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Room Electromagnetics Applied to an Aircraft Cabin with Passengers

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Room Electromagnetics Applied to an Aircraft Cabin with Passengers

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Abstract— A closed single room environment is viewed as a lossy cavity, characterized by diffuse scattering from walls and internal obstacles. The theory of wideband propagation in such an environment is applied, similar to studies in acoustics and reverberation chambers. UWB measurements from 3 to 8 GHz have been performed for a part of an aircraft cabin with access points on the ceiling and receive antennas at arm rest (AR) and head rest (HR) positions. The measurements were performed with and without 24 passengers on the seats. The environment is characterized by the reverberation time and volume, remaining parameters such as path loss and absorption areas are derived just from these two parameters. The agreement with measurements is good, indicating that this is a useful method, even for estimating body absorption of people in realistic environments.

Index Terms—UWB propagation, room acoustics, room electromagnetics, diffuse scattering.

I. INTRODUCTION

Indoor microwave propagation has been treated in detail for a number of years. Modeling of the impulse response has previously been given as a cluster model, the so-called SV-model [1], and for narrowband path loss simple statistical models have been developed. Ray tracing is a popular method, and even full wave solutions have been obtained numerically [2]. The method applied in this paper is aimed to find a very simple model with only few parameters and is based on considering the indoor environment as a lossy cavity where all the losses are lumped into one parameter. The method has been applied previously to a single large office environment [3,4] and was coined 'Room Electromagnetics' in analogy with the well-known 'Room Acoustics'[5]. The acoustics community has been applying the method since the 1920's (Sabine's equation), so it is surprising that it has not been used earlier by the microwave community, considering that the only basic difference from acoustics is the polarization. Later considerable

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work has been performed on reverberation chambers [6], which are closed enclosures with stirring to randomize the field distribution.

It is important to distinguish between coherent scattering from the walls and diffuse scattering from random objects and rough surfaces. Most ray tracing methods rely implicitly on coherent reflections from smooth surfaces allowing image methods to be applied. It is the main point of this paper that most real world indoor environments are of a random nature including equipment, furniture and people, and thus incoherent or diffuse scattering must be present. The basic model is very simple and considers a first arriving LOS (line-of-sight) signal if present, and this part may be computed as traditional free space propagation. Multiple reflections and scatterings will give rise to a tail with exponential decay and a time constant noted as the reverberation time, similar to the acoustics case, see Figure 1.

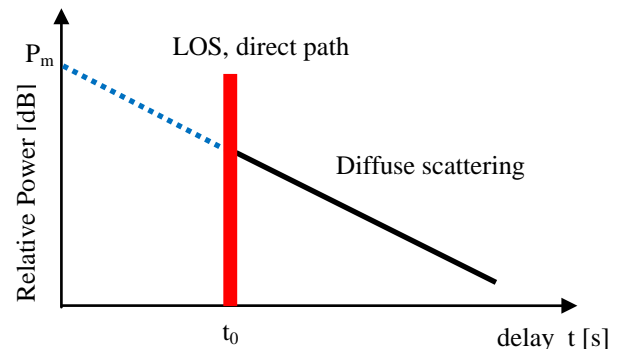


Fig. 1. Model of mean impulse response consisting of direct LOS path and an exponential tail of diffuse scattering with time constant τ .

It is noteworthy that the tails of the impulse response ($t > t_0$) have the same exponential slope and magnitude, regardless of the measuring positions within the indoor environment and is independent of type of antenna in theory [4]. The model above is mainly for the NLOS situation; for the LOS a direct path should be added at time t_0 or earlier. This seems to indicate that a simple theory is possible with a reduced number of parameters. The physics behind the phenomenon is that multiple scattering from the walls diffuses the energy in such a way that the reverberation time is the same, regardless of measuring positions within the room; it is a characteristic parameter of the room, to be established experimentally. This does not mean that the mean power is the same everywhere; as the energy

propagates through the room it gradually loses energy to the surroundings.

The power impulse response is the most important parameter for considering a communication system, since we can derive important parameters like path loss and rms delay spread from it. It is easy to see that if the LOS part is neglected or negligible, the rms delay spread is equal to the reverberation time. In the present paper, we are comparing the experimental results of measurements in an aircraft cabin with theory including the effect of passengers on the seats. The propagation of a UWB channel within the passenger cabin was previously studied in [7, 8, 9], whereas the effect of human presence in a midsize Airliner is investigated in [10]. One of the common drawbacks of these previous investigations is the lack of a simple theory which allows us to effectively quantify the influence of human body on UWB propagation. This paper succeeds in applying room electromagnetics to a large wide-bodied double-decker aircraft cabin with cylindrical structure and high density of seating.

The paper is organized as follows. A brief explanation of the cabin and measurement scenario is presented in section II. Section III presents a brief theory of room electromagnetics. A comparison between calculation from theory and measurements is presented in section IV. Section V discusses the observations before a final conclusion is delivered in section VI.

II. MEASUREMENT CAMPAIGN

Measurements were carried out at the front section upper deck of a double-decker large wide-bodied aircraft cabin using a vector network analyzer (VNA) in the frequency range from 3 to 8 GHz.

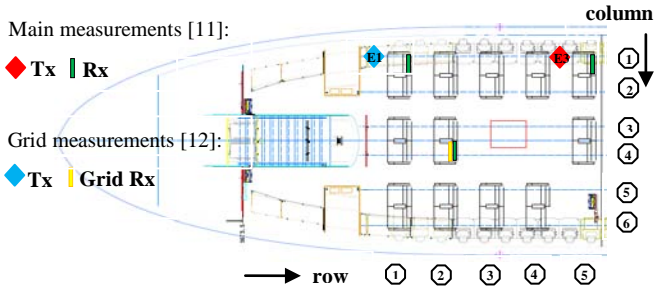


Fig. 2. The measured cabin layout with transmitter E1 located at the front, receivers are located at various seats $\{(row, column) | (1,1), (5,1) \text{ and } (2,4)\}$. Grid measurements were performed with transmitter located at E3, receivers are located at seat (2,4).

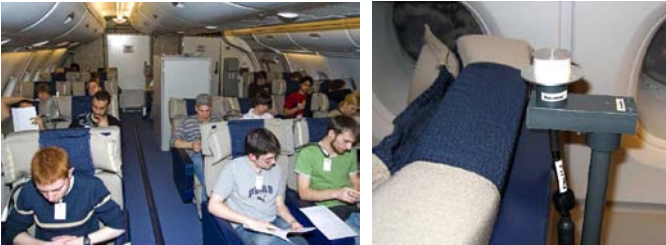


Fig. 3a (left): The cabin was occupied by 24 students during measurement. Fig. 3b (right): Receiving antenna mounted at head rest position.

The end of the aircraft section was shielded during measurements where there are two aisles at the front of the seating area and a staircase to gain access to the lower deck. For detailed information about the measurement techniques and the cabin environment we refer to the published papers [11,12].

III. ROOM ELECTROMAGNETICS

Assuming that the diffuse energy in steady state is uniformly distributed over the volume leads to the following expressions [4,5,6]. The reverberation time is given by

$$\tau = \frac{4V}{cA'} \quad [s] \quad (1)$$

where A' is the effective absorption area, V the volume, and c the velocity of light.

The average power density, also for the steady state uniformly distributed case is

$$S = c \frac{\tau P_t}{4\pi V} \quad [Watt/m^2] \quad (2)$$

where P_t is transmitted power, assumed to be equal to the absorbed power. Since it is assumed that the radiation is uniformly distributed in angle, the directivity of any antenna is 1, and the received power $P_r = S \frac{\lambda^2}{4\pi}$ so the path gain for steady state is

$$P_{ms} = \frac{P_r}{P_t} = \frac{c\tau}{V} \left(\frac{\lambda}{4\pi}\right)^2 pol \quad (3)$$

where pol is a polarization factor set equal to 0.5 for completely random polarizations.

Often the pulse width is much shorter than the reverberation time so the power never reaches steady state. The solution may be found by solving [4, eq. 10]. The solution for a rectangular pulse shape of width Δ and magnitude 1 is

$$U(t) = \tau e^{-t/\tau} (e^{\Delta/\tau} - 1) \quad t \geq \Delta \quad (4)$$

Note that for $\Delta \gg \tau$ $U(\Delta) = \tau$ like in (3). In the opposite case as in our situation $\Delta \ll \tau$, the result is $U(\Delta) = \Delta$, so the final result is

$$U(t) = P_m e^{-t/\tau} = \frac{\Delta c}{V} \left(\frac{\lambda}{4\pi}\right)^2 \cdot pol \cdot e^{-t/\tau} \quad t > t_0 \quad (5)$$

Where t_0 is the arrival time of impulse, P_m is the value for $t=0$ (Fig. 1).

The mean diffuse power at a given position defined by the arrival time t_0 is found by integrating over the mean impulse

$$P_{\text{mean}} = P_m / \Delta \int_{t_0}^{\infty} e^{-t/\tau} dt = P_m \tau / \Delta e^{-t_0/\tau} = P_{\text{ms}} e^{-t_0/\tau} \quad (6)$$

IV. COMPARISON WITH MEASUREMENTS

A. Reverberation time

Without the prior knowledge of effective absorption area and volume, the reverberation time can only be derived from the measurement data. Figure 4 shows examples of impulse responses measured from one access point (E3) to three different occupied seats. The resolution is 0.2 ns corresponding to the total bandwidth of 5 GHz. The straight line is the best fit to all three curves between 40 and 140 ns. The negative slope of the best fit line corresponds to reverberation time, in this particular case, $\tau = 21.7$ ns.

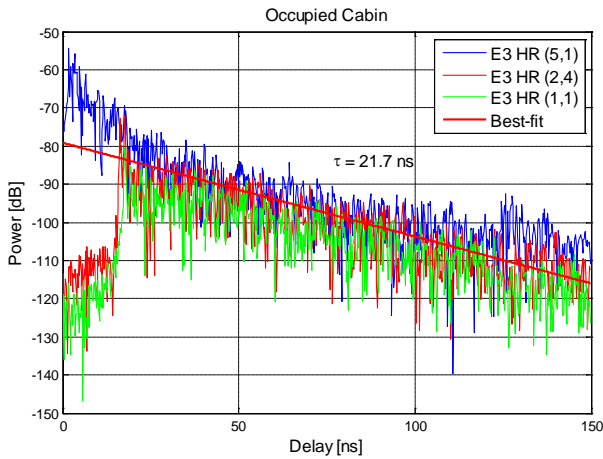


Fig. 4. Impulse responses measured from one access point to different seats in head rest (HR) positions, where seat = {(row, column)} (5,1), (2,4) and (1,1)}. The responses are derived from all 1600 frequency points from 3 to 8 GHz. The arrival times correspond approximately to the distances between antennas.

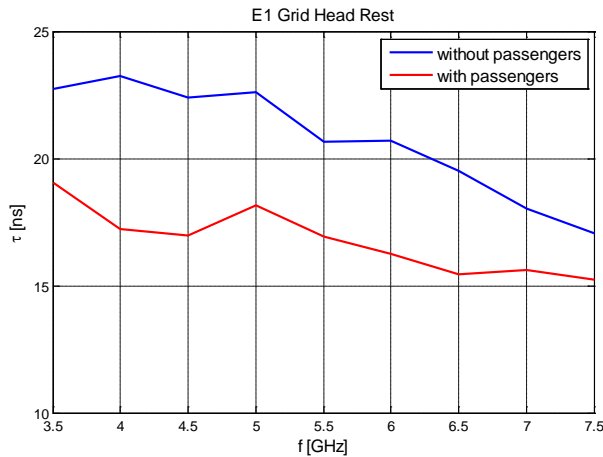


Fig. 5. Reverberation times as a function of frequency and occupancy of seats. Averaged over 13 closely spaced points measured in a grid [12]. Bandwidth of 1 GHz.

The receiver located at nearest seat (5,1) has a clear LOS link to the emitter, hence the impulse response is dominated by LOS component and near scattering at the beginning of the

impulse. This deviates very much from the impulse responses measured from other receivers at seat (2,4) and seat (1,1). After about 25 ns, all the three tails are about the same, both in slope as well as in amplitude, this verifies the general diffuse theory. Due to the lack of spatial averaging, the results may not be highly accurate. However, this can be resolved by using the data obtained from grid measurements for two seats as reported in [12], and the frequency dependence is studied with a bandwidth of 1 GHz. Following the assumption that the exponential decay of diffuse component would be the same regardless of the measured positions as indicated before, only the grid measurement data set derived from one of the seats (2, 4) with emitter E1 is investigated in the following section. The dependence of reverberation time on frequency as well as seat occupancy are investigated in Figure 5, where the reverberation time derived by best fitting the measured impulse responses is found to fall between 15 ns and 25 ns.

B. Mean Power

The path loss is averaged over 13 closely spaced points [12] at a distance of 3.25 m from the access point, corresponding to a delay t_0 of 10.8 ns, as derived from eq. 6. The exact volume of the whole measurement area is not known, but is evaluated at $V = 100 \text{ m}^3$. The resulting path loss is compared with theory in Figure 6 with good agreement. One of the possible reasons for the disagreement at the lower frequencies is probably the dominance of the quasi-LOS signal.

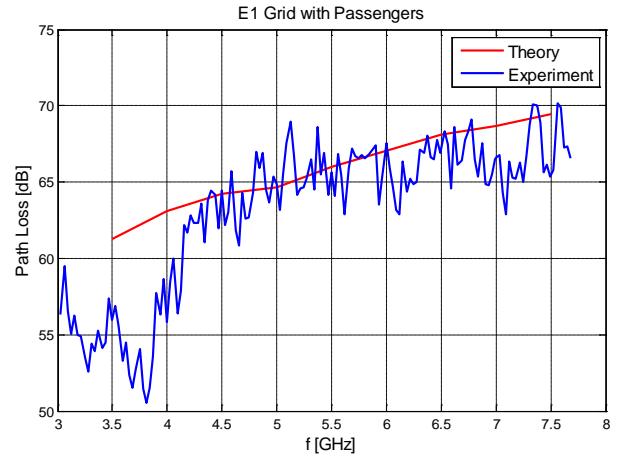


Fig. 6. Measured path loss as a function of frequency (blue) and the theoretical curve (eq. 6) as a function of frequency (red) in an occupied cabin.

C. Absorption

The effective absorption area A' can be derived from equation (1).

$$A' = \frac{4V}{c\tau} \quad [\text{m}^2] \quad (7)$$

Due to the missing of an exact value of volume V , the results of the relative value A'/V is plotted in Figure 7. The passenger absorption is calculated as the difference between the occupied and empty cases, and it seems to be relatively inde-

pendent of frequency, and approximately equal to 0.15V. Assuming the whole measured area has a volume of 100 m^3 , an absorption area of 15 m^2 is obtained. Considering all 24 seats within the measured area which are fully occupied during the measurement, each of the passengers contributes to about 0.63 m^2 of absorption area, if each human body is assumed to absorb the same dose.

V. DISCUSSION

In realistic indoor environments there may be many obstacles and rough surfaces which lead to a considerable amount of random, multiple scattering. This may be checked experimentally by measuring the mean impulse response at different positions, and if there is exponential decay in delay and the slope and level is independent of position, then the diffuse radiation is given by a simple theory, similar to what has been applied in acoustics. In cases with a strong line-of-sight signal this should be added. In general, the agreement with the measurements in an aircraft cabin is satisfactory considering the simplicity of the theory. Once the volume and reverberation time are known then the path loss as a function of distance can be derived. Generally the randomness of the polarization is unknown but here complete randomness has been assumed.

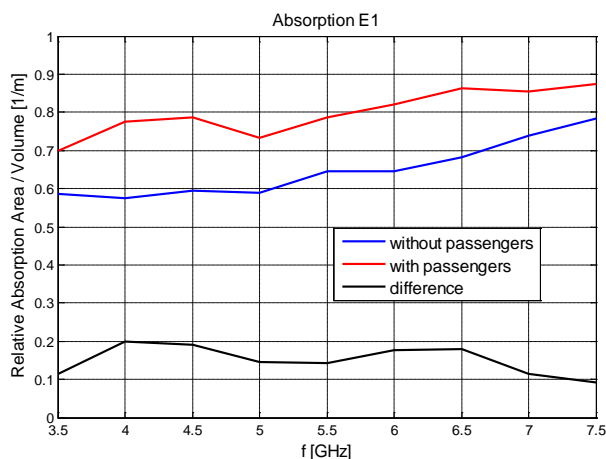


Fig. 7. The relative absorption A/V for the cabin with and without passengers as a function of frequency derived from the reverberation time from Fig. 5. The difference may be attributed to the absorption by the passengers.

The physics of the situation is that for steady state the diffuse energy is uniformly distributed over the volume, however, for impulse radiation, the energy at a given time is only distributed over the volume covered by the delay time. The effective volume increases with time whereas the energy density decreases.

The presence of the passengers reduces the reverberation times, followed by the increase in path loss and absorption. It is interesting that by assuming all passengers absorb the same dose, it is possible to evaluate the exposure. Nevertheless, the dominance of LOS component at short distances between antennas may need to be included, before the theory of diffuse energy can be applied.

VI. CONCLUSION

In this paper, channel characteristics within aircraft cabins with passengers were studied using developed theory from room electromagnetics. The theory allows a cylindrical aircraft cabin with high density seating to be characterized using volume and reverberation time, hence path loss and absorption area can be derived accordingly. This allows the influence of passengers on radio wave propagation within aircraft cabins to be further quantified by an absorption areas contributed by the passengers on average.

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