A MULTIPATH MODEL AT 60 GHz BASED ON TRANSPORT THEORY

Ramakrishna Janaswamy[1], Email: janaswamy@ecs.umass.edu
Department of Electrical & Computer Engineering, 215-D Marcus Hall
University of Massachusetts, Amherst, MA 01003-9292, USA

I. INTRODUCTION

There has been a lot of interest lately in using mm-waves for high speed indoor wireless communications. Signals generated by mm-wave systems encounter various obstacles and get attenuated due to reflection, absorption, and diffraction, thereby resulting in shadowing and fluctuations. To perform an initial system design, variation of mean path loss from transmitter is desired. In the microwave band, the most commonly used shadow model is the log-normal model, where the mean signal strength on a dB scale drops off logarithmically with distance from the transmitter. The constant of proportionality, known as the path loss exponent, varies anywhere from 1.5–6 depending on the type of environment. Limited work of such nature has been reported at 60 GHz. In references [6], [13], a pathloss exponent close to free space is suggested for small indoor regions. In [10], a path loss exponent of 4.4 is reported based on measurements conducted in small non-line-of-sight (NLOS) regions (size $\leq 17\,\mathrm{m}$). However, it is not clear if the value of the exponent could be extrapolated to larger regions. Reference [7] also provides measured data in small NLOS regions (range $\leq 14\,\mathrm{m}$). At large ranges and in a dense multipath environments, the signal strength is expected to drop off more rapidly due to high penetration loss. An exponential increase in loss with distance in an area populated densely with obstacles has been reported in [9] at the lower frequency bands. In this paper, we apply transport theory [3, Ch. 8] and present a new shadow fading model at 60 GHz in an environment consisting of lossy and scattering obstacles. The model neglects the phenomenon of diffraction as diffraction losses tend to be very high at mm-wave frequencies. In a real building, most obstacles will be distributed in a horizontal plane and we consider two dimensional propagation in a horizontal plane to simplify the analysis. The input parameters for the models are the obstacle occupational density, obstacle number density, and mean geometric cross section of the obstacles. The model yields a closed form expression for the mean excess loss.

II. THEORY

All sources and obstacles are assumed to be invariant with respect to the z-axis and propagation is assumed to take place in the xy-plane. The transmitter is assumed to be located at the origin with the obstacles distributed in the radial and azimuthal directions. Let us denote by p_0 (≤ 1) the obstacle occupational density or the obstacle occupational probability. This quantity is equal to the ratio of the total area occupied by the obstacles to the total area of the region under consideration and can be easily estimated from building floor plans and obstacle cross-sectional areas. In transport theory, one works directly with statistically averaged power quantities and signals are added in power rather than in voltage. Hence the quantity being modeled is the mean incoherent intensity which is the quantity of interest when many obstacles are present. The loss at any point under this model is the result of absorption as well as scattering by the obstacles. Reference [11] previously discussed the use of statistical Boltzmann equation in predicting path loss in a dense multipath environment. Our approach is based on the concept of specific intensity which is the statistical average of the magnitude of the Poynting vector at any spatial location. The specific intensity in 2D is a function of three arguments: two spatial coordinates $\boldsymbol{\rho} = (x, y) \equiv (r_a, \phi)$, r_a being the radial distance and ϕ being the azimuthal angle, and one angular coordinate ξ denoting the azimuthal direction of the average Poynting vector. After suitable normalization, we express the specific intensity as $I(\boldsymbol{\rho}, \xi) = U_d(\boldsymbol{\rho}) + \boldsymbol{s} \cdot \boldsymbol{F}(\boldsymbol{\rho})/\pi$, where $\boldsymbol{s} = \boldsymbol{x}\cos\xi + \boldsymbol{y}\sin\xi$, U_d is the average intensity (units of Watts/m) and $\boldsymbol{F}$ is the flux density vector (units of Watts/m). The relationship between the specific intensity, the average intensity and the flux vector are

$$U_d(\boldsymbol{\rho}) = \frac{1}{2\pi}\int_{2\pi} I(\boldsymbol{\rho}, \boldsymbol{s})\, d\xi \tag{1}$$

$$\boldsymbol{F}(\boldsymbol{\rho}) = \frac{1}{2\pi}\int_{2\pi} \boldsymbol{s} I(\boldsymbol{\rho}, \boldsymbol{s})\, d\xi \tag{2}$$

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For a z-directed line source located at the origin and radiating a power P_t per unit length (along the z-axis), the diffusion equation satisfied by the average intensity can be obtained as

$$\nabla^2 U_d - \kappa_d^2 U_d = -\frac{P_t \rho_n \sigma_{tr}}{\pi} \delta(x)\delta(y), \tag{3}$$

where ∇^2 is the Laplacian operator, $\rho_n = p_0/A_0$ is the obstacle number density, A_0 is the average obstacle cross sectional area, $\kappa_d = \sqrt{2\sigma_a \sigma_{tr}}\, \rho_n$ is the diffusion constant, σ_a (units of m) is the absorption cross section of the obstacles per unit length (along the z-axis), and σ_{tr} is the transport cross section of the obstacles per unit length. At 60 GHz, the size of typical obstacles is very large compared to the wavelength and the following approximations hold [12], [3]: $\sigma_a \sim \sigma_g, \sigma_{tr} \sim \sigma_g$, where σ_g is the geometric cross section of the obstacles per unit length. Hence $\kappa_d \sim \sqrt{2} p_0 \sigma_g / A_0$. The excess loss is defined as the ratio of flux density in the absence of the obstacles to that available in the presence of the obstacles:

$$\ell_{\text{ex}}^T(r_a) = \frac{F_\rho(\kappa_d = 0)}{F_\rho(\kappa_d)} \tag{4}$$

where F_ρ is the radial component of the flux density and is a measure of the power flow away from the source. A direct relationship between U_d and $\boldsymbol{F}$ can be obtained starting from the equation of transfer:

$$\boldsymbol{F} = -\frac{\pi}{\rho_n \sigma_{tr}} \nabla U_d \tag{5}$$

For an azimuthally invariant environment $(\partial/\partial\phi = 0)$ the solution of (3) and (5) yields

$$F_\rho(r_a) = \frac{P_t \kappa_d}{2\pi} K_1(\kappa_d r_a), \tag{6}$$

where $K_1(\cdot)$ is the modified Bessel function of the second kind of order one [1]. The mean excess loss $\ell_{\text{ex}}^T(r_a)$ can then be easily obtained as

$$\ell_{\text{ex}}^T(r_a) = \frac{1}{\kappa_d r_a K_1(\kappa_d r_a)} \sim \frac{\exp(\kappa_d r_a)}{\sqrt{\pi \kappa_d r_a/2}}, \quad \kappa_d r_a >> 1 \tag{7}$$

The excess loss on a dB scale using transport theory is then

$$L_{\text{ex}}^T(r_a) = -10 \log\left[\kappa_d r_a K_1(\kappa_d r_a)\right] \sim \frac{10\sqrt{2}\log(e) p_0}{A_0/\sigma_g} r_a - 5 \log\left(\frac{\pi p_0 r_a}{\sqrt{2} A_0/\sigma_g}\right), \quad \kappa_d r_a >> 1. \tag{8}$$

If all obstacles are identical hexagons of diagonal d_h, then $A_0 = 3\sqrt{3} d_h^2/8$, $\sigma_g \simeq d_h$ and it is seen than the slope of the linear term in (8) is $9.46\, p_0/d_h$ dBm^{-1}. The total mean loss $\bar{L}_t$ at a distance r_a is the sum of the free-space loss $20\log(4\pi r_a/\lambda)$, the mean excess loss due to obstacles, $\langle L_{\text{ex}}(r_a)\rangle$ given in (8), and the loss $L_{\text{atm}}(r_a)$ due to atmospheric attenuation. It is possible to fit, using least square approach, the loss predicted by these models to a path-loss exponent model that is commonly used in propagation studies, particularly at lower bands [4]. But at 60 GHz, adequate number of measurements have not been conducted to justify validity of such a model in a NLOS situation and we will not do such a fitting.

III. COMPARISON OF RESULTS

We will now demonstrate whether it is possible to recover the observed trends in excess loss by comparing with measured results available at 60 GHz. In the transport theory model, the parameter of interest is $\kappa_d = \sqrt{2} p_0 \sigma_g / A_0$. We first show comparison with NLOS measurements reported in [7]. The parameter p_0 can be estimated from the floor plan and the amount of furniture present in the region. Using Figure 2 of [7], we estimate the fraction of the area occupied by the obstacles as $p_0 = 0.121$. As the main purpose of the comparison with measurements is to show whether the models developed could show the proper trends, we extract the other parameters by directly fitting the models to measured values. A minimum mean square error fit of the analytical formula (8) with experimental data yields $\sqrt{2} p_0 \sigma_g / A_0 = 0.666\,\text{m}^{-1}$. Assuming hexagonal obstacles, we arrive at $d_h = 0.395\,\text{m}$ ($\Longrightarrow \rho_n \simeq 0.7763\,\text{m}^{-2}$). Fig. 1 shows the excess loss of the model generated with these fitted parameters. Also shown in the figure is the result obtained by assuming the obstacles to be non-reflective [5]. The mean error and the standard deviation of error for the transport model are -0.9 dB and 8.6 dB respectively.

Fig. 2 shows the excess mean loss computed using the model with $\kappa_d = 0.566$ at 60 GHz. Comparison is shown with measured results available in [10] in a NLOS situation. Unlike the previous measurement set, no details are provided in [10] on the floor plan and the furniture. The various parameters are chosen by directly fitting the analytical formula (8) with experimental data. Compared to the measured results, the mean error and standard deviation of error are -1,4 dB, 10 dB respectively. From the measurement comparisons shown in Figs. 1 and 2, it is concluded that the model developed can predict useful results as long the involved parameters are known. The average obstacle cross-sectional A_0 area may be determined directly from the individual cross-sectional area of the obstacles present in the region. The number density is $\rho_n = p_0/A_0^2$. The geometric cross section σ_g may be taken to be the average linear dimension of all the obstacles present. The results thus generated using (8) should be representative of the NLOS environment and should yield better loss estimates than the path loss exponent models available in [13] or [7].

IV. SUMMARY

New shadow fading model, (8), is presented that takes into account absorption and scattering of incident waves by obstacles. The input parameters for the model are the obstacle occupational density, obstacle number density, and mean geometric cross section of the obstacles. The model yields a closed form expression for the mean excess loss in a typical office environment. Comparison with measured excess loss in NLOS situations has been shown to demonstrate the utility of the model. The model is expected to be valid when the density of obstacles is sufficiently large, *i.e.*, $p_0 > 0.1$.

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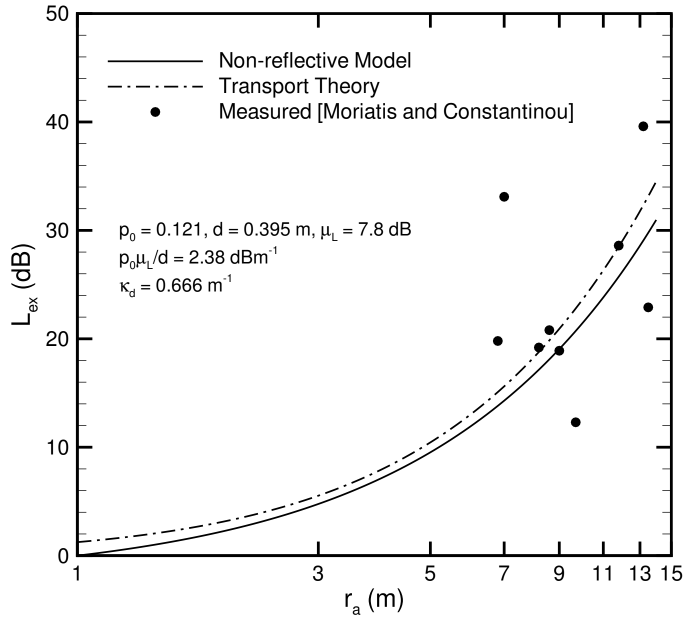

Fig. 1. Mean excess loss predicted by models versus measurements [7].

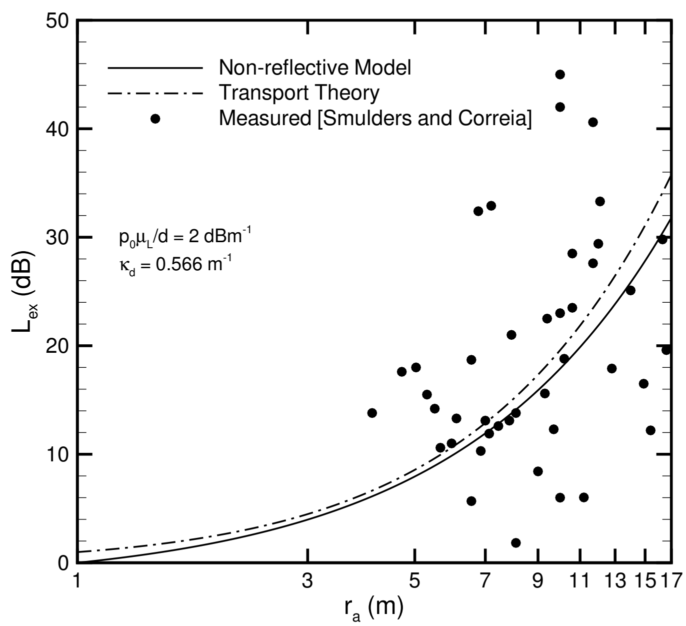

Fig. 2. Mean excess loss predicted by models versus measurements [10].