reason the computation may be more complicated.
DISCUSSION

Discussor's name: F. Davarian

Comment/Question:
Does the 7 dB model agreement indicate RMS error, absolute error, or some other kind of error?

Author/Presenter's reply:
This is the standard deviation of the difference in dB between each measured and predicted value of path loss.

Discussor's Name: G. S. Brown

Comment/Question:
Did you make any phase measurements and/or phase prediction using the models?
Do you plan to do such measurements and/or model predictions in the future?

Author/Presenter's reply:
We have not made phase measurements. We have no plans to make such measurements.