USE OF A BUILDING DATABASE IN PREDICTION OF THREE-DIMENSIONAL DIFFRACTION

Thomas A. Russell
Stanford Telecommunications, Inc.
1761 Business Center Drive
Reston, VA 22090

Theodore S. Rappaport and Charles W. Bostian
Mobile and Portable Radio Research Group
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Abstract
This paper describes the use of a building database and a three-dimensional formulation of the Fresnel-Kirchoff diffraction theory to compute the shadowing by buildings in the general situation where diffraction can occur by building edges of both horizontal and vertical orientation. The storage format of buildings in a geographic information systems database is described. An algorithm is presented for identifying the nearest diffracting building and deriving the necessary information for the evaluation of the diffraction integral. Example results are presented to show the utility of this approach.

1. Introduction
The feasibility of using a building database in prediction of mean field strength for cellular radio systems has been demonstrated by Ikegami et al. [1]. This paper proposes a technique for extending the use of the building database to include diffraction paths around edges of both vertical and horizontal orientation, thus including all three dimensions of the environment. This approach is applicable to the typical system using base station antennas atop tall towers, where diffraction is introduced chiefly by roof edges, as well as to the proposed system involving lamppost-level base stations where the dominant diffraction path will most likely be around a side building edge. The flexibility to examine situations which do not fall neatly into one of these two categories is also a key advantage of the three-dimensional approach.

Although this paper does not address diffraction by multiple successive edges, the methods proposed here have been used as the basis of a diffraction prediction computer program [2] that uses numerical techniques and recursion to compute in a rigorous manner the multiple diffraction effects of a small number of obstructing buildings (limited by computation time).

2. The Building Database
We are investigating the use of computer software packages known as geographic information systems (GIS) as an aid to database management and analysis. GIS packages are sets of software utilities that facilitate the storage and manipulation of digital geographic information of any type. The specific GIS package we are investigating is the Geographic Resources Analysis Support System (GRASS), developed by the U.S. Army Construction Engineering Research Laboratories in Champaign, Illinois, for use on UNIX-based workstations, and available in source code form.

GRASS stores, displays, and analyzes data in two different forms: cells and vectors. A cell is a portion of a rectangular grid and contains a single attribute in the form of an integer. This integer may signify elevation in meters or it may map to a type of vegetation cover, for example. Elevation data are available from the U.S. Geological Survey (U.S.G.S.) in the form of digital elevation models and can be input to the GRASS database through existing routines. The other basic form of data representation in GRASS, the vector, is a line defined by its endpoints. Vectors can be used to define a closed area, which can then be given an attribute. This is similar to a cell except that when vectors are used there is not the resolution limit set by the grid pattern, as the boundaries of the vector area are defined by the vector endpoints, whose precision is limited only by the original information source.
The vector area representation is our storage format for buildings, where the attribute contains the mean height above sea level of the rooftop and the area is defined by the coordinates of the four corners. This requires the approximation of buildings as simple boxes. A building with sections of different heights is represented as multiple buildings connected together. Our model development and testing was based on the Virginia Tech campus, where the building corner coordinates could be found on blueprints and the building heights were also readily available. It appears that in a general urban area, this information may be very difficult to find. Given the number of floors and an average height per floor, an approximate rooftop height could be derived from the underlying topography with the aid of GRASS, but identifying the exact corner coordinates may prove to be a problem.

Input of building information can be accomplished in several ways. If the information is already stored in a different database, conversion to the GRASS storage format should be possible. If the building information is in paper map format, the data can be manually entered with a digitizer.

Identification of Diffracting Buildings

The building information is stored in a coordinate system, such as the Universal Transverse Mercator (UTM) system, which allows approximation of small sections of the spherical earth with an orthogonal set of horizontal axes in terms of easting and northing, and a vertical axis signifying mean height above sea level (all in meters). For a specified transmitter location the axes are translated in the horizontal plane such that the transmitter, or source point, S, is at \((e,n,0)\). Figure 1 presents this in top view, where the y axis, which is not affected in these manipulations, is directed out of the page, and the receiver is at the observation point, P, given by \((e_p,n_p)\). For each new observation point, a set of horizontal axes \((u,v)\) is defined by rotating the \((e,n)\) axes such that the projection of P lies on the v axis (see Figure 1). The u coordinate of P is thus the horizontal component of the distance from S to P, computed by

\[ u_p = \sqrt{e_p^2 + n_p^2}. \]  

(1)

By definition the v coordinate of P is zero. The \((u,v)\) coordinates of each building corner is then found from its \((e,n)\) coordinates by

\[ u = e(e_p/u_p) + n(n_p/u_p), \]  

(2)

\[ v = -e(n_p/u_p) + n(e_p/u_p). \]  

(3)

If the building database is very large and the coordinate transformations begin to take a large amount of computer time, the database should be reduced by defining a window about the area of interest and deleting buildings outside the window, before input to the prediction program.

Figure 1. Coordinate system transformation. The \((u,v)\) axes are defined by the source and observation points, S and P, respectively.

After the \((u,v)\) coordinates of the building corners are found, each building is bounded by its maximum and minimum values of \(u\) and \(v\). A building is then flagged for further consideration with OBSTRUCT = TRUE if all of the following are true: \(u_{max} > 0, u_{min} < u_p, v_{max} > -\text{MAXDIST}, v_{min} < \text{MAXDIST},\) where MAXDIST is set large enough (at least 10 wavelengths) such that if it is remotely possible for the building to obstruct the signal significantly, the building will be flagged. The flagged buildings are then searched to find the nearest one by checking the values of \(u_{max}\). All of the manipulations so far, which may be performed on many buildings, require minimal computations. Now, having identified a building that obstructs the horizontal projection of the radio path to some degree, the Fresnel zone clearance is considered and the vertical dimension is included in the final determination as to whether to compute the diffraction by the building.

A clearance of at least 0.55 Fresnel zones is a criterion traditionally used in radio engineering [3] to determine whether an obstruction introduces significant diffraction. The heights of the transmitter, the receiver, and the rooftop, their respective horizontal coordinates, and an application of the principle of similar triangles provide the degree of clearance over the roof edge. If there is 0.55 Fresnel zone clearance past the two side edges and the roof edge of any one of the four vertical faces of the building, then that building is considered to be diffracting. If the building does not meet the criterion, it is marked with a flag to remove it from
consideration, and the group of buildings flagged with OBSTRUCT are searched again for the next nearest building.

3. Diffraction Prediction

Fresnel-Kirchoff diffraction theory provides a scalar description of the electromagnetic wave. By applying a scalar solution to a vector phenomenon we simplify the problem but lose the ability to model any dependence on polarization. Experiments on large-scale terrain obstacles generally show little impact of polarization on diffractive shadowing [4], but polarization effects are known to increase as the distances (relative to wavelength) to the diffracting edge decrease [5]. Scale-model measurements of polarization dependence using aluminum sheets by Neugebauer and Bachynski [5] show that diffraction by a conducting knife edge exhibits a maximum 0.4 dB difference between the results for vertical and horizontal polarizations at a distance of 50 wavelengths, and a maximum 2 dB difference at a distance of 29 wavelengths, for situations involving up to 30 dB of diffraction loss. At 900 MHz, a typical mobile radio frequency, 26 wavelengths is equal to 6.7 m or 22 ft, a reasonable distance to assume between obstacles and termination points in an outdoor radio system. Thus, for up to 30 dB diffraction loss, we can expect a maximum error due to polarization effects of 2 dB.

The Fresnel-Kirchoff approach requires the assumption of perfectly absorbing material in the obstacle edges. With real buildings that have some finite conductivity, there will be some reradiation, or scattering, from the edges. This source of diffuse radiation may be important but is neglected with this approach. It should be included, as necessary, along with other sources of scattered and reflected energy, in a more comprehensive model of urban propagation.

A single diffraction field component at P, in this case a rooftop diffraction field, is found by [6]

\[ E(P) = \frac{i}{2} E_{fs} \int_{\xi_1}^{\xi_2} e^{i\pi \xi^2/2} d\xi \int_{\eta_1}^{\infty} e^{i\pi \eta^2/2} d\eta, \quad (4) \]

where

\[ E_{fs} = \frac{e^{ik(s+p)}}{(s+p)}, \quad (5) \]

\[ \xi_1 = x_1 \frac{2(s+p)}{\lambda sp}, \quad \xi_2 = x_2 \frac{2(s+p)}{\lambda sp}, \quad (6,7) \]

\[ \eta_1 = y_1 \frac{2(s+p)}{\lambda sp}, \quad \eta = x_1 + \infty \quad (8) \]

and \((x_1, x_2)\) and \((y_1, \infty)\) bound a semi-infinite rectangular aperture, denoted Region R in Figure 2. \(E_{fs}\) is the free-space field at P (with no diffraction); the variables \(\xi\) and \(\eta\) are known as the diffraction parameters, which are dimensionless variables of integration. The wavelength is represented by \(\lambda\) and the propagation constant, \(k\), is equal to \(2\pi/\lambda\).

Lengths \(s\) and \(p\) are the distances from the origin, \(O\), of the \(xy\) plane to points \(S\) and \(P\), respectively, where the \(xy\) plane is defined as a vertical plane perpendicular to the horizontal component of \(SP\), the line connecting \(S\) and \(P\), and the origin of the plane is the point of intersection of the building face with \(SP\). All lengths are measured in meters. The solid, obstructed portion of the \(xy\) plane, marked by hash marks in Figure 2, is actually the projection of the building face on the \(xy\) plane. This technique is used because in the derivation of (4) the aperture screen is assumed to be nearly perpendicular to \(SP\). Point \(Q\) in the aperture of Figure 2 is considered a secondary (Huygens) source of radiation and the mechanism by which the wave changes direction.

![Figure 2. Geometry and construction of the aperture screen.](image)

The \(x\) coordinates of the two corners defining the building edge provide the set of values for \((x_1, x_2)\) needed in the diffraction model, and the values for \(s\), \(p\) and \(y_1\) are easily determined from the \(u\) coordinates and an application of similar triangles. Equation (4) contains the product of two integrals in the Fresnel form, which are computed with numerical integrations. Alternatively, a table look-up method could be used.

The total field at \(P\) is found as the sum of the field contributions due to each edge by

\[ E(P) = \sum_{n} E_n(P), \quad (9) \]

where each \(E_n(P)\) is found according to (4). The rules for constructing aperture screens for each building edge, and for sorting these according to which edges diffract the wave successively and which edges diffract different portions of the wavefront a single time, are detailed elsewhere [2].
These prediction methods are illustrated by simulating the movement of a receiver past a building. Figure 3 presents the results of applying the diffraction integral (4) to each diffracting edge, showing that there are regions where each field component is dominant, and demonstrating the necessity of considering each component. The total diffraction field is computed from the individual components either as a phasor sum or as a power sum.

Figure 3. Three predicted diffraction field components in the shadow of a building.

Comparison With Measurements

Continuous-wave measurements at 914 MHz were made on the Virginia Tech campus and used for comparison throughout the development of these models. An example comparison is shown in Figure 4. In this case a transmitter was mounted on a 15 foot pole on the sidewalk parallel to the front of Davidson Hall, and a receiver mounted on a mobile cart travelled down a perpendicular sidewalk, into the shadow of the building. A 20 wavelength Hamming window was used to filter the measured data. The predictions are based on the application of the above diffraction model to building coordinates taken from a blueprint. Very good agreement between measured and predicted occurs for predicted signal levels up to 17-20 dB below free-space levels.

4. Conclusions

A method has been described for using a building database in the prediction of diffractive shadowing. The method has been used as the basis of a C language program which, based on tests, appears to be a useful tool for describing the transition from line of sight propagation to light shadowing to heavy shadowing. The greatest constraint on this approach may be the availability of building information. Preliminary comparisons with measurements, such as in Figure 4, show an underestimation of field strength in the case of heavy shadowing that may be due to alternate, low-power sources of field strength dominating after the diffraction field drops to low values. It will be necessary to combine these diffraction prediction models with models for reflections and scattering to provide a more realistic portrait of urban area propagation.

Figure 4. A comparison between measured and predicted signal strengths for an area of the Virginia Tech campus.

5. References


6. Acknowledgements

This work was supported by the Mobile and Portable Radio Research Group Industrial Affiliates Program and DARPA ESTO at Virginia Tech.