A Comparative Study of Wireless Propagation Simulation Methodologies: Ray Tracing, FDTD, and Event Based TLM *

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Abstract

This paper compares ray tracing, finite difference time domain, and the event driven transmission line matrix models as tools for making site specific path-loss predictions in cluttered environments. A brief overview of each type of model is presented. The accuracy and computational cost of a ray tracing, FDTD, and event based TLM model are compared for a small, indoor propagation experiment. The potential for producing accurate, site specific path-loss databases using the fast event based TLM model is discussed in the conclusion.

1 INTRODUCTION

Accurate radio channel models are essential for predicting the performance of wireless networks that operate in cluttered environments (see, e.g., [1–3]). Network performance in these types of environments is determined by interactions between the application traffic pattern, network protocol stack, and radio channel characteristics. Accurate performance predictions must account for all three of these elements.

Network protocol simulations typically rely on empirical models of the physical radio channel. Empirical models are attractive because they are computationally cheap to use. Empirical models are constructed in one of two ways. They can be based on simplifying assumptions concerning the physical geometry of the propagation space. For example, free space models assume that the propagation volume is free of obstacles. Empirical models can also be constructed with a 'best fit' to experimental measurements obtained in a particular environment. For example, an equation can be devised that approximates measured path-loss as a function of distance, where the measured path-loss data was obtained in an urban canyon. In [4], several empirical models of both types are described.

Physically based radio channel models are necessary to make site specific predictions of radio channel behavior (see, e.g., [5–7]). There are two basic approaches to physical modeling of radio channels; ray tracing methods and finite difference methods. Ray tracing methods are based on the geometric theory of optics, and are, in fact, closely related to the computer graphics technique of the same name. Finite difference methods, which can be broadly considered to include transmission line matrix and finite differ-

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ence time domain techniques, are discrete approximations to Maxwell's equations, and they simulate the propagation of an electromagnetic wave.

Ray tracing and finite difference techniques are computationally expensive. Finite difference schemes, in their complete form (see, e.g., [8]), are widely regarded as being unsuitable for simulating wave propagation over large areas. However, simplifications incorporated into transmission line matrix methods have allowed path-loss predictions to be computed for relatively large areas (see, e.g., [9]). Ray tracing methods are relatively insensitive to the dimensions of the space under consideration, but they scale poorly when the physical geometry is complex and/or there are a large number of potential signal receivers.

Attempts to construct hybrid ray tracing and FDTD propagation models are described in [6] and [10]. Largely, these efforts attempt to compute path-loss using ray tracing techniques, with FDTD methods being employed for small areas in which ray tracing does not provide accurate results. When considering large areas and very large numbers of receivers, this approach suffers from the same computational drawbacks as ray tracing methods. The added FDTD scheme serves to improve accuracy in those areas where ray tracing is likely to give poor results, but it does not reduce the simulator execution time.

An event driven variation of the transmission line matrix method is described in [11]. This event driven model is designed for use with cluttered environments, in which most objects are opaque at radio frequencies. The model is executed on a three dimensional spatial grid, with grid points being updated only when the electric field amplitude at that point is sufficiently strong. This greatly reduces the computational effort needed to simulate areas where the radio wave can not penetrate large volumes of space. Moreover, because the method is grid based, the computational cost is independent of the number of receivers (see, e.g., [5]).

This paper compares ray tracing, finite difference time domain, and the event driven transmission line matrix models as tools for making site specific path-loss predictions in cluttered environments. Sections 2, 3, and 4 provide an overview of each model and its relative merits in the context of this study. Section 5 demonstrates the use of each method with representative simulation tools.

2 RAY TRACING

Ray tracing models are based on the geometric theory of optics. The fundamental assumption is that high frequency waves can be accurately approximated by a discrete number of rays emanating from the wave source. Associated with each ray is its power, which diminishes with distance according to some empirical model (frequently, a free space model is used). The distance traveled by the ray is determined directly from its path through a three dimensional geometric model. Calculating this path is the computationally difficult part of using a ray tracing method.

Ray tracing begins with the generation of a ray by the transmitter. The ray follows a straight line until it encounters a surface. At a surface, the ray can be split into new rays to model different physical effects. Typically, these effects include reflection from the surface, transmission through the surface, and, possibly, diffraction around the sharp edge of a surface. Other effects can also be simulated (see, e.g., [12–14]). The ray tracing process terminates when the ray reaches the receiver or some threshold criteria is met (e.g., after some distance traveled or some number of reflections/transmissions/diffractions occur). This process is repeated until some predefined number of rays have found a path to the receiver or some number of rays have been attempted. At this point, the approximate signal characteristics of the radio channel can be computed using information about the arriving rays.

Ray tracing is accurate for a broad range of scenarios (see, e.g., [10, 13]). The computational cost, however, can be very high (see, e.g., [14]). The computer time needed to complete a ray tracing simulation grows with the number of surfaces in the geometric model. It also increases as the number of receivers is increased, since at least one ray is required for each possible receiver.

3 FDTD

Finite difference time domain methods are a class of numerical techniques, which broadly includes transmission line matrix methods, for solving the Maxwell's equations in the time domain. Simple finite difference schemes, based on the linear wave equation and using low order numerical methods, are generally preferred for radio wave propagation modeling. In their simplest form, finite difference methods approximate physical geometry with a three dimensional grid, and the electromagnetic field evolution is computed at each grid point. In more complex models, the regular three dimensional grid is replaced with an irregular mesh that more accurately conforms to the shape of curved geometric features.

Finite difference methods, and related transmission line matrix methods, are grounded in well established physical laws, and as such they can be applied to a very large class of problems. The computational effort needed to conduct a simulation is proportional to the number of grid points. For a three dimensional problem on a regular grid, the computational cost grows roughly as the fourth power of the grid resolution. The grid resolution is determined, in part, by the size of the simulated space and, in part, by the type of information that is required. To compute, for example, the impulse response of a radio channel requires a grid resolution that is much finer than the signal wave length.

4 EVENT BASED TLM

The event driven TLM method is based on a simple model of radio wave propagation through a homogeneous, three dimensional space. This simple model is given by the linear wave equation

$$\frac{\partial^2}{\partial t^2}U(t,x,y,z) = c^2\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)U(t,x,y,z)$$

where t is time, c is the propagation speed, x, y, and z are Cartesian spatial coordinates, and $U(t,x,y,z)$ is the scalar electric field potential at the space-time coordinate (t,x,y,z). A discrete approximation of this partial differential equation can be constructed as a three dimensional transmission line network (see, e.g., [15]). This model can, in turn, be optimized for computation by reinterpreting it as a discrete event system (see, e.g., [16]). The details of this transformation for the wave equation are given in [11].

In an inhomogeneous space, different wave-carrying mediums are modeled as homogeneous spaces. The different media are joined using reflection/transmission junctions that model reflection, transmission, and wave speed changes when a wave moves across a medium interface. A detailed description of the medium interface model can be found in [11]. The resulting method is second order accurate within a homogeneous space, and first order accurate at material interfaces.

Two simplifications can be made without reducing the model's utility for predicting radio channel path-loss. Both of these simplifications are based on the fact that the most useful portion of the radio signal is carried by the wave front, and the receivable portion of the wave front is moving through the air. This suggests, first, that waves traveling in other types of materials (e.g., concrete or earth) can be discarded. A simplified version of the reflection/transmission junction that only propagates reflected waves implements this simplification.

The second simplification restricts propagation calculations to the wave front by using two distinct cutoff thresholds. The first threshold is an *absolute* threshold, and a grid point will not propagate any disturbance with a magnitude that is below this threshold. The second threshold is a *relative* threshold, and it defines a local cutoff threshold relative to the largest disturbance that has passed through the point. To be precise, let U_{max} be the largest signal amplitude observed at a point, y the junction output being considered, c_{abs} the absolute cutoff, and c_{rel} the relative cutoff. Then the output y will be propagated only if $y > c_{abs}$ and $y > U_{max} \cdot c_{rel}$.

If this model is simulated using a very coarse grid, then accurate path-loss predictions can be made at receivers for which there is an open air path to the transmitter. With a very fine grid, it is possible to construct the impulse response of the virtual radio channel between the transmitter and each receiver.

The computational cost of the event based TLM

method is determined by the number of *active* grid points. If the propagation space is cluttered with objects that do not transmit radio signals, then the number of active grid points will be small when compared to the total number of grid points in the space. This can significantly reduce the computational complexity with respect to other finite difference techniques.

5 PROPAGATION EXPERIMENT

The accuracy and computational cost of a ray tracing, FDTD, and event based TLM model were compared for a small, indoor propagation experiment. Measurement data against which to compare the simulator predictions was gathered in a laboratory room at ORNL. For the experiment, a transmitter was placed at one bench in this room, and signal strength measurements were taken at 90 locations on a bench at the opposite side of the room. These measurements were used as the basis for the accuracy comparison.

A VRML model of the room was constructed that describes its dimensions and large objects that might have a significant impact on the measured signal strength. The VRML model was built with one centimeter accuracy. Large objects, such as shelves and tables, were modeled, but small objects, such as bench equipment, were omitted. Figure 1 shows the VRML model of the room and the location of the 90 receivers and the transmitter. The transmitter (TX) is 80cm from the edge of the bench on the right, and the 90 receivers (RXs) were set up on the opposite bench as indicated. The receivers were placed at 3.12cm intervals. The first receiver was located 50cm from the bench edge. The dimensions of the room are 7.39m X 7.39m X 3.66m. The wall is concrete and 25cm thick. The table and benches consist of wood and metal. Note that several small pieces of equipment were not included in the VRML model.

A pair of IEEE 802.15.4-based transceivers were used to obtain the experimental data. One node was configured as a transmitter and the other node as a receiver. The transmitter parameters were chosen as follows; 0 dBm transmitter power at 2405 MHz and vertically polarized antenna with 0 dB gain. The Receiver Signal Strength Indicator (RSSI) was used to measure the received signal strength.

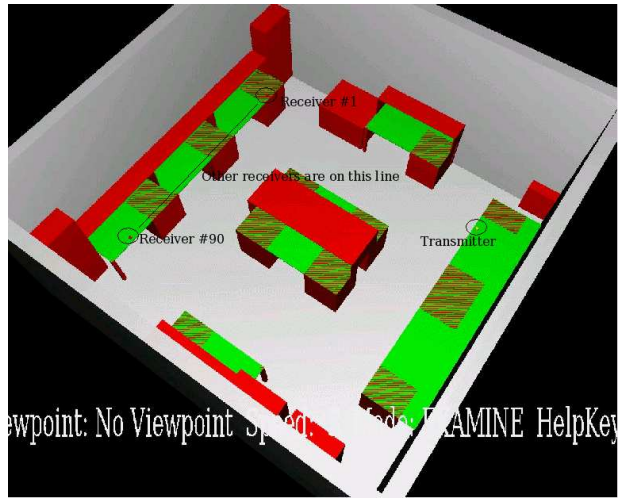

Figure 1. 3D view of the room used for the validation study.

Before taking measurements, the devices were calibrated in a shielded enclosure. One ZigBee transmitter and one receiver were placed in a small chamber made from Eccosorb absorbing foam. Two calibration measurements were taken, the first with the transmitter and receiver separated by 20cm, and the second at a distance of 30cm. The measured RSSI value was 5 dB less than the expected path loss value, as calculated with the free space propagation equation, for the 20cm case, and 7 dB less for 30cm case. This indicates that the receiver power is actually 5 dB lower than the RSSI value.

To obtain the measurements, the transmitter was placed as shown in Fig. 1. The receiver was used to take measurements at 90 positions along the line shown in Fig. 1. Thirty packets with 50 byte payloads were transmitted for each of the 90 measurements, and the resulting RSSI values were recorded.

The VRML model was used to construct inputs for three different propagation simulators. Wireless Insite[17], a commercial ray tracing tool, was used as a

representative example of available ray tracing software. XFDTD, from the same company that provides Wireless Insite, was used as an example of available FDTD tools. Our own event based TLM simulator implements the event based TLM model. The VRML model was used directly by the event based TLM simulator. Figure 2 shows the XFDTD model that was constructed based on the VRML model. For the simulation runs, the absolute and relative cutoff thresholds for the event based TLM model were set at 10^{-6} and 10^{-3} respectively. The XFDTD software was set to use a $-70dBm$ cutoff threshold. The event based TLM and FDTD models used 10cm grid resolutions.

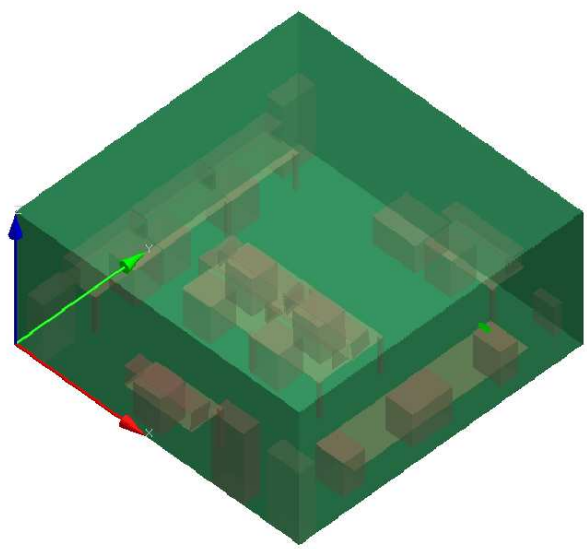

Figure 2. 3D model for FDTD simulation.

Figure 3 shows the measured path loss, path loss computed using Wireless Insite, and the path loss computed with the event based TLM. Figure 4 show the 3D model used for FDTD simulation and the resulting field snapshot. All the methods provide accurate results with respect to measured path loss data.

The simulation completion time for the ray tracing, FDTD, and event based TLM models are shown in Table 1. These execution times include simulator

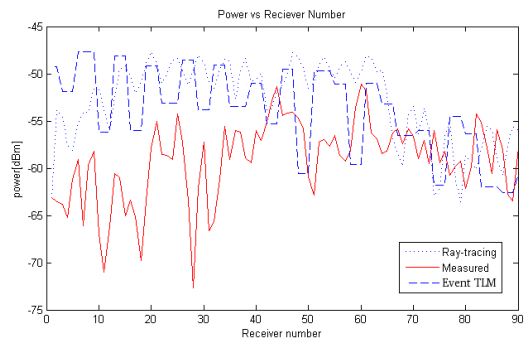

Figure 3. Measured and simulated path loss as a function of receiver location for the ray tracing and event based TLM models.

initialization. The ray tracing model includes only the 90 receiver locations for which measurement data obtained. These simulations were performed on a 1.8GHz Pentium 4 PC with 1.5GB RAM and running the Windows operating system.

Table 1. Execution time for the ray tracing, FDTD, and event based TLM models.

Model	Execution time
Ray tracing	4 minutes 55 seconds
Event based TLM	5 minutes 13 seconds
FDTD	14 hours 32 minutes 22 secs

Note that, while the event based TLM and ray tracing models require roughly the same amount of execution time, the event based TLM model provides received signal power at every grid point. In contrast to this, the execution time of the ray tracing model is roughly proportional to the number of receiver locations. This is shown clearly in Fig. 5, which shows the execution time for the ray tracing model as new receiver locations are added to the simulation.

6 CONCLUSIONS

The event based TLM method, ray tracing, and FDTD models have been shown, in this particular experiment, to generate comparable path-loss predic-

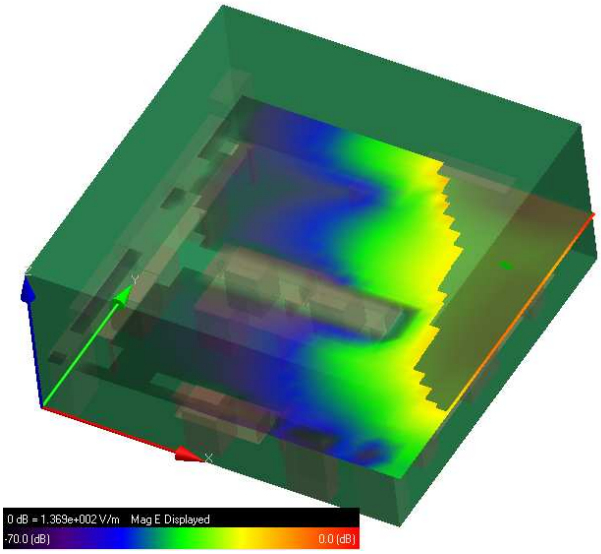

Figure 4. EM field simulated using FDTD technique.

tions. The accuracy of the simulations was validated using RF received power measurements. However, the execution times are not similar. In the case of ray tracing the execution time is proportional to the number of potential receivers, and the FDTD and TLM model execution time is dependent on the grid size. The execution time of the TLM model is about 168 times smaller than the FDTD method using the same grid size and cutoff thresholds.

A fast, grid based path-loss prediction tool makes it, in principle, possible to build 3D, site specific path-loss databases. Such a database could be included in protocol level wireless network simulations. An accurate, site specific path loss database combined with wireless protocol models could make it possible to accurately predict wireless network performance in cluttered environments.

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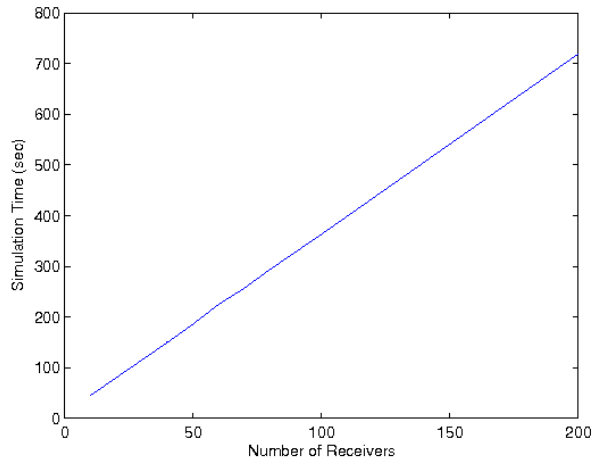

Figure 5. Simulation time of the ray tracing model as a function of the number of receivers.

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