Ray Tracing Prediction of Indoor Radio Propagation

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Abstract: Indoor wireless systems will be used in a large variety of office, factory and residential environments. Thus, adequate guidelines for radio port placement are needed to ensure satisfactory performance at the lowest cost. These guidelines must be derived from a large body of site-specific propagation data. However, collecting a statistically significant database through measurements is a daunting task. Alternatively, this database can be generated by using propagation models, validated by measurements. Several models exist for the statistical characterization of microwave propagation within buildings. However, statistical models do not provide site-specific information. We propose a hybrid model in which ray tracing is used to predict, at any given location, the local mean of the received power and the delay profile. Variations about the mean values can then be captured via a statistical description matched to the local environment.

We describe an efficient 3-D ray tracing algorithm which accounts for all (transmitted as well as reflected) rays reaching the receiver location after an arbitrary number of reflections. We include the effects of the angle of incidence, the material dielectric constant and the antenna patterns. The predicted values for the local means of the received power are then compared against measurements to establish the accuracy of this approach.

I. INTRODUCTION

The emergence of a variety of wireless indoor systems has created the need for an efficient way to evaluate radio port layout alternatives for specific environments. Measurements, while indispensable to validate any other approach, are impractical in the scale necessary to cover a wide variety of environment and system solutions. A building-specific prediction tool can be very valuable when designing a system for a specific environment. It can also serve, moreover, as a general performance evaluation tool, which can be used to assess a large variety of system choices or parameter values. In theory, propagation characteristics could be exactly computed by solving Maxwell’s equations with the building geometry as boundary conditions. Clearly, this approach is beyond the computing power of current workstations. Fortunately, for the purposes outlined above, it is not necessary to have exact agreement between measured and predicted values. What is important is to characterize large scale variations in local mean values in order to rank-order the port lay-out schemes or system design alternatives under consideration. Variations about the mean, within a small region, can be characterized statistically, and can be suitably included in the link fade margins.

Site-specific algorithms have been presented by McKown and Hamilton [1], Bertoni et al [2] and others [3-8]. Here, we make different assumptions and tradeoffs, according to the motivation outlined above. Specifically, we predict the local mean of the received power as the scalar sum of the powers of all the multipath components reaching the specified location. For each path we compute the loss, in excess of the free space propagation loss, as the product of the magnitude squared of the reflection and transmission coefficients and the antenna radiation patterns. We compute the reflection and transmission coefficients, for each object, from a multilayer dielectric model, maintaining angle and polarization dependencies. Furthermore, we accommodate an arbitrary number of surfaces, whether walls, floors or ceilings.

We describe here an efficient 3-D ray tracing technique for the prediction of the local mean power and RMS delay spread of an arbitrary building. We have applied this technique to the AT&T Bell Laboratories facility at Crawford Hill. The predicted values for the local means of the received power are compared with measurements and are found to follow the same trend, although the predicted values are somewhat higher than the measured values. This can be expected since we assume perfectly specular reflection and transmission. Finally, we discuss using this prediction technique as the kernel in a port-layout placement software tool. Also, we discuss using this kernel in a more general system evaluation package, where a large variety of alternatives can be studied, such as multicasting, antenna directivity, antenna diversity, polarization diversity, frequency plans, etc.
II. METHODOLOGY

We begin by specifying the transmit and receive points in 3 coordinates. Each surface (wall, floor or ceiling) is modeled as a multilayer dielectric and the reflection and transmission coefficients for both polarizations are computed using the recursive approach described in [9]. We assume both antennas to be vertically polarized dipole antennas. The reflection coefficients, transmissions coefficients and antenna patterns are sampled with a resolution of ten samples per degree and stored in look-up tables.

The sequence of computations begins with the direct path, followed by all paths with one-reflection, two-reflections, and so on, up to the specified number of reflections. For every path, the distance-dependent loss is simply the free space propagation loss, and is proportional to the total path length squared. The total path loss is computed as the product of the propagation loss times the reflection losses, the transmission losses and the antenna radiation patterns.

An arbitrary path is defined by the sequence of surfaces (walls, floor or ceiling) of which the signal must reflect to travel from the transmitting to the receiving antenna. We make the simplifying assumption that all reflecting surfaces are orthogonal. This is true in many buildings and we defer treating the case of walls set at arbitrary angles, or curved surfaces, for future work. With this assumption, the coordinates for the image of a point reflecting over a surface are found simply by reflecting the coordinate corresponding to the axis parallel to the surface normal. For example, Figure 1a shows a point, $P$, with coordinates $(a,b,c)$, and a reflecting surface parallel to the $yz$ plane and located a distance $D$ along the $x$ axis. It can be seen that the image, $I$, has coordinates $(2D-a,b,c)$. This suggests the general procedure, (explained in detail below and in Figure 1), in which the coordinates of the image of the receiver antenna, for an arbitrary path involving multiple reflections, are found by successively reflecting the receiver antenna coordinates over the sequence of reflecting surfaces defining the path under consideration. Once the coordinates for the (highest order) image of the receiving antenna are known, we can compute the overall path length as the length of the line joining this image to the receiving antenna. Furthermore, the coordinates of all reflection points are easily computed as explained in the following example.

Consider a rectangular room, shown in Figure 1b, with walls 1 and 3 parallel to the $yz$ plane, and located at points $D_1$ and $D_3$ along the $x$ axis, and walls 2 and 4 parallel to the $xz$ plane, and located at points $D_2$ and $D_4$ along the $y$ axis. The transmitting antenna is located at point $T$, while the receiving antenna is located at point $R$, with coordinates $(a,b,c)$. To trace path 2–4–3, from $T$ to $R$, reflecting off walls 2, 4 and 3, we need to find three images. First, $I_3$, the first order image of the receiver antenna, i.e., the one-reflection image, of the receiver over wall 3, is found by reflecting the receiver coordinates $(a,b,c)$ over wall 3. Thus, $I_3$ has coordinates $(2D_3-a,b,c)$. Then, the second order image, at point $I_{3,4}$ is found by reflecting the first order image over the semi-infinite plane containing wall 4, yielding coordinates $(2D_3-a,2D_4-b,c)$. Finally, the first wall in this path, wall 2, is also normal to the $y$ axis. Thus the coordinates of the highest order image, at point $I_{3,4,2}$, are found by reflecting the $y$-coordinate again, yielding coordinates $(2D_3-a,2D_4-2D_2-b,c)$. Once all images are found, the complete path and all reflection points are found as follows. The first reflection point, $r_1$, is found at the intersection of the line $T-I_{3,4,2}$ with wall 2. The second reflection point, $r_2$, is found at the intersection of the line $r_1-I_{3,4}$ and wall number 4. Similarly, $r_3$ is found at the intersection of line $r_2-I_3$ with wall 3. Finally, the path 3–4–2 is completed with the segment $r_3-R$.

We have found that the predicted propagation loss does not change more than 1 dB when including paths with three or more reflections. However, the predicted RMS delay spread is still affected by weak, highly delayed paths, but does not change by more than 2 ns if paths with three or more reflections are not included.

III. SIMULATIONS VERSUS MEASUREMENTS

In order to obtain an early assessment for the performance of this approach, we performed measurements of propagation loss versus distance in the first floor of the Crawford Hill building at AT&T Bell Laboratories in Holmdel, New Jersey. The elevation and floor plan are shown at the top and bottom of Figure 2, respectively. The elevation shows that the internal partition walls do not extend all the way to the true ceiling due to the presence of a "false ceiling". This false ceiling is considered to be transparent at the frequencies of interest. All measurements were performed at 2.0 GHz, with dipole antennas at a height of 3 m. At each point, a total of 1000 individual power measurements were recorded while moving the receiving antenna over a circular area of a few wavelengths in diameter. For each point, the local average, maximum and minimum values are extracted and recorded. All measurement sessions began and ended with a calibration measurement of the received power at 1 m. We utilized a 100 mW power amplifier, yielding an average received power at 1 m of -21 dBm. This value was very consistent and did not change whether the transmitter was in a room or out in the corridor.
We performed three types of measurements, depicted in Figure 2. In all cases the transmitter is shown as a black square placed in the central corridor, near the reception area. One type of measurement was a Line-of-Sight (LOS) measurement, where the transmitting and receiving antennas were placed at various distances along the center of the corridor. The second involved obstructed paths within a single room, the receiver antenna was placed at various points, starting close to the door and moving towards the opposite wall. The third was obstructed paths at the same location within different rooms, where the receiver antenna was placed in various rooms along the corridor about 2 m into each room.

Figures 3 and 4 show the predicted values (solid line) and the measured values (dashed line) for the mean propagation loss, referenced to the loss at 1 m, versus the distance between the transmitting and receiving antennas. It can be seen that the predicted and measured values follow the same trend. However, the predicted values consistently underestimate the measured propagation loss. This may well be due to the fact that, so far, we have assumed perfectly smooth and lossless dielectric layers at the reflection and transmission points.

Although further measurements are clearly needed to refine the techniques presented here, the approach followed should be quite suitable to the purposes outlined earlier.

IV. SITE-SPECIFIC PERFORMANCE EVALUATION TOOL

To evaluate radio port placement alternatives, a large number of potential receiver locations must examined per placement. For example, the contour map in Figure 5 for the building shown in Figure 2, (82 walls) was constructed from 1495 individual receiver locations. This computation required 15 minutes and 28 seconds on a SUN 10 when all paths with up to two reflections were included. A statistical representation of the same data is given in Figure 6. The histogram shows that most paths have a propagation loss between 40 to 60 dB above the loss at 1 m. The "outage" curve, shows the fraction of locations that would be out of service in a system is designed to accommodate a propagation loss equal to or less than the abscissa. Thus, the prediction techniques described previously are sufficiently efficient that a particular port layout scheme can be evaluated in a reasonable time. Deterministic or heuristic rules can then be devised to determine the minimum number and locations for the radio ports necessary to achieve a target outage for a given maximum allowable loss.

This approach provides enough information to evaluate the effects of multicasting, antenna directivity, antenna diversity, polarization diversity, etc. Moreover, this tool can be readily expanded to analyze interference from co-channel and adjacent-channel users as well as interference from other systems. At this point, issues relating to frequency re-use, band sharing, and coexistence with existing systems and devices could be explored.

V. CONCLUSIONS

We have presented an efficient 3-D ray tracing algorithm which accounts for all transmitted and reflected rays reaching a receiver location after an arbitrary number of reflections. Transmission and reflection coefficients, for each polarization, are derived from a multilayer dielectric model for walls, ceilings and floors. We include the effects of the angle of incidence and antenna patterns. The predicted values of the local mean of the received power have been compared against measurements to demonstrate the accuracy of this approach.

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REFERENCES


Figure 1: Using images to trace a three reflection path.

Figure 2: Floor plan and elevation of the 1st floor of the AT&T Crawford Hill building showing receiver locations for Line-of-Sight and Obstructed paths, and rays traced with up to two reflections.
Figure 3 and 4: Measured and predicted propagation loss, relative to 1m in line-of-sight and obstructed locations.

Figure 6: Histogram and cumulative distribution of propagation losses, for the 1st floor of the Crawford Hill building, with a single transmitter antenna located in the reception area.

Figure 5: Contour map of received power for the first floor of the Crawford Hill building, (82 walls, 2 reflections).