

Research Article

Validation of Three-Dimensional Ray-Tracing Algorithm for Indoor Wireless Propagations

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A 3D ray tracing simulator has been developed for indoor wireless networks. The simulator uses geometrical optics (GOs) to propagate the electromagnetic waves inside the buildings. The prediction technique takes into account multiple reflections and transmissions of the propagated waves. An interpolation prediction method (IPM) has been proposed to predict the propagated signal and to make the ray-tracing algorithm faster, accurate, and simple. The measurements have been achieved by using a single Wi-Fi network access point as a transmitter and a laptop as a receiver. Measured data had been collected at different positions in indoor environment and compared with predicted signals. The comparison of the predicted and measured received signals gave root mean square error of 2.96 dB and std. deviation of 2.98 dB.

1. Introduction

The indoor wireless environments suffer from weak coverage due to the building construction and the multipath effect inside the buildings. The interest grows in the indoor coverage to serve the costumers with data and voice anytime anywhere. The ray-tracing (RT) algorithms have been used widely for accurately predicting the site-specific radio propagation characteristics [1]. Ray tracing is more economical method of predicting the propagation of radio waves in indoor, metropolitan, and rural areas, and it only requires the floor plan of the site, dielectric properties of the construction materials, and a high-performance general-purpose computer. It provides deterministic prediction models of small-scale and large-scale path loss in a wide range of operating environments. The ray tracing reduces the cost and the time consumption for a large amount of measurements, and it provides accurate information about the channel for the wireless networks.

Two-dimensional ray-tracing algorithm has been developed in [2] to predict the radio propagation in the indoor radio channel from the layout of the floor plan in a complex

laboratory environment. It shows that the two-dimensional ray-tracing algorithm can accurately model the indoor radio channel. The characterization of the indoor wireless propagation channel using a vector three-dimensional image ray-tracing (3D-IRT) approach has been presented in [3]. This technique sets a threshold value to decrease the computational time and reduce the usage of the memory resources. Three-dimensional ray-tracing algorithm has been proposed in [4] to reduce the computational time by using the utilizing the electromagnetic engine at the expense of the geometric engine. Similar technique has been proposed in [5] but with an offline electromagnetic field calculation.

The main purpose of our simulator is to study indoor wireless propagations for indoor wireless networks for different types of systems and building constructions to develop an indoor location update and paging algorithm. We are looking for a versatile and accurate algorithm to predict the received signal strength (RSS) inside indoor environments. This work represents the development of three-dimensional ray-tracing algorithm for indoor wireless networks followed by the measurement procedure. Comparison between predicted and measured received signals for WLAN has been achieved.

2. Ray-Tracing Algorithm Simulation

The simulator starts by creating a custom layout of the indoor environment. The user has to define the area of the building, wall locations and materials, ceiling height, and the locations of the transmitters and receiver. The system parameters such as the operating frequency, the transmitter and receiver gains, transmitter elevation angle (vertical), transmitter propagation angle (horizontal), and the number of reflections and refractions are defined by the user. The ray tracing starts with the reflection phenomena on the basis that the vast majority of the energy is contained in the reflected components followed by transmission. The other effects such as diffraction, scattering have less effect for indoor radio propagations [6].

Site-specific propagation model has been used with brute-force ray-tracing method, where a bundle of transmitted rays has been considered that may or may not reach the receiver. By using the concept of ray tracing, rays may be launched from a transmitter location and the interaction of the rays with partitions within a building modeled using well-known reflection and transmission theory. The transmitter (Tx) and receiver (Rx) are modeled as points at discrete locations in three-dimensional space. All the possible angles of departure and arrival at the transmitter and receiver are considered to determine all possible rays that may leave the transmitter and arrive at the receiver as shown in Figures 1(a) and 1(b).

First, the model determines whether a line-of-sight (LOS) path exists. If so, it computes the received LOS signal. The averaged LOS power from the averaged LOS delay profile is represented using the free space or Friis equation [1, 7]

$$(P_R)_{\text{refl}} = P_T G_T G_R \left(\frac{\lambda}{4\pi(d_0 + \dots + d_n)} \right)^2, \quad (1)$$

where P_T is the transmitted power, G_T is the power gain of the transmitted antenna, G_R is the gain at the receiving antenna, λ is the transmitted wave length, d is the distance between the transmitter and each reflection point, and n represents the number of reflections.

Next, the model traces a source ray in a specified direction and detects whether an intersection occurs. If no intersection is found, the process stops and a new source ray in a direction making an angle (angle step) of 10° with the original ray initiates. Once an intersection has occurred, the received signal is computed for a reflected and transmitted ray, each of which is traced to the next intersection in the same way. This recursion continues until the number of reflections and transmissions reached maximum defined value (3 for this simulation) as shown in Figures 1(a) and 1(b), or the ray energy falls below a specified threshold (-75 dBm) as in [8].

The averaged reflected power is assumed to be the free space value for the unfolded path length multiplied by the square of the voltage reflection coefficient (Γ) [1, 7], or

$$(P_R)_{\text{refl}} = P_T G_T G_R \left(\frac{\lambda}{4\pi(d_0 + \dots + d_n)} |\Gamma| \right)^2. \quad (2)$$

In this model, there is no need to collect more information about the propagation constant of the medium which is varying from one place to another inside the building [9]. The reflection and transmission coefficients have been calculated using the following relations [10, 11] at each intersection point between the rays and the building structures (walls, ceiling and floors). Each reflection and transmission coefficient is calculated with respect to the incident angle between the incident ray and the surfaces of the walls and the transmission angles between the transmitted ray and the surfaces of the walls, respectively, for perpendicular and parallel polarizations separately

$$\begin{aligned} R_{\parallel} = \Gamma_{\parallel} &= \frac{n_i \cos \theta_i - n_t \cos \theta_t}{n_i \cos \theta_i + n_t \cos \theta_t}, \\ R_{\perp} = \Gamma_{\perp} &= \frac{n_i \cos \theta_i - n_t \cos \theta_t}{n_i \cos \theta_i + n_t \cos \theta_t}, \\ T_{\parallel} &= \frac{2n_i \cos \theta_i}{n_i \cos \theta_i + n_t \cos \theta_t}, \\ T_{\perp} &= \frac{2n_i \cos \theta_i}{n_i \cos \theta_i + n_t \cos \theta_t}, \end{aligned} \quad (3)$$

where Γ_{\parallel} and Γ_{\perp} are the parallel and perpendicular reflection coefficient, respectively, while T_{\parallel} and T_{\perp} are parallel and perpendicular transmission coefficient, respectively, n_i and n_t are the incident and transmission media refractive index, respectively, and θ_i and θ_t are incident and transmission angles, respectively. Incident of electromagnetic wave is considered as unpolarized (containing an equal mix of parallel and perpendicular polarizations); the reflection coefficient equals to average of the parallel reflection coefficient (R_p) and the perpendicular reflection coefficient (R_s). Thus, the reflection coefficient $R = (R_p + R_s)/2$ [12, 13].

In RT algorithms, the rays propagate with a certain departure and elevation angles. The small is the angle step between each ray and its subsequent ray, the more accurate and precise is the RT algorithm. This leads to increase the time needed to propagate the rays, calculate reflective and transmission coefficients, and calculate the received signals at each intersection position [14]. Increasing the angle step leads to reduce the number of the propagated rays. The rays will reach fewer positions. The receiver position (Rx) in the simulation could be in a region, where there are no propagated rays as shown in Figure 1(a). An interpolation prediction method (IPM) has been proposed to predict the propagated signal at these positions. IPM uses the nearest neighbor interpolation algorithm. This algorithm constructs new data points of the propagated signals at a certain positions of the receiver by interpolate their nearest known data points. The number of the nearest known data points depends on the position of the receiver around which the propagated rays had been reached. If we consider an omnidirectional transmitter with departure and elevation angles from 0 to 360° with angle step 5° , the simulation time becomes 434.22 seconds in Intel Core 2 Duo processor at 2.2 GHz and 3 GB RAM. While if we consider 10° angle step, the simulation time will be 98.49 seconds plus the time for calculating the interpolated positions 0.024 seconds,

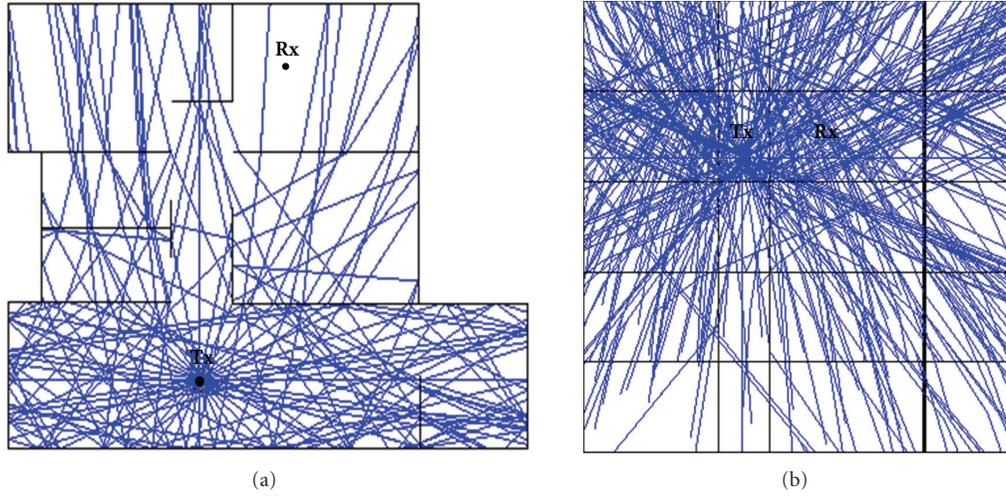


FIGURE 1: 3D representation of the transmitter (Tx), receiver (Rx), and the reflected and transmitted rays as (a) a top view of the building and (b) a side view.

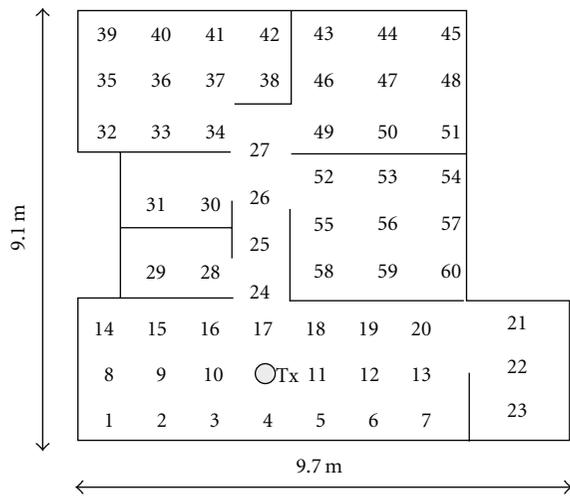


FIGURE 2: Floor plan of the building showing the location of the transmitter (Tx) and the measurement positions for the receiver (numbered).

which is 22.69% from the previous case. That means that the reduction in simulation time is 77.31% for 5° angle step difference.

3. Measurement Procedures

The measurement procedure has been conducted in a five-story apartment building with cement walls and concrete floors and ceiling. Figure 2 shows a floor plan of the fourth floor flat with an area of 9.7 meter by 9.1 meter and ceiling height of 2.9 meter. The measurements have achieved by using wireless LAN access point with 2 dBi gain antenna as a transmitter (Tx). The transmitted power is 13 dBm and the operating frequency is 2.437 GHz (channel 6). The transmitter (Tx) located in the middle of the main hall and 0.45 meter above the floor as shown in Figure 2. The position

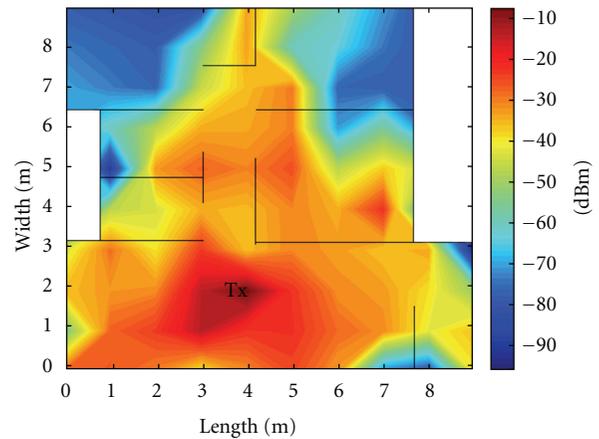


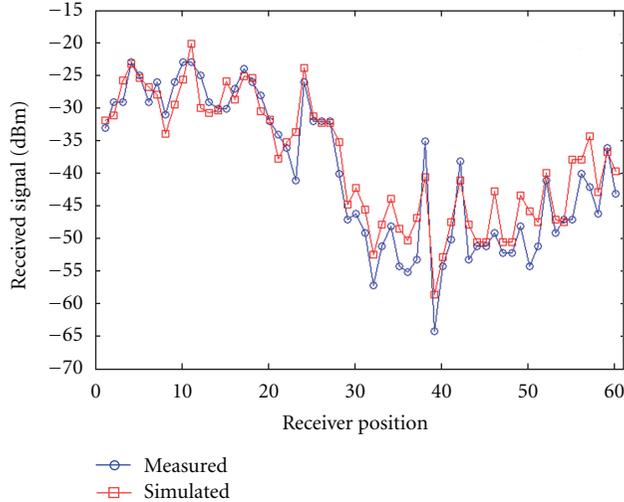
FIGURE 3: Contour of the received signal with respect to the transmitter.

of the transmitter is selected to ensure LOS and NLOS paths between the transmitter (Tx) and the receiver positions (numbered).

The receiver is Intel Wi-Fi Link 5100 AGN network adapter with 7 dBi gain, operates at 2.4 GHz. The receiver is moved to collect measured signals at 60 positions (numbered) throughout the flat as shown in Figure 2 at the same height as the transmitter (0.45 meter) and separated one meter from each other. The positions from 1 to 21 and 24 to 27 are considered to have LOS propagation. The other receiver positions are distributed along the flat and have NLOS propagation. All the doors left open during the measurement to ensure that the reflected rays can reach to all the rooms. To simplify this analysis, we assume that the rooms are empty such that all reflections originate from only the walls, floors, and ceilings. Reflections and refractions due to windows and furniture were not considered in the simulation.

TABLE 1: RMSE and σ of the predicted signal.

No. of reflections	0	1	2	3	4	5
RMSE (dB)	6.47	4.80	4.24	2.96	3.44	4.95
σ (dB)	4.65	3.41	3.09	2.98	3.37	4.22

FIGURE 4: The measured and simulated received signals with 0° to 360° elevation angle and propagation angle for three reflections.

4. Results

The received signal plane view is shown in Figure 3. The received signal has the maximum value at the transmitter (Tx) and degrades as the distance from the transmitter increases. It gives a general view of the received signals.

Root mean square error (RMSE) and the standard deviation (σ) for different number of reflections between the measured and predicted signals have been calculated to find the optimum number of reflections for best prediction. Table 1 shows that three reflections give the minimum root mean square error and standard deviation. The root mean square error between the measured and the predicted signals is about 2.96 dB, and the standard deviation is 2.98 dB when three reflections are used for 10° step angle. While RMSE is about 2.66 dB and σ is about 2.37 dB when considering 5° step angle for the same number of reflections. The difference between RMSE and σ for 5° and 10° angle step is very small. This result indicates that the proposed IPM has reduced the variations of the predicted received signal strength, and thus, the precise of the ray-tracing algorithm in addition to reduce the computational time and memory resources.

The measured and the predicted signals vary with about the same slope. Figure 4 shows the behavior of the predicted signal when the elevation and propagation angles of the transmitter are considered from 0° to 360° using the proposed interpolation prediction method (IPM). As seen in Figure 4, the received signals of the simulation are relatively close to the measurements and behave quite similar. The minimum error between the measured and the predicted signals is about 0.17 dBm at the receiver position (4). The

maximum error is at the receiver position (55). It is about 9.19 dBm. The small error at position (27) is about 0.22 dBm, and it could be due to the guiding effect of the corridor surrounding by walls, floor, and ceiling, so the reflected rays tend to flood the area. The mean error for all the positions is about 3.00 dBm.

5. Conclusions

A three-dimensional ray-tracing simulator has been developed to study the indoor radio wave propagation for wireless communications networks. The number of the reflected rays has been optimized. The number of three reflections has been found as the optimum number of reflections with RMSE 2.96 dB and standard deviation of 2.98 dB with the consideration of reflected and transmitted rays for 10° angle step. This number was used to simulate the propagation of electromagnetic wave for wireless local area networks (WLANs) inside a building. The proposed interpolation prediction method (IPM) helps to have a complete prediction throughout the predicted area and reduce the propagation and computation process. The comparison shows that the general behavior of the predicted and measured received signals is quite similar.

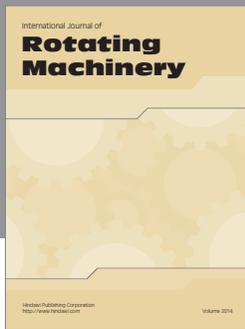
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