Site Specific Propagation Prediction Models for PCS Design and Installation

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ABSTRACT This paper presents new site specific propagation prediction methods for emerging personal communication system (PCS) services which will offer high capacity in urban settings. The propagation prediction models, composed of three dimensional diffraction and ray tracing, are being implemented as software tools on SUN computer workstations. A Geographical Information System (GIS) software package is being used to interface building and terrain data with the propagation prediction programs. Early work at Virginia Tech's Mobile & Portable Radio Research Group (MPRG) show that the predicted signal strengths are within a few decibels (dB) of average measured signal strengths for some test cases [1], [10].

I. INTRODUCTION

Building and terrain databases can be used to compute the field strengths at the receiver induced by radio wave diffractions and ray reflections. Diffraction characterizes the bending behavior of radio waves around obstacles. Multiple diffraction occurs when there are more than one obstacle blocking the direct path between the receiver and the transmitter. For multiple diffraction, the electric field distribution at the first building edge can be used to compute the electric field distribution at the next edge [7]. The received electric field is the summation of the top and side diffracted electric fields. Recursive techniques can be applied to compute the total field strengths at the receiver due to a series of diffractors.

At proposed PCS frequencies in the microwave bands, geometrical optics can be used to predict ray reflections and penetration of radio signals into buildings. Geometrical optics is an approximation of the electromagnetic wave theory when the propagating wavelengths are much smaller than building dimensions. For preliminary study, we assume building surfaces are smooth and planar so that only specular reflections occur. Snell's laws of reflection and refraction are used to quantitatively determine the reflected and penetrated rays. The penetrated field strengths are negligibly small compared to diffracted and reflected field strengths for outdoor receivers since signal attenuation by buildings is large. Therefore, the penetrated rays emerging from buildings are neglected without sacrificing much accuracy for the prediction of PCS users outside of buildings. However, inside tall buildings in an urban setting, penetrating signals can be large. Scattering effects are also ignored since the power of the scattered rays are relatively small compared to specular rays [11].

II. DIGITAL DATABASES

Geographical Resources Analysis Support System (GRASS).

Fig. 1 Buildings and roads overlaid on terrain in GRASS

Buildings are represented as vectors. A building is simplified to have smooth and flat vertical wall surfaces. For instance, an actual rectangular building is represented by the four corner (x,y) coordinates and the height attribute. An irregular building shape such as a pentagon is represented by five corner locations and a height above ground. Such representation formats can accommodate any building shape as long as the walls are orthogonal to the ground and the roof is horizontally flat. Two adjoining buildings can be represented as two separate buildings sharing a common set of wall coordinates but with different height attributes. In GRASS, the building data are stored in two separate files: the digit file and attribute file. The digit file stores the coordinates of the building corners in a clockwise or counterclockwise fashion. The attribute file includes the relative building heights above the ground [2]. Fig. 1 shows an example display of buildings and roads on top of terrain for parts of downtown Washington DC. The darker area signifies lower terrain ele-
The buildings and roads can also be overlaid on signal level and interference level contours for coverage prediction output.

III. DIFFRACTION MODELS

Much of Virginia Tech's preliminary work on building microwave diffraction was done by Russell [9]. A diffracting building edge is modeled as a perfectly absorbing knife edge. The received electric field at P in Fig. 2 involves the Kirchoff diffraction integral,

$$E(P) = \frac{i}{2}\lambda \int_{r_s}^{r_p} \left[ \cos(\alpha) - \cos(\beta) \right] \exp(ik(r + r_P)) dR$$  \hspace{1cm} (1)

where $S$ denotes the location of the transmitting point source. This equation cannot be evaluated numerically in its present format but can be approximated if the distance $q$ is much smaller than the distance $s$ and $p$. This is referred to as the small angle approximation. Assuming that the small angle approximation condition holds, $r_s$ and $r_p$ can be approximated using a binomial series expansion,

$$r_s = s + \frac{x^2}{2s} + \frac{y^2}{2s}, \quad r_p = p + \frac{x^2}{2p} + \frac{y^2}{2p}.$$  \hspace{1cm} (2)

The term $[\cos(\alpha) - \cos(\beta)]$ in equation (1) is reduced to $\cos(\theta)$ which is now independent of $x$ and $y$. The amplitude factor $r_s r_p$ is estimated as $sp$. After the above approximations, the Kirchoff diffraction integral in equation (1) is simplified to

$$E(P) = -\frac{1}{2} \lambda E_f \sin(\theta) \int \exp\left(i\frac{\mu^2}{2}\right) d\mu \int \exp\left(i\frac{\tau^2}{2}\right) d\tau$$  \hspace{1cm} (3)

where $E_f$ is the free space electric field at $P$,

$$E_f = \frac{\exp(ik(s+p))}{s+p}$$  \hspace{1cm} (4)

and

$$\mu_i = x_i \frac{2(s+p)}{\lambda sp}, \quad \tau_i = y_i \frac{2(s+p)}{\lambda sp} \hspace{1cm} i = 1, 2$$  \hspace{1cm} (5)

for $i=1, 2$. Notice that equation (3) is arranged in the well known Fresnel integral format. The Fresnel's integral is evaluated by Romberg's numerical integration techniques from 0 to 5 and approximated for any value greater than 5. A table look up method will be used for fast Fresnel's integral computation. The complex Fresnel's integral of equation (3) can be separated into $\sin$ and $\cos$ functions such that

$$F(\mu) = \int_0^\mu \exp\left(i\frac{\sigma^2}{2}\right) d\sigma = C(\mu) + S(\mu)$$  \hspace{1cm} (6)

where

$$C(\mu) = \int_0^\mu \cos\left(i\frac{\sigma^2}{2}\right) d\sigma \quad S(\mu) = \int_0^\mu \sin\left(i\frac{\sigma^2}{2}\right) d\sigma.$$  \hspace{1cm} (7)

Equation (7) above have the following special properties:

$$C(\infty) = \frac{1}{2} \quad S(\infty) = \frac{1}{2} \quad \text{and} \quad \begin{align*}
C(\mu) &= -C(-\mu) \\
S(\mu) &= -S(-\mu).
\end{align*}$$

A single rectangular aperture shown in Fig. 2, consisting of three diffracting edges, which constitutes three dimensional diffraction. The received electric field at $P$ is the summation of the horizontal and two vertical edge diffracting electric fields. Equation (3) is used to compute the electric field due to a single diffracting edge. The integration limits for the top horizontal edge are from $x_1$ to $x_2$ and $y_1$ to $\infty$. The left side vertical edge integration limits are from $-\infty$ to $x_1$ and $y=0$ to $\infty$. The right side vertical edge integration limits are from $x_2$ to $\infty$ and $y=0$ to $\infty$. The $\sin(\theta)$ term in equation (3) is around unity for the case of small angle approximation and can be neglected.

Most diffractions that occur in the real world are of multiple types as shown in Fig. 3. Equation (3) is not applicable to multiple diffraction calculations since the electric field at the right diffracting edge has been diffracted by the left edge. However, equation (3) can be manipulated to yield the general form,

$$E(P) = \xi \int_0^\mu \exp\left(i\frac{\mu^2}{2}\right) d\mu \int_0^\tau \exp\left(i\frac{\tau^2}{2}\right) d\tau \hspace{1cm} (8)$$

where

$$\xi = -i \times \exp(ikp) \frac{s}{2p \lambda (s+p)}.$$  \hspace{1cm} (9)

$\mu_i$ is described in equation (5) and $E_Q(y)$ is the received electric field above the top edge at the left diffracting screen as a function of $y$. If the diffracting edges are oriented vertically, as in the case of diffraction around corners, then the electric field $E_Q$ is now $x$ dependent. $E_Q$ at the present diffracting edge is computed from $E_Q$ of the previous diffracting edge. $E_Q$ at the present diffracting edge is then used to calculate $E_Q$ for the next diffracting edge. This recursive computation method results from the idea of Huygens' principle, which treats an intermediate observation point as a new radiating source. In summary, the electric field at the receiver is obtained by recursive calculations from the first to the last diffracting edges. Terrain also plays an important role in diffracting propagating radio waves. Between each diffracting building, our program will check for ground locations that block more than 55% of the Fresnel zone. Basically, the terrain profile is reconstructed for the specified path between diffracting buildings to see if ground diffraction occurs. If ground diffraction does not exist, our program proceeds to the next path between buildings. Otherwise, the obstructing ground is regarded as diffracting knife edge.

In order to solve the second integral of equation (8), the magnitude
Ray tracing simulates propagating waves that obey Snell's laws. The amount of reflected, transmitted, and lost energy of a ray is a function of the surface material, surface roughness, propagating wavelength, and angle of incidence. For our first efforts, a rough estimate of reflection and transmission coefficients can be made. From early results, it is estimated that the reflection coefficient is about 0.5, regardless of the incident angles [10]. Additional work at MPRG also includes better models for reflection coefficients.

The ray tracing implementation is divided into two stages: 2D and 3D. Rays are initially traced in the horizontal (2D) directions. The process involves launching rays horizontally at 1° angular spacing, or smaller for 360° around the transmitter. Intersecting buildings are searched and the reflected ray vectors are computed. If a ray is intercepted by the receiver, then that ray is terminated in the tracing process. The received electric field by the ray tracing model is the summation of all the intercepted ray strengths. To avoid the problem of counting the same ray or missing some rays, as mentioned by Honcharenko, Berton [3], and Schaubach [10], the receiver antenna is substituted by a receiving circle of radius $d$. The receiving radius, $d$, should be equal to $L/4$ so that the same ray is not counted more than once. At the same time, all the possible intercepted rays are accounted. The receiving circle radius is a variable which changes depending on the intercepted ray unfolded path length, $L$. If a ray is intercepted by the receiver, then its launched angle, number of reflections, and the total path length are stored to be used later by the 3D ray tracing routine.

An efficient way of searching for intersecting buildings is to group the buildings into bounding blocks. If the launched ray intersects the block, only buildings within the block are searched. This eliminates unnecessary searches of all the buildings in the database. Circles can be used to bound buildings and find possible ray intersection with a building. The introduction of the bounding circles greatly simplifies the building searching process. If the incident ray intersects the circle, then it may or may not intersect the building inside. Once a bounding circle intersecting a ray is found, the next step is to search for the reflecting wall of the enclosed building. If the ray does not intersect the building, then the search proceeds for the next closest intersecting circle. The check for its circle intersection is done by calculating the perpendicular distance from the ray to the center of the circle. If the perpendicular distance is less than or equal to the circle radius, then the ray intersects the circle.

The calculation for the reflecting ray vectors is outlined below. After the reflecting wall is found, the next objective is to find the coordinate of point $(x, y)$. Fig. 4 shows a ray intersecting one of the building walls.
The sine rule from trigonometry is used to find the distance \( r \) from \( T_x \) to \( (x',y') \),

\[
r = \frac{a \times \sin (\pi - \theta - \phi)}{\sin (\theta)}
\]

(13)

where

\[
a = \sqrt{(x_1 - x')^2 + (y_1 - y')^2}
\]

(14)

and is defined as

\[
\theta = \arctan \left( \frac{m_2 - m_1}{1 + m_2 m_1} \right)
\]

(15)

\( m_1 \) and \( m_2 \) are the slopes of the ray and the wall, respectively, and \( \alpha \) is the launched angle shown in Fig. 4. The 2D reflecting coordinate is \( x_r = r \times \cos (\alpha) \quad y_r = r \times \sin (\alpha) \) (16)

Once the intersecting coordinate is determined, we proceed to calculate the reflecting vector shown in Fig. 5. Spherical coordinates are used to denote the ray vectors. In Fig. 5, the geometry shows that the angles \( \eta, \theta \), and \( \sigma \) are related by \( \eta = \theta + \sigma \), and

\[
\sigma = \pi - \arctan \left( \frac{y_2 - y_1}{x_2 - x_1} \right)
\]

(17)

After the ray tracing process in 2D is completed, proceed to the 3D ray tracing process. The 3D ray tracing technique relies on the 2D ray tracing results to minimize the launching of non-received rays, which is a computational improvement over techniques outlined in [10]. Launching rays in a spherical manner is not efficient since most of the rays are not received. It is only necessary to launch rays in the azimuthal directions that are known to intersect the receiver from 2D results. The elevation angle of the ray to be launched is calculated from the difference between the transmitter and receiver heights and the unfolded path length of received 2D ray. If a ray overshoots any building in its path, then it is lost and does not contribute any energy to the receiver. The ray tracing methods also consider terrain reflections. Terrain reflection is checked along the bouncing ray path between buildings. If no terrain interference is found, the program proceeds to the next ray and repeats the procedure. If terrain obstructions exist, then the terrain reflected ray vectors need to be determined. This can be done by constructing a plane from three local elevation points and calculating the intersection coordinate of the plane and the ray.

The ray strength due to reflection at the receiver depends on the total number of reflections, reflection coefficients, and the total path length traveled. The magnitude of electric field of each ray can be expressed as,

\[
|E_r| = \frac{P_{in} Z_0}{4 \pi L_n} \prod_{i=1}^{n} |t_i(\theta_i)|
\]

(18)

where \( P_{in} \) is the effective radiated power (W), \( Z_0=120\pi \) is the free space impedance (\( \Omega \), \( L_n \) is the unfolded path length (m) for the \( n^{th} \) ray, and \( i \) is reflection coefficient at \( i^{th} \) reflection for each \( n^{th} \) ray. The average received power is the power sum of each received ray \([8]\),

\[
P_{recv} = \sum_{n} |E_{r_n}|^2
\]

(19)

Finally, the total average received power is the summation of the average power of direct, reflected rays, and diffacted waves.

V. CONCLUSION

This paper has presented principles and techniques for predicting radio signal levels at the receiver in presence of buildings and terrain. Both diffraction and reflection models are discussed. The diffraction models approximate the Fresnel-Kirchoff diffraction integral and use numerical techniques to obtain its solution. The ray tracing part is the implementation of Snell’s law of reflection and transmission. It is still early to access the accuracy of these models but preliminary results showed promising agreement between predicted and measured signal levels. Our work will lead to automated Computer Aided Design tools for rapid installation, design, and analysis of high capacity wireless PCS in built-up environments.

REFERENCES


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