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DEVELOPMENT OF A PROPAGATION MODEL IN THE 20-60 GHZ BAND FOR WIRELESS INDOOR COMMUNICATIONS

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ABSTRACT

A propagation model for indoor wireless communications in the 20- 60 GHz band is developed using electromagnetic theory. Scattering from rough surfaces or volume scattering from random collections of objects may be included by incorporating statistical components into the model.

1. INTRODUCTION

A model for indoor radio propagation at 60 GHz will be useful for predicting the performance of high speed wireless data networks. If the environment (room size, shape, wall material, furnishings) is completely specified in detail, then in principle a model based on electromagnetic field theory can be found. Scattering from rough surfaces or volume scattering from random collections of objects can be included by incorporating statistical components into the model. However, in complex environments it may be difficult to make such a model, and it may be more useful for system designer to have a general model which applies to broad classes of environment, e.g. partitioned offices, meeting rooms, laboratories, factories. The references in [1] contain empirical statistical models for indoor radio, and some measurements have been conducted at 60 GHz [8].

In this work, a preliminary model is proposed based on electromagnetic theory for the idealized cases of a small office and a large open area office environment. The model can predict the signal intensity, standing wave patterns, multipath spread, and frequency selective characteristics. The model serves as a first step towards the development of more complete models which take more details of the indoor environment into account.

2. STATISTICAL ASPECTS OF EM THEORY

Given a complete description of an environment (e.g. a room or group of rooms in a building) in terms of the conductivity σ, permittivity ϵ, permeability μ at all points in space, and the location of a source of electromagnetic waves, one can in principle calculate the electric and magnetic fields from classical electromagnetic theory based on Maxwell's equations. However, in many cases, such a procedure is extremely difficult and may mask important physical effects. For some environments comprising a large collection of objects, an averaging procedure is desired which will yield results that are applicable to all such collections of objects which have similar properties in some average sense, i.e. similar statistical properties. For environments including random rough surfaces, electromagnetic waves scattered from such surfaces may be best described statistically, i.e. in terms of the statistical properties of the surface. Thus to develop a model, the statistical aspects as well as the deterministic aspects of electromagnetic theory must be considered. For example, an electromagnetic wave scattered from a rough surface may include both a specular and a diffuse component, where the diffuse component is scattered in all directions, whereas the specular component is scattered in one particular single direction. Whether a surface is rough or smooth depends on the wavelength and angle of incidence. For example, an asphalt road surface will act as a mirror (road glare) near sunset or sunrise, but will reflect light diffusely at other times of the day when the sun is high above the horizon.

3. MODELS OF THE INDOOR ENVIRONMENT

To develop the EM theory model, the following structures will be considered in order of complexity: single surface, hallway, small office, large open area office with partitions. Conducting, dielectric, and rough boundaries will be considered in each case.

3.1 Single smooth surface

Consider a single smooth surface with transmitter T at (y_0, z_0) and receiver R at (y, z) shown in Figure 1 with $\overline{r}$ the position vector of R relative to T. The signal at R is the sum of the direct and reflected wave, where the reflected wave appears to emanate from the image I. If an impulse $\delta(t)$ is sent from T, then the signal at R is the impulse response $h(t)$ of the channel from T to R given by:

$$h(t,\overline{r}) = \frac{G_0}{r_0}\delta(t - r_0/c) + \frac{G_1}{r_1}\rho_1\delta(t - r_1/c) \tag{1}$$

where $r_0(r_1)$ is the distance from $T(I)$ to R, and G_k are the product of the amplitude radiation patterns of T and R in the direction of the direct or reflected ray. ρ_1 is the complex reflection coefficient, which is given by the Fresnel formulas for TE and TM polarizations (e.g. [2]) in terms of the grazing angle θ with respect to the surface, and the complex permittivity ϵ_r of the ground.

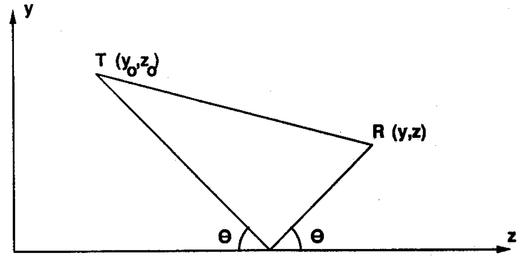

Figure 1. Smooth surface.

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Depending on the relative location of T and R, the direct and reflected rays may add in or out of phase. The resulting interference patterns are illustrated in [3] at 11 GHz with $y_0 = 341\lambda$ and $y = 68\lambda$ over the range $|z - z_0|$ up to $20,000\lambda$ over a surface with $\epsilon_r = 15 + j0$. Thus the received signal power at a single frequency will depend on the location of R and will show peaks and dips around the $1/r^2$ falloff. At large distances, the signal will fall off as $1/r^4$ due to first order cancellation of the direct and reflected rays.

3.2 Single rough surface

A rough surface can be described as the sample function of a Gaussian random process with mean zero and variance h^2 and correlation distance T_c. T_c is related to the period of a periodic surface, or to the reciprocal of the bandwidth of the random process. Considering the two rays in Figure 2, a surface may be considered rough if their phase difference $\triangle\phi = 4\pi h sin\theta/\lambda = \pi$ is such that the two departing rays are exactly out of phase [4]. For such values of h and θ, there is no specular reflection and all energy must be redistributed in other directions (diffuse scattering), whereas if $\triangle\phi = 0$, then the surface is perfectly smooth and there is no diffuse scattering at all. We arbitrarily choose the midway point $\triangle\phi = \pi/2$ as the dividing line between rough and smooth [4] and define the Rayleigh criterion that a surface is considered rough if

$$h > \frac{\lambda}{8sin\theta}. \tag{2}$$

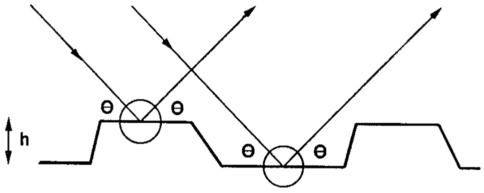

Figure 2. Rough surface.

For a rough (random) surface, the specular (amplitude) reflection coefficient ρ is now a random variable for which we can find a mean value by averaging over an ensemble of surfaces. Since ρ is complex Gaussian, the mean scattered power is $\langle \rho\rho^* \rangle = \langle |\rho|^2 \rangle = \rho_{rms}^2$. The variance of the random variable ρ is given by $D(\rho) = \langle \rho\rho^* \rangle - \langle \rho \rangle \langle \rho^* \rangle$. Expressions for $D(\rho)$ and $\langle \rho\rho^* \rangle$ are given in [4]. The specular reflection coefficient ρ_s is reduced to become [5][6]

$$\rho_{rms} = \rho_s exp\left[-2\left(\frac{2\pi h sin\theta}{\lambda}\right)^2\right] \tag{3}$$

The remaining power is scattered diffusely in all directions. General results are given in [4] for different values of T_c/h. Outside a narrow cone about the direction of specular reflection, the amplitude of the field is Rayleigh-distributed.

If the correlation distance $T_c \gg \lambda$, and $h \gg T_c$ [4,p 89,397], then the diffusely scattered power follows Lambert's law, according to which the power density in the reflected field in a given direction from a surface of given area is proportional to the cosine of the angle between that direction and the normal to the surface. This result assumes that the incident radiation is a plane wave, i.e. $T_c^2 \ll A$, where A is the area of the surface, so that the grazing angle θ is constant over the surface. For this case, (surface uniformly illuminated by a distant source), all of the incident power P_0 is diffusely scattered, and the diffuse signal power dP in an element of solid angle $d\Omega$ from an element of area dA on the surface has the angular distribution

$$dP_R = (1/\pi)(P_0/A)cos\theta dA d\Omega \tag{4}$$

where $w = P_0/A$ is the radiant emittance of the surface. [7][5][4]. The total received power P_R is independent of position provided that $y \ll \sqrt{A}$.

Using this result, the received signal power is obtained in [7] assuming that the receiving antenna has area A_R and directional antennas at both R and T. If we specialize these results for isotropic antennas at T and R, we obtain

$$P_R = P_0 A_R/r_0^2 + \int_A cos\theta_1 cos\theta_2 \frac{A_R}{r_{1a}^2 r_{1b}^2} dA \tag{5}$$

where the delayed path length $r_1 = r_{1a} + r_{1b}$ is different for each element of area dA at which scattering occurs. For this case, the channel impulse response $h(t,\overline{r})$ will contain a continuum of delays. The maximum excess delay depends on the size of the surface A, however the magnitude of long delays rapidly approaches zero. The phase at each delay is random.

If R and T are near the surface so that the grazing angle is not constant, then we have a 'glistening surface' and the diffuse reflection coefficient must be determined by integrating over small elements of surface over which the grazing angle is constant. It is found that this diffuse reflection coefficient depends on the parameter

$$K_\beta = \frac{y_0 + y}{|z - z_0| 2h/T_c} \tag{6}$$

[4,pp. 251-266]. For R and T isotropic or nearly so, and $y, y_0 \ll |z - z_0|$, if $K_\beta > 1$, then the scattered energy comes from near the point of specular reflection, ρ is very close to its value for a smooth surface, and the channel impulse response is not changed significantly. However, if $K_\beta \ll 1$ then the scattered energy comes from two zones in the vicinity of T and R with a normalized reflection coefficient $\rho_d = 0.25$ relative to the reflection coefficient for a smooth surface. In general, ρ_d is in the range 0.2-0.4. For this case, the channel impulse response contains delayed components scattered from these two zones (and not from the specular reflection point) and will be different from the smooth surface case.

The interference between the direct wave and specularly reflected component yields a series of minima and maxima. However, if the surface produces a diffusely scattered field, then the phase of the scattered component is incoherent, i.e. at any point in space it may assume any phase with equal probability. Thus the received field will vary in a random manner and may be described with a statistical distribution and a correlation distance (autocorrelation radius) as R changes position [4,p.278]. The received field strength is the result of the superposition of the direct wave with constant amplitude and phase, and the scattered field with Rayleigh distributed amplitude and phase, and thus is Rician-distributed.

3.3 Rectangular waveguide hallway

A hallway (without doors) may be modelled as a rectangular waveguide with dielectric walls at $y = 0, y = b, x = 0, x = a$ with transmitter T at (x_0, y_0, z_0) and receiver R at (x, y, z) as shown in Figure 3. The signal at R is the sum of the direct and an infinite sum of reflected waves, where the reflected waves appears to emanate from the images I_{kl}. located at points $(x_k, y_l, z_0) = (2ma \pm x_0, 2mb \pm y_0, z_0)$ [not including the point (x_0, y_0, z_0) at T]. The overall attenuation due to the dielectric walls is calculated in [5] by considering the number of reflections experienced by a ray travelling a distance z to obtain

$$L = 5\lambda z \left(\frac{1}{a^2} log_{10} \frac{1}{\rho_{TE}} + \frac{1}{b^2} log_{10} \frac{1}{\rho_{TM}} \right) \tag{7}$$

The effect of rough surfaces is to add a continuum of excess delays due to diffuse scattering. When a ray strikes a rough surface, the specular reflection is reduced by the factor (3). Using this result, the additional loss due to surface roughness for a distance z is [5]

$$f = exp[-\pi^2 h^2 \lambda (a^{-4} + d^{-4}) z] \tag{8}$$

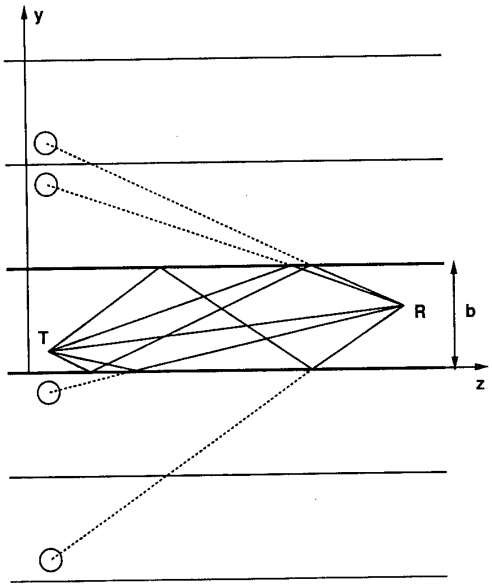

Figure 3a. Hallway (side view).

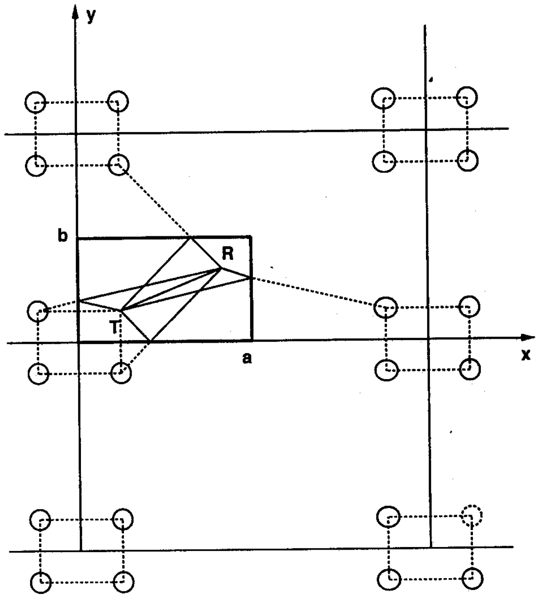

Figure 3b. Hallway (end view).

3.4 Small office (rectangular box)

A small office (without doors or windows) may be modelled as a rectangular box or cavity with dielectric walls at $y = 0, y = b, x = 0, x = a, z = 0, z = d$ with transmitter T at (x_0, y_0, z_0) and receiver R at (x, y, z) as shown in Figure 4. The signal at R is the sum of the direct and an infinite sum of reflected waves appearing to emanate from the images I_{klj} located at points $(x_k, y_l, z_j) = (2ma \pm x_0, 2nb \pm y_0, 2id \pm z_0)$. If an impulse $\delta(t)$ is

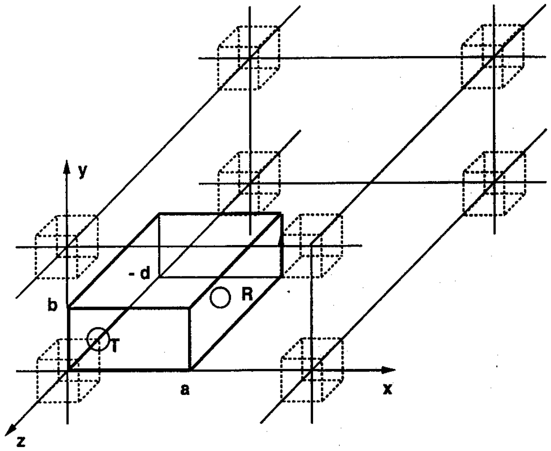

Figure 4. Small office (rectangular box).

sent from T, then the signal at R is the impulse response $h(t)$ of the channel from T to R given by:

$$h(t,\bar{r}) = \sum_{klj} \frac{G_{klj}}{r_{klj}} \rho_{klj} \delta(t - r_{klj}/c) \tag{9}$$

where $r_{klj} = \sqrt{(x-x_k)^2 + (y-y_l)^2 + (z-z_j)^2}$ are the distances from T or I_{klj} to R, and ρ_{klj} is the complex reflection coefficient, which varies with the angle of incidence θ_{klj} (with $\rho_0 = 1$ for the direct path) and the particular surface (vertical or horizontal in Figure 4). The integers k, l, j run over all images and the source. G_{klj} are the product of the amplitude radiation patterns of T and R in the direction of the appropriate ray. If we consider single reflections only, then there are 6 images, one for each of the six surfaces of the box. It is straightforward to find the image coordinates and corresponding angles of incidence, and thus the r_{klj} and ρ_{klj} in (9).

The effect of rough surfaces is to add a continuum of excess delays due to diffuse scattering. When a ray strikes a rough surface, the specular reflection is reduced by the factor (3) and the remaining power is added to the diffuse signal. Purely diffuse scattering can provide signals which are fairly evenly distributed in the box [7].

The effect of windows along one wall may be approximated by simply removing that wall and the correponding reflections and images. The effect of a wall full of bookshelves may be approximated by assuming a very rough surface with no specular reflection (if the books are not neatly stacked). Alternately, book spines may be considered a slightly rough surface with correlation distance on the order of a book thickness.

3.6 Large open area office

A large office (without doors or windows) may be modelled as a rectangular box or cavity with dielectric walls as before. However, we now consider the addition of low partitions used to create individual workspaces. For example, we could assume the partitions to be $b/3$ or $b/2$ high with a ceiling height $b = 3.6$ m spaced at regular intervals of 2-3 m, and that the boundaries of each partition are made of metal, T may be located on the ceiling near the center of the room, i.e. at $(a/2, b/2, d)$ and R may be located at $y = 2b/3$.

Thus these partitions will cause additional specularly reflected fields as well as diffracted fields to be added. The diffracted fields may be neglected in a first approximation, since they fall off much more rapidly than reflected fields at millimeter wavelengths.

4. DISCUSSION

The channel impulse response and hence the rms delay spread may be estimated for simplified indoor environments from electromagnetic theory and geometrical considerations. The effects of diffuse scattering may be important at millimeter wave frequencies, where some wall types (e.g brick or concrete) may be rough according to the Rayleigh criterion. Numerical results illustrating the calculated rms delay spread and channel transfer function in an empty hallway and office will be presented at the conference. It remains to validate and refine this model using actual measurements.

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