A Fast Indoor Coverage Prediction Scheme at 60 GHz Based on Image Processing, Geometrical Optics, and Transport Theory

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***Abstract*—3D ray tracing is used to accurately predict path loss, phase, and Received Signal Strength for various environments. In this paper, we develop a fast and approximate prediction scheme for indoor path loss using digital image processing, geometrical optics and transport theory. The proposed algorithm is tested in an apartment environment, and its performance is compared against a commercial 3D ray tracing software suite, Wireless InSite®.**

I. Introduction

To optimize wireless systems, including 5G and mmWave, channel modeling and generation of accurate Channel State Information (CSI) is of utmost importance. A comprehensive review on propagation models for 5G wireless networks [1], and extensive studies on propagation analysis in complex indoor environments [2], [3], have been published. However, the prediction of accurate CSI, including the phase of the received signal, using 3D ray tracing can be computationally expensive. In this paper, we propose a rapid scheme that combines image processing, geometrical optics (GO), and transport theory method to predict the signal coverage for indoor environments. The features in the room, such as the layout and furniture, are required to run the algorithm and are extracted from the floor plan to estimate the received signal strength (RSS).

II. Proposed Approaches

Signal coverage prediction using ray tracing requires the layout of the room, as represented in Fig. 1(a), to model the multipath via reflections, transmissions, and diffractions. The effects of additional scatterers including humans and furniture is also included in ray tracing. Ray paths in Wireless InSite® may undergo multiple reflections, transmissions, and diffractions. As a result, InSite produces very accurate RSS prediction. However, depending on the indoor propagation scenario and the interactions allowed per ray, it ends up taking a relatively long duration (in the order of minutes to tens of minutes) per simulation.

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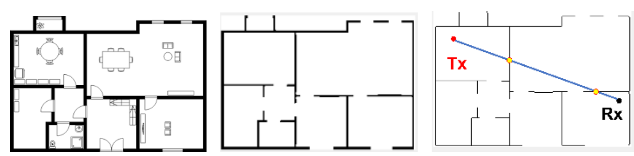
A. Floor Plan Simplification

For the development of the faster algorithm here, the floor plan is simplified. Figure 1(a) shows a floor plan used in Wireless InSite® for 3D ray tracing. The wall is represented by conspicuously bolder lines, which is one of the fundamental rules for designers and architects. This feature can be incorporated into image processing algorithms to detect the walls. Next, the lines and curves that represent the furniture and the doors are eliminated. The erosion (morphology) algorithm, defined by applying the structuring element or mask, and eroding the edge of the image, is used for deletion of the doors and furniture. In the erosion algorithm, the pixel whose neighboring pixels behave the same as the one with the mask is kept, otherwise they are eliminated. The structuring element applied in this scenario is a 1×3 and a 3×1 square mask. Erosion is performed using two masks respectively and the order does not matter. Fig. 1(b) shows the result of applying the erosion algorithm. The bold lines in Fig. 1(b) are further compressed by a skeleton algorithm [4] into single-pixel width lines to represent internal walls, as shown in Fig. 1(c).



(a) (b) (c)

Figure 1. The original floor plan (a), the result after erosion (b), and the result after skeleton algorithm (c).

B. Estimation of RSS using Geometric Optics

With the simplified floor plan, paths between the transmitter (Tx) and receiver (Rx) are identified, with a maximum of 5 transmissions and 1 reflection allowed per path. Keeping the number of reflections allowed per path to 1 reduces the maximum number of paths between the Tx and Rx significantly and thus saves computation time. With the knowledge of the location of the internal walls, intersection of propagation paths with internal walls is easily identified, which is needed for computation of the transmission loss through the walls. For computation of the reflection loss, image theory is used. The point of intersection and the angle of incidence are determined by using 2-D geometry methods in the coordinate system created on the floor plan. The transmittance, T_{in}, and the reflectance, Γ_{in}, are calculated using the following relationship [5]:

$$T_{in} = \frac{T_{aw}T_{wa}e^{-j\beta\cos\theta_{in}d}}{1-T_{wa}^2} \quad , \tag{1}$$

$$\Gamma_{in} = \frac{\Gamma_{aw}\Gamma_{wa}e^{-j2\beta\cos\theta_{in}d}}{1+\Gamma_{aw}\Gamma_{wa}e^{-j2\beta\cos\theta_{in}d}}, \tag{2}$$

where the subscripts "aw" and "wa" implies the process from air to wall and from wall to air, respectively, β is the wave number in the wall, θ_{in} is the angle of incidence, and d is the distance of travel of the wave in the wall. The dielectric properties of the material of the wall and the thickness of the walls are needed to compute the transmittance and reflectance. The total received power P_R is defined as:

$$P_R = \frac{\lambda^2}{8\pi\eta_0}\left|\sum_{i=1}^{N_p} E_i\right|^2 \quad , \tag{3}$$

where N_P is the number of paths, λ is the wavelength, η_0 is the impedance of free space (377 Ω), and E_i is the electric field of the i^{th} path at the receiver.

C. Improvement in RSS prediction using Transport Theory

Since the calculation in the previous subsection does not include the effect of the furniture, the signal loss due to furniture is incorporated using transport theory [6]. The excess loss due to furniture is given by an analytical expression in transport theory. Considering the average obstacle cross sectional area A_0, the obstacle occupational density p_0, the radial distance r_a, the geometric cross section of the obstacles per unit length σ_g, and defining the "diffusion constant" $k_d \sim \sqrt{2}\sigma_g p_0/A_0$, the mean excess loss due to obstruction by furniture on a dB scale can be written as [6]:

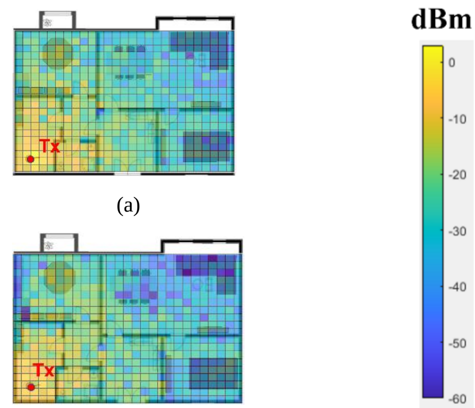
$$\begin{aligned} L_{ex}^T(r_a) &= -10\log[k_d r_a K_1(k_d r_a)] \\ &\sim \frac{10\sqrt{2}\sigma_g p_0 \log e}{A_0} r_a - 5\log\left(\frac{\pi p_0 \sigma_g r_a}{\sqrt{2}A_0}\right) \\ & \qquad k_d r_a \gg 1 \quad , \end{aligned} \tag{4}$$

where $K_1(.)$ is the modified Bessel function of the second kind of order one.

III. Results

An apartment, as shown in Fig. 2, based on the selected floor plan in Fig. 1 is constructed in Wireless InSite® to obtain the true values of the RSS with 5 transmissions, 3 reflections and 1 diffraction allowed in tracing the rays. A transmitter with half-wave dipole antenna operating at 60 GHz and a receiver grid with the spacing of 0.5 m are placed in the apartment at the same height of 1 m. The performance of the proposed algorithm is compared to the Wireless InSite® prediction in Fig. 3. The bright yellow pixels indicate receivers with higher RSS. There is an overall good agreement of the RSS prediction between our algorithm and Wireless InSite®, with the root mean square (RMS) error in the prediction being 9.5 dB. The disagreement may be due to approximations in transport theory, utilization of 1 reflection and no diffraction per ray, and neglect of 3-D propagation of the rays in our algorithm. However, due to the simplifications made in our algorithm, the simulation time of our algorithm is 29 seconds, which is significantly faster than Wireless InSite®, which took 38 minutes (~75 times higher). It is an absolute advantage for optimizing the placement of the transmitter, which requires enormous time for running multiple simulations with respect to different deployments.

Figure 2. Apartment layout produced using Wireless InSite®.



(b)

Figure 3. Signal coverage obtained by (a) the proposed algorithm, and (b) Wireless InSite®.

IV. Conclusion

An algorithm based on image processing, GO, and transport theory is introduced in this paper to provide a rapid and approximate estimate of signal loss in indoor environments. Further improvements in the algorithm will be made to improve its prediction capabilities.

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