A RAY TRACING TECHNIQUE TO PREDICT PATH LOSS AND DELAY SPREAD INSIDE BUILDINGS

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Abstract

This paper presents a ray tracing technique to predict path loss and delay spread in buildings. A computer program to predict radio propagation in buildings based on site-specific information such as wall locations and building materials is described. Using geometrical optics-based assumptions, rays are traced in three dimensions from a transmitter location. Line-of-sight, specularly transmitted, specularly reflected, and non-specularly transmitted and reflected rays are included in the model. The individual rays are combined coherently as a function of excess delay to form a power delay profile. Power delay profiles are used for qualitative comparison of measured and predicted propagation. Statistics such as path loss and rms delay spread are computed from the power delay profiles to provide quantitative comparisons. For the office environment studied, reasonable agreement between measured and predicted power delay profiles is found, path loss is predicted to within 6 dB, and rms delay spread is predicted to within 20 ns.

1. Introduction

Buildings vary greatly in size, shape, and type of construction materials. This can make propagation prediction difficult. The statistics of propagation measurements vary greatly from building to building and only broad conclusions can be made [1]. Work in [2] showed that radiation can exit a building and return after being scattered by neighboring buildings.

Large scale building features impact the average path loss and rms delay spread. Path loss between a transmitter and receiver separated by some distance d can be computed as the spatial average of the instantaneous CW path loss over a small-scale area or the time or spatial average of a wide band power delay profile. The path loss determines the average available signal level at the receiver for a given transmitter power and can be used to determine coverage. Rms delay spread, the square root of the second central moment of the power delay profile, is a quantitative measure of the amount of time dispersion in a multipath radio channel.

Ray tracing represents the high-frequency limit of the more rigorous electric field problem and can give quick approximate solutions when more elaborate methods are unworkable. Ray tracing is a tractable method of predicting the delay spread and path loss of in-building radio signals. The time delays of individual multipath components can be linked to specific radio paths. This concept is similar to radar systems that use the time delay to estimate the distance to a target. The lack of significant difference in propagation characteristics throughout the low microwave band [7], [8] indicates that a geometrical optics model may be valid in determination of the arrival times of individual multipath components. This could provide accurate prediction for a variety of frequencies where differences in reflection and transmission coefficients as a function of frequency are included in the model.

Ray tracing methods have been proposed for propagation prediction in microcellular environments [3], [4], [13], and in buildings using image theory [5], [6]. A two-dimensional ray tracing method has been proposed in [11]. This paper presents a three-dimensional ray tracing method to predict the path loss and time delay spread of indoor radio channels [12].

2. The Ray Tracing Model

The model uses "brute force" ray tracing to account for all possible propagation paths. An electromagnetic image theory model, where reflections are modeled as being due to image sources (equivalence), is practical when only a few reflections are to be considered and the propagation environment is represented in a block form. However, image theory is cumbersome when multiple reflections from randomly oriented objects are considered.

Our algorithm is implemented on a UNIX-based workstation modified from a PC-based graphical ray tracer written in C++ [9]. As an object-oriented language, C++ has the capability to manipulate data structures such as vectors, objects, and the functions that match them, in a modular fashion. Due to the numerous ray-object intersection tests and extensive data arrays required for ray tracing, there are considerable requirements on the computer operating platform.

AutoCAD™ is used as the building database manager for the prediction tool. This program was selected because it is considered an industry standard CAD package, and it is believed that building blueprint data may be readily available in an AutoCAD format. AutoCAD supports a standard drawing exchange format allowing data to be exported in ASCII. This exchange format is used to export the building database directly from AutoCAD to the propagation prediction programs.

3. Source Ray Directions

The transmitter and receiver are modeled as points at discrete locations within the three-dimensional database. In order to determine all possible rays that may leave the transmitter and arrive at the receiver, it is necessary to consider all possible
angles of departure and arrival at the transmitter and receiver. To keep all ray manipulation routines general, it is desirable that each ray tube occupy the same solid angle \( d\Omega \), and each wavefront be an identical shape and size at a distance \( r \) from the transmitter. Additionally, these wavefronts must be subdivisible so that an increased ray resolution can be handled easily. An ideal wavefront is shown in Figure 1. For reference, let a unit sphere be a sphere with radius \( r=1 \). The total wavefront at a distance \( r=1 \) from the source is the surface of this unit sphere. The problem then becomes one of subdividing the sphere surface into equal area “patches” that are all the same size and shape and completely cover the surface.

![Ideal wavefront](image)

**FIGURE 1.** Ideal wavefront represented by each source ray

To represent discrete wavefronts by source rays, a solution is adapted from the theory of geodesic domes [10]. An icosahedron is inscribed inside the unit sphere. Then, a triangular icosahedron face is subdivided to generate the desired ray resolution. Each triangle edge is tessellated into N equal segments where N is the tessellation frequency [10]. Lines that are each parallel to one of the three sides are drawn to subdivide the triangle into smaller equilateral triangles. Rays are launched at angles that pass through the vertices of the triangles. Wavefronts are hexagonal for rays that pass through interior and edge vertices. Rays that pass through the twelve original icosahedron vertices are pentagonal. As the tessellation frequency increases, the wavefronts decrease in size, but keep their shape and relation to their nearest neighbors. The angular separation between a ray and its nearest neighbor is nearly identical for each nearest neighbor. For a given tessellation frequency of N, the number of source rays traced is \( 10N^2 + 2 \) [10].

The angular separation between rays decreases as the number of rays increases. Thus, this method of launching the source rays provides wavefronts that completely subdivide the surface of the unit sphere with nearly equal shape and area. In Figure 2, the solid line indicates the difference in minimum and maximum ray separation between a ray and its neighbor for different source rays. The dotted line is the difference in ray separation for a given source ray and its own nearest neighbors. The curves are slightly different because of the differences between the pentagonal ray wavefronts launched at the original icosahedron vertices and the hexagonal ray wavefronts launched from the tessellated faces of the icosahedron. This method of determining source ray directions is described in more detail in [12].

4. Propagation Models

The propagation of energy from the transmitter to the receiver occurs in various modes such as by direct, specularly reflected, specularly transmitted, and diffusely scattered paths. In considering these modes for the propagation model, it is important to recognize the path loss dependence of each mode. Direct (line-of-sight) rays exhibit a \( 1/d^2 \) power dependence according to Friis free space transmission. Specularly reflected and/or transmitted rays also follow a \( 1/d^2 \) dependence, where \( d \) represents the total ray path length. For example, the specularly reflected ray shown in Figure 3, whose path segments are labeled \( r_1 \) and \( r_2 \), has a power dependence proportional to \( 1/(r_1 + r_2)^2 \). However, the diffusely scattered field, comprised of the path segments \( s_1 \) and \( s_2 \), exhibits a multiplicative dependence given by \( 1/(s_1 + s_2)^2 \). The multiplicative dependence is due to the additional spreading loss the ray experiences after re-radiation from the scattering surface.

For the results presented here, the theoretical Fresnel reflection and transmission coefficients for lossless, homogeneous, infinite planar surfaces were used to model the amplitudes of reflected and transmitted rays. The vertical (parallel)

![Building Interfaces](image)

**FIGURE 3.** Transmitted, reflected, and scattered rays at a planar interface.
polarization coefficients were used for the floor and ceiling, and horizontal (perpendicular) polarization coefficients were used for walls. Figure 4 shows the reflection and transmission coefficient magnitudes for $\varepsilon_r = 2.44$ at 1.3 GHz.

At microwave frequencies, it is likely that significant diffracted energy will reach the receiver at some locations. Although wavelengths are short enough to utilize geometrical optics assumptions, it is expected that there will be some discrepancy between measured and predicted propagation impulse responses. For the results presented here, diffraction has not been included in the model, however, it is a current focus of this research.

In summary, the model includes direct, reflected, transmitted, and scattered fields represented by the rays where each propagation mechanism is treated separately. The field amplitude of the $i$th ray at the receiver is given by

$$|E_i| = E_0 f_{i1} f_{i2} L_1(d) L_2(\Psi_i) \prod_j \Gamma(\theta_{ji}) \prod_k T(\theta_{ki})$$

where $E_0$ is the field strength at 1 meter, $f_{i1}$ and $f_{i2}$ are the field radiation antenna patterns, $L_1$ is the path loss of the $i$th multipath component, and $L_2$ is the additional path loss due to scattering with scattering angles $\Psi_i$. The transmission and reflection coefficient magnitudes as a function of angle are $T(\theta_{ki})$ and $\Gamma(\theta_{ji})$.

5. Tracing Rays at a Boundary

The computer program uses ray tracing in three dimensions to find each ray path by which significant levels of energy radiated from the transmitting location reaches the receiving point. For a given execution of the program, multiple receiving locations can be defined, so the procedure described here can be applied to each receiving point. The ray tracing is accomplished by an exhaustive search of a ray tree accounting for the decomposition of the ray at each planar intersection. First, the program determines if a line-of-sight path exists, and if so computes the received signal. Next, the program traces a source ray in a direction determined by the source ray algorithm described in Section 3 and detects if an object intersection occurs. If no intersection is found, the process stops and a new source ray is initiated. Once the program determines that an intersection has occurred, it then checks to see if the ray from the intersection point directly to the receiver is blocked. If this ray is not blocked, the program identifies the ray as reflected or transmitted and specular or non-specular (scattered) and computes the received signal. Next, the program divides the source ray into a transmitted and reflected ray that are initiated at the intersection point on the boundary. These rays are then treated in a similar fashion to source rays. This recursion continues until the ray intensity falls below a specified threshold or no further intersections occur. Multiple scattering is not included in the model and scattered rays are not traced recursively. Multiple scattering of a ray will not contribute significantly to the received power since the amplitude of these rays decreases rapidly with distance.

6. Identification of Specular Rays

Consider a transmitter and receiver above a single infinite planar surface. To determine the ray-traced impulse response by a brute force method, it is necessary that the solution include only one specular reflected ray regardless of how many discrete source rays are traced. The following test is used to determine if the ray reaching a receiving point is specular, so that such rays are received. The total (unfolded) path length, $d$, that the ray travels from the transmitter to the receiver is determined. A reception sphere (from [11], extended to three dimensions [4]) is constructed about the receiving location with a radius proportional to the unfolded path length and the angular spacing between neighboring rays at the source. If the ray intersects the sphere, it is considered the closest approximation to the true specular ray. Otherwise, the ray is diffusely scattered. It is important to emphasize that the reception sphere radius is proportional to the unfolded path length from the source to receiver and is different for each received ray.

The reception sphere effectively accounts for the divergence of the rays from the source. For ray separation $\alpha$ sufficiently small, the ray intercepting the sphere will be an accurate measure of the ray that would pass directly through the receiving point. The physical interpretation of the reception sphere can be justified with the aid of Figure 5. This figure is a two dimensional representation of a ray being traced. Two adjacent rays, launched at $\pm \alpha$ relative to the test ray, are also shown. Note that in three dimensions, any ray will have more than two adjacent rays and the angular separation of the adjacent rays will not necessarily coincide with the coordinate axes.

As shown in Figure 5, a reception sphere with the correct radius can receive exactly one of the rays. If the radius is too large, two of the rays could be received and would, in effect, count the same specular ray path twice. Likewise, if the radius is too small, it is possible that none of the rays will intercept the sphere and the specular energy will be excluded. The path loss error of receiving two rays would be a few dB. A missed specular ray could lead to a much larger error if a significant amount of energy is carried by that ray. In order to make sure that the specular ray is not missed, the ray wavefront is considered a circle circumscribed about the hexagonal (or pentagonal) wavefront shape. Although it is possible to receive two

![FIGURE 4. Fresnel reflection and transmission coefficient magnitude model for vertical and horizontal polarization.](image-url)
specular rays with this approach, multiple specular rays from the same surface are eliminated by processing the ray-traced impulse response estimate.

7. Processing Ray-Traced Impulse Responses

For each ray-traced multipath component, the total path length, field strength relative to the level at one meter, departure angles from the transmitter, and arrival angles at the receiver are written to a raw data file. In order to compare ray-traced impulse responses with measured data from [8], the raw data is convolved with a 4 ns rms width probing pulse to form a power delay profile. The convolution is performed coherently where the amplitude of each multipath component is determined from equation (1) and the phase is based on the carrier frequency and path length of the multipath component. The power delay profile is used because the program predicts path loss as influenced by large-scale variations in building geometry. The received power is computed by integrating the area under the power delay profile, and path loss is referenced to the free space path loss at 1 meter.

8. Results

The ray tracing program has been run with building blueprint information from the second floor of Whitemore Hall, an academic building on the campus of Virginia Tech. The interior is constructed with drywall mounted on metal studs that extend fully to the 4.5 meter high ceiling. In [8], extensive measurements were made at 1.3 GHz in Whitemore Hall with vertically polarized omni-directional dipole antennas 1.2 meters above the floor and a 4 ns rms baseband pulse width. Both the transmitter and receiver were stationary and the received signal was time averaged. Figure 6 shows the floor plan where the measurements were taken and the walls that were included in the AutoCAD prediction database. The floor and ceiling were also included in the database. The transmitter location is indicated with a 'Tx' and the nine receiver locations are indicated by the letters 'A' through 'I'. Table 1 presents the path loss in dB with respect to free space path loss at 1 meter and rms delay spread in ns for the measured and predicted power delay profiles at the nine receiver locations. The path loss difference between measured and predicted is less than 6 dB and the rms delay spreads differ by less than 20 ns for each location.

![Figure 6: Floor plan of the second floor of Whitemore Hall. The transmitter and receiver locations are circled to indicate where measurements and predictions were made. Ray-traced impulse responses are compared at locations B and H.](image)

**Table 1:** Table of measured and predicted path loss and rms delay spread for the locations indicated in Figure 6.

<table>
<thead>
<tr>
<th>Location</th>
<th>Type</th>
<th>Path Loss (dB wrt 1 m FSPL)</th>
<th>RMS Delay Spread (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Measured</td>
<td>17.3</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>16.1</td>
<td>5.8</td>
</tr>
<tr>
<td>B</td>
<td>Measured</td>
<td>19.4</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>14.9</td>
<td>3.8</td>
</tr>
<tr>
<td>C</td>
<td>Measured</td>
<td>41.9</td>
<td>24.0</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>41.6</td>
<td>19.4</td>
</tr>
<tr>
<td>D</td>
<td>Measured</td>
<td>43.5</td>
<td>19.8</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>42.5</td>
<td>13.3</td>
</tr>
<tr>
<td>E</td>
<td>Measured</td>
<td>17.7</td>
<td>38.1</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>17.3</td>
<td>21.0</td>
</tr>
<tr>
<td>F</td>
<td>Measured</td>
<td>23.9</td>
<td>43.4</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>20.9</td>
<td>23.8</td>
</tr>
<tr>
<td>G</td>
<td>Measured</td>
<td>22.3</td>
<td>16.4</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>25.2</td>
<td>30.8</td>
</tr>
<tr>
<td>H</td>
<td>Measured</td>
<td>42.9</td>
<td>35.4</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>40.9</td>
<td>22.9</td>
</tr>
<tr>
<td>I</td>
<td>Measured</td>
<td>47.1</td>
<td>34.0</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>42.0</td>
<td>13.9</td>
</tr>
</tbody>
</table>

Figure 7 shows the measured and predicted power delay profiles at the line-of-sight location B in Figure 6. The ray-traced power delay profile appears to accurately predict the measured power delay profile. The path loss is within 4.5 dB, and the rms delay spread is within 5 ns. The measured and pre-
predicted power delay profiles for location H are shown in Figure 8. Notice that this is an obstructed topography. Agreement between measured and predicted power delay profiles is not nearly as good as for the LOS case, but the total path loss is within 2 dB and the rms delay spread is within 15 ns. The arrival times of individual multipath components are predicted by the model. Although the amplitudes are not correct, only the walls, floor, and ceiling were included in the building database. It is likely that unmodeled objects such as room furnishings contribute to the difference. Also, diffraction and reflection-diffraction multipath components were not modeled. The results presented here indicate that accurate site-specific prediction of multipath impulse responses, path loss, and delay spread in buildings is possible using a geometrical optics based model. We are currently investigating methods to enhance the accuracy of this prediction tool.

FIGURE 7. Measured data and a ray-traced power delay profile for line-of-sight location B in Whittemore Hall. The measured path loss is 19.4 dB and the predicted path loss is 14.9 dB greater than free space path loss over 1-meter. The measured and predicted rms delay spread are both less than 10 ns.

FIGURE 8. Measured data and a ray-traced power delay profile for obstructed location H in Whittemore Hall. The measured path loss is 42.9 dB and the predicted path loss is 40.9 dB greater than free space path loss over 1-meter. The measured rms delay spread is 35.4 ns and the predicted rms delay spread is 22.7 ns.

9. Conclusion

This paper has described a ray tracing technique to predict path loss and delay spread in buildings. A novel approach has been used to determine the ray directions from the source in three dimensions. Line-of-sight, specular and non-specular transmissions and reflections have been included in the propagation model. This method has shown that accurate impulse response, path loss, and delay spread prediction in buildings is possible using site-specific information, although model refinements are still needed. With such a propagation prediction tool, personal communications systems (PCS) could be designed and installed more rapidly and economically than if measurements were required for each building.

10. References


11. Acknowledgments

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