International Journal of Applied Research 2019; 5(1): 533-536

ISSN Print: 2394-7500
ISSN Online: 2394-5869
Impact Factor: 5.2
IJAR 2019; 5(1): 533-536
www.allresearchjournal.com
Received: 12-11-2018
Accepted: 17-12-2018

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Analysis of wide-band microwave propagation in a room on the line of room Acoustics

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Abstract
The various aspects of diffuse wideband microwave propagation in a room are analyzed with the established discipline of room acoustics. It has been shown that an equivalent to Sabine's equation for reverberation time in a room is valid for the completely diffused field depending only on the volume, the surface area, and an effective absorption coefficient. An exponential decay of the power as a function of the delay is a consequence of the assumptions. Furthermore, the concept of reverberation distance is also valid. This is the distance from a transmitting antenna where the received diffuse, randomly scattered power equals the direct line-of-sight received power, such that the diffuse power dominates for distances larger than the reverberation distance. It is also a consequence of the theory that the refuse fields incident on the antenna are uniformly distributed in the angle. The main difference from the acoustic case, apart from materials parameters is polarization. Thus, we consider both transmitting and receiving antennas are vertically polarized.

Keywords: Indoor radio communication, diffuse fields, reverberation time, polarization

1. Introduction

It is not surprising that there is a close resemblance between room acoustics and room electromagnetic, since the wave-lengths are typically of the same order for acoustic audio frequencies and microwave frequencies, namely in the centimeter range. Room dimensions are much larger than the wavelength, so quasi-optical ray propagation dominates. In both cases, there is a distinction between specular reflection from a quasi-smooth surface, and diffuse scattering from rough surfaces and from individual scatterers, such as pieces of furniture. In both cases, ray tracing has been popular, assuming known properties of materials. However, a large number of rays is needed to describe the diffuse field, while, in contrast, the present theory for diffuse propagation is very simple. We can expect a certain level of diffuse scattering leading to a reverberation in the acoustic case as well as in the electromagnetic case. In the latter case, this has to be considered when designing a communication system, in order to avoid inter-symbol interference. However, one difference is that the acoustic case is ultra-wideband, while the radio case usually has a small relative bandwidth, and hence a nearly constant wavelength over the communication band. Another difference is the presence of polarization in the electromagnetic case. The purpose of this paper is to demonstrate the applicability of methods applied in room acoustics to microwave propagation in a room.

Most indoor studies of coverage and delay spread in the communications area have been for building as such, consisting of corridors, halls, and offices, and the concern has been related to the influence of walls and floors [1]. A stochastic approach for indoor diffuse scattering is described in [2], treating path-loss distributions. Extracting diffuse scattering from measurements is discussed in [3], and recently ultra-wideband diffuse scattering has been measured in several rooms [4]. A similar approach as in the present paper was used in [5], where the power delay profile was calculated based on averaging plane-wave reflection coefficients of smooth surfaces. In this paper, we will concentrate on the link between an access point placed in the ceiling of the room, and users placed in a number of positions around the room. The focus will be on the delay aspects.

Theoretical Analysis

We shall make some assumptions about a diffuse field in analogy with the corresponding acoustic quantities [6]. Although the electromagnetic case is different due to polarization, this experiment only addresses the case of vertical-to-vertical polarization, which may then be considered as a scalar case. Consider a narrow ray tube in space, with rays of intensity in the directions ɵ and φ.

$$dI(\theta,\varphi) = \frac{\left|E_\theta(\theta,\varphi)\right|^2 + \left|E_\varphi(\theta,\varphi)\right|^2}{2Z_0} d\Omega = I(\theta,\varphi) d\Omega \quad watt/m^2/steradian \qquad \text{-----(1)}$$

E is the peak electric field, and Z_0 is the free-space impedance. The corresponding energy density at a point is found by dividing by the velocity of light, c:

$$dW(\theta,\varphi) = \frac{I(\theta,\varphi)}{c} d\Omega watt - s/m^3/steradian. \qquad \text{----- (2)}$$

The relationship between intensity and energy density may also be derived from the standard definitions of energy density,

$$W = W_e + W_m = \frac{1}{4}\varepsilon\left|E\right|^2 + \frac{1}{4}\mu\left|H\right|^2 = \frac{1}{2}\varepsilon\left|E\right|^2 = \frac{1}{c} \quad \text{watt-s/m}^3 \qquad \text{------(3)}$$

Since the mean values of electric and magnetic energies are equal in the far field.

In a totally diffuse field, the intensity will not depend on the direction, so integrating equation (2) over all directions gives an energy density as

$$W = 4\pi\frac{1}{c} \quad \text{att-s/m}^3 \qquad \text{-----(4)}$$

Thus the total stored energy of diffuse radiation in the room is the energy density, W, times the volume, V, assuming a uniform distribution. Assume now that the intensity in equation (1) is incident on a wall area, A, which partly absorbs it. The total power absorbed is an integration of equation (1) over a half space, i.e.,

$$P_{abs} = \eta A \int_0^{2\pi}\int_0^{\pi/2} I(\theta,\varphi)\cos\theta\sin\theta d\theta d\varphi \quad \text{watt} \qquad \text{------(5)}$$

where the cosine term is needed for defining the apparent aperture in the direction 9, and η is the fraction of energy absorbed by the area, A. Since I is independent of direction,

$$P_{abs} = \eta A\pi I = \frac{c\eta A}{4} W \quad \text{watt} \qquad \text{-------(6)}$$

With an input source power of S(t) watt, we can now formulate the final power balance in the room using equations (4) and (6). The input power is balanced by the increase in energy/second and the losses at the walls,

$$S(t) = V\frac{dW}{dt} + \frac{c\eta A}{4} W \quad \text{watt,} \qquad \text{-------(7)}$$

with c being the velocity of light. This agrees with the standard acoustical equation for room acoustics [6], except that here the velocity of sound is replaced by the velocity of light.

Electromagnetic Reverberation Time

If the source is turned off, S(t)=0, Equation (7) is a homogeneous equation with the solution

$$W = W_0 e^{-t/\tau}, \quad \tau = \frac{4V}{c\eta A}. \qquad \text{------(8)}$$

τ is the electromagnetic "reverberation time," depending only on volume and absorption area. It is identical to Sabine's equation in acoustics[6] except for the change of velocity.

The steady-state solution after the constant source has been on for a time much larger than τ may be found from depending only on the input power and the absorption area.

$$\frac{dW}{dt}=0, \quad W_0=\frac{4S}{c\eta A}, \qquad \text{------- (9)}$$

In the case where the average delay profile has an exponential decay, then τ equals the rms delay spread.
The general solution to equation (7) is a convolution integral:

$$W(t)=\frac{1}{V}\int_0^{\infty} s(t-t^{'})e^{-t^{'}/\tau}dt^{'}. \qquad \text{-------- (10)}$$

Path gain in a Random Environment
In order to evaluate the received power after steady state has been achieved, we must use the antenna properties in a random field. Let us first consider a receiving antenna in a random filed.

$$D(\theta,\varphi)=\frac{4\pi I(\theta,\varphi)}{\int_{4\pi} I(\theta,\varphi)\sin\theta d\theta d\varphi}=1 \quad \text{for constant I.} \qquad \text{-------- (11)}$$

The directivity, D, of any antenna in a completely random field is thus unity, and the received power at the antenna is the intensity times the receiving area of the antenna, $\frac{\lambda^2}{4\pi}$. Using equations (4) and (9), we get

$$P_{rei}=I\frac{\lambda^2}{4\pi}=W_0\, c\frac{\lambda^2}{(4\pi)^2}=\frac{S\lambda^2}{4\pi^2\eta A}, \qquad \text{------- (12)}$$

so the path gain after steady state has been reached is

$$\frac{P_{rei}}{s}=\frac{\lambda^2}{4\pi^2\eta A}. \qquad \text{------- (13)}$$

Theoretical Reverberation Distance
It is clear that near the transmitting antenna, there will be a strong line-of-sight field dominating over the diffuse field. The question is, how near? The power received from the transmitting antenna will be

$$P_{dir}=\frac{SD_1D_2\lambda^2}{4\pi r^2 4\pi} \text{ watt} \qquad \text{-------- (14)}$$

where D_1 and D_2 are the two directivities.
Using equations (13) and (14), we can find the distance where the two powers are equal. This distance is called the reverberation distance, and is given by

$$r_d=\frac{1}{2}\sqrt{D_1D_2\eta A}. \qquad \text{------- (15)}$$

For distance closer than r_d, the direct path dominates, for larger distances, the diffused energy dominates.

Reverberation Distances
From equation (15), we now have all the information needed to calculate the reverberation distances as a function of position. The reason why the reverberation distance depended on the position in the room was due to the fact that the antenna directivities varied. The true geometrical distances from the access point to all the user locations are shown in Figure 1, together with the calculated reverberation distances. It was noted that for locations 2,3, and 4, the true distances were much smaller than the reverberation distances (position 10 was not measured). This then was the explanation of the Ricean distribution at these points: they were so close that the direct path dominated over the diffuse fields.

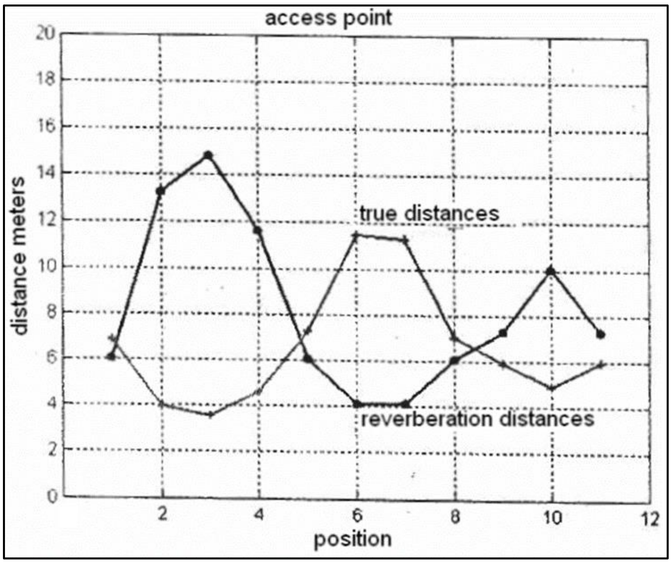

Fig 1: Reverberation Distances

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