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Room Electromagnetics

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Abstract

In analogy with the established discipline of room acoustics various aspects of diffuse wideband microwave propagation in a room are treated. It is 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 versus delay is a consequence of the assumptions. Furthermore, the concept of a reverberation distance is also valid. This is the distance from a transmit 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. A number of measurements in a large room support the theory with an effective absorption coefficient of 0.5. The power delay profiles around the room from a transmitter in the ceiling vary only in the first arriving part of the impulse, whereas the tail being dominated by the diffuse field has the same power level for a given delay and the same decay rate all over the room. It is also a consequence of the theory that the incident diffuse fields on an antenna are uniformly distributed in angle.

1. Introduction

It is not surprising that there is a close resemblance between room acoustics and room electromagnetics, since the wavelengths 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 like pieces of furniture. In both cases ray tracing has been popular assuming known properties of materials, but a large number of rays are 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, which in the latter case has to be considered when designing a communication system in order to avoid inter-symbol-interference. One difference, however, is that the acoustic case is ultra wideband, while the radio case usually has a small relative bandwidth hence nearly constant wavelength over the communication band; another difference being 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 buildings as such, consisting of corridors, halls and offices, and the concern has been related to influence of walls and floors [1]. A stochastic approach for indoor diffuse scattering is described in [2] treating pathloss 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, the resulting delay profiles being non-exponential. Here we are concentrating on a single rather large room, typical of open office structures with partitions between cubicles. Such an environment would typically have many users in a wideband wireless system including MIMO, and in such a case an accurate characterization of the radio channel in power, delay and angle is important. In the present 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.

The theoretical part relies heavily on the established knowledge in acoustics [6], while the experiments are new. The theory is covered in section 2, while sections 3-6 give the experimental results. The paper concludes with a discussion. A preliminary version was published in [7], unfortunately with some errors, which are corrected here.

2. Theory

In this section we shall make some assumptions on a diffuse field in analogy with the corresponding acoustic quantities [6]. Although the electromagnetics 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

$$dI(\vartheta, \varphi) = \frac{|E_{\vartheta}(\vartheta, \varphi)|^2 + |E_{\varphi}(\vartheta, \varphi)|^2}{2Z_0} d\Omega = I(\vartheta, \varphi) d\Omega \quad \text{Watt/m}^2 \text{ /steradian} \quad (1)$$

in the directions ϑ and φ . 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

$$dW(\vartheta, \varphi) = \frac{I(\vartheta, \varphi)}{c} d\Omega \quad \text{Watt s/m}^3 \text{ /steradian} . \quad (2)$$

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

$$W = W_e + W_m = \frac{1}{4} \epsilon |E|^2 + \frac{1}{4} \mu |H|^2 = \frac{1}{2} \epsilon |E|^2 = \frac{I}{c} \quad \text{Watt s/m}^3 \quad (3)$$

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 (2) over all directions gives an energy density as

$$W = 4\pi \frac{I}{c} \quad \text{Watt s/m}^3 \quad (4)$$

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 (1) is incident on a wall area A , which partly absorbs it. The total power absorbed is an integration of (1) over a half-space, i.e.

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

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

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

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

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

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.

2.1 Electromagnetic reverberation time

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

$$W = W_0 e^{-t/\tau} \quad (8)$$

$$\tau = \frac{4V}{c \eta A}$$

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

$$\frac{dW}{dt} = 0 \quad (9)$$

$$W_0 = \frac{4S}{c \eta A}$$

depending only on the input power and the absorption area.

In the case that the average delay profile has an exponential decay, then τ equals the rms delay spread.

The general solution to (7) is a convolution integral

$$W(t) = \frac{1}{V} \int_0^{\infty} S(t-t') e^{-t'/\tau} dt' \quad (10)$$

2.2. 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 field.

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

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 $\frac{\lambda^2}{4\pi}$ so using (4) and (9) we find

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

so the path gain after steady state has been reached is

$$\frac{P_{rei}}{S} = \frac{\lambda^2}{4\pi^2 \eta A} \quad (13)$$

2.3. Theoretical reverberation distance

It is clear that near the transmit 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 transmit antenna will be

$$P_{dir} = \frac{SD_1 D_2}{4\pi r^2} \frac{\lambda^2}{4\pi} \quad \text{Watt} \quad (14)$$

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

$$r_d = \frac{1}{2} \sqrt{D_1 D_2 \eta A} \quad (15)$$

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

3. The measured environment

The room is a rectangular room with dimensions 11*20*2.5 meters with windows at two sides and filled with cardboard partitions with metallic frames, an overview drawing is seen in Figure 1 and a photo in Figure 2. Other elements were book cases, tables, chairs and computers. The transmitter was positioned near the ceiling at the middle of the room, and the 11 positions of the receivers are indicated on the drawing. Access points 2 and 3 were outside the room. Results for position 10 are not given, since the experiment failed. The antennas were monopole planar arrays with additional parasitic elements, the transmit array with 16 (4*4) active elements looking downwards from the ceiling and the receive array with 32 (4*8) elements looking upwards. The transmit array is seen in Figure 3 and the receive array in Figure 4. Note that only vertical polarization is considered.

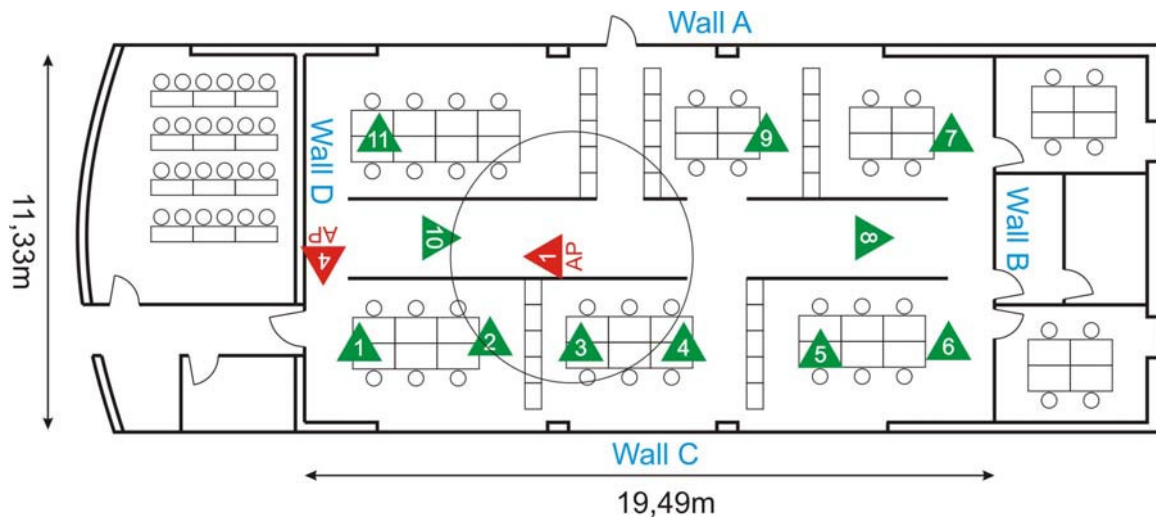


Figure 1 Outline of office environment with indication of 2 access points (AP) and 11 user positions. The circle is the approximate reverberation distance around AP1.



Figure 2 A view of part of the room



Figure 3 Transmit array positioned at ceiling

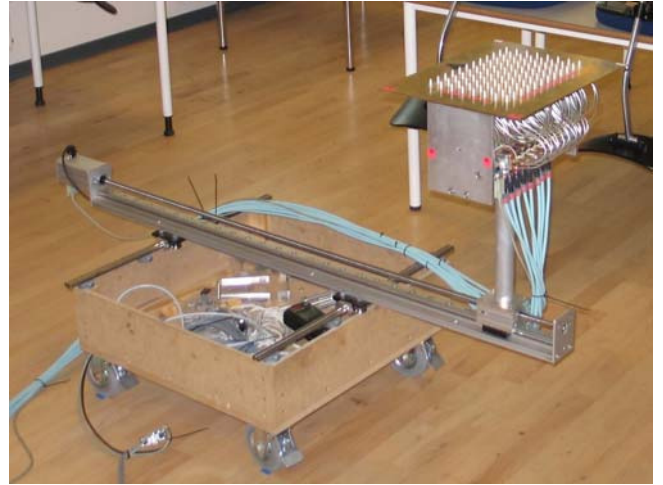


Figure 4 Receive array

The array elements have a maximum directivity of 6.1 dB and a loss of 1.5 dB due to the coupling to the other elements. The maximum is at an elevation around 45° from horizontal. As may be seen from Figure 4 the receive array may move along a slide to obtain more independent measurements. The frequency was 5.8 GHz and the bandwidth 100 MHz. More information on the sounder may be found in reference [8]. The wideband data from the sounder contain the complex impulse responses from each transmitter element to each receiver element from which the mean value in power of the impulses are obtained. The complex responses are normalized to the back-to-back measurement.

4. Total power distributions at the different positions

The distribution of the power at each site is an informative measure of the radio channel, whether it is Rayleigh, Rice or has some other distribution. Figure 5 shows the cumulative probabilities on a log scale at the ten user positions with the powers normalized to have zero dB mean power. The positions are numbered from 1 to 11, but the measurements at position 10 were not available, so there are only ten positions. It is clear that the distributions fall in two distinct categories, one group (2, 3, and 4) shows a clear Ricean distribution with a K-factor around 9 dB, whereas the remaining points have distributions close to Rayleigh. The Ricean group has the shortest distance from the transmitter, about 4 meters and all of those positions had near line-of-sight to the transmitter. All other positions show distributions close to Rayleigh fading. This is a surprise since some of them have also near line-of-sight to the transmitter.

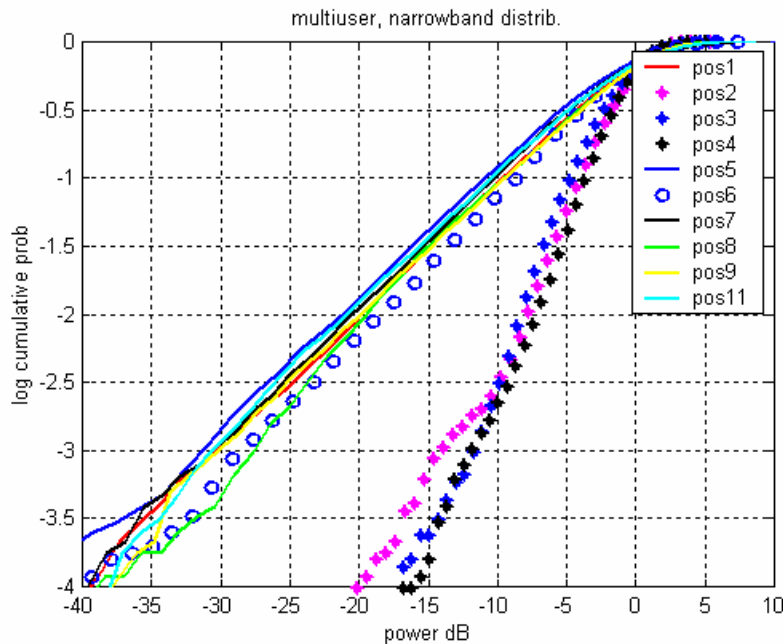


Figure 5 Cumulative probability distributions of the power at the various positions in the room. Powers are normalized to the mean power.

5 Mean power delay profiles

The ten power delay profiles are shown in Figure 6 and again the difference between the two groups is apparent. Positions 2, 3, and 4 (dashed lines) have the highest peaks and a non-exponential decay. The remaining positions, which had Rayleigh distributions, are remarkable in the sense that they have the same power in the tail. Note, that the PDP's are normalized to the input power and includes the pathloss. In order to see this more clearly the delay profiles are plotted again in Figure 7 without the Ricean cases. The decay rate is close to 0.18 dB/ns for all of them, which gives a reverberation time τ of 24.1 ns. We can now use the expression for the reverberation time, eq. (8), to determine the average absorption coefficient,

$$\eta = \frac{4V}{c\tau A} \quad (16)$$

Putting in the actual numbers for our case $V=522.5 \text{ m}^3$, $A=560 \text{ m}^2$ (all walls, floor and ceiling), $c=0.3 \text{ m/ns}$ results in $\eta=0.51$. Whether this is a reasonable number for this particular room is difficult to judge, but the fact that the tails of all the impulses have the same level ensures that the diffuse field has spread uniformly to the whole room. We are now in a position to evaluate not only the slope but also the level. Using eq. (13) we find a steady state power of -65 dB when using all the known quantities. Since each antenna has an efficiency of -1.5 dB we subtract 3 dB and get a final value of -68 dB. Taking position #5 as an example we find a mean power of -77dB (relative to the back-to-back measurement), but considering that the impulse peaks 40 ns later, there is a loss of $40 \text{ ns} * 0.18 \text{ dB/ns} = 7.2 \text{ dB}$, so there is a disagreement of only 2-3 dB, which may be explained by the fact that the impulse is too short to reach steady state for the room in question. So the interpretation of the impulse responses is quite clear. There is an overall decay rate valid everywhere established by the access point, but the start of the impulse depends on the delay, and thus distance, from the access point. In the beginning of the impulse there may be an overshoot, depending on the local shadowing, which is important for the total energy, but the tails are dominated by the common diffuse scattering.

Similar measurements at the other access point, AP4, near the wall are shown in Figure 8. The conclusions are exactly the same, so the response tails are also independent of the position of the access point. The total delay to the end of the room is naturally larger, which gives a smaller total power as discussed above. There is a different slope (model 2) of 0.60 dB/ns in the beginning for position 1. This may be explained by the fact that the reflections from the end wall have not arrived yet, but they do so after 50 ns.

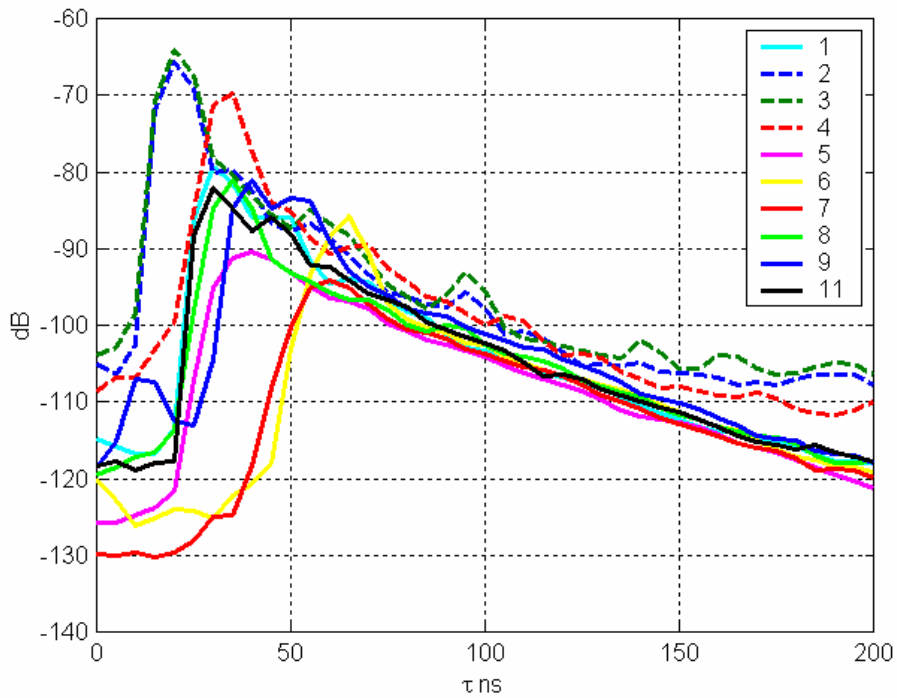


Figure 6 Average power delay profiles at the various positions

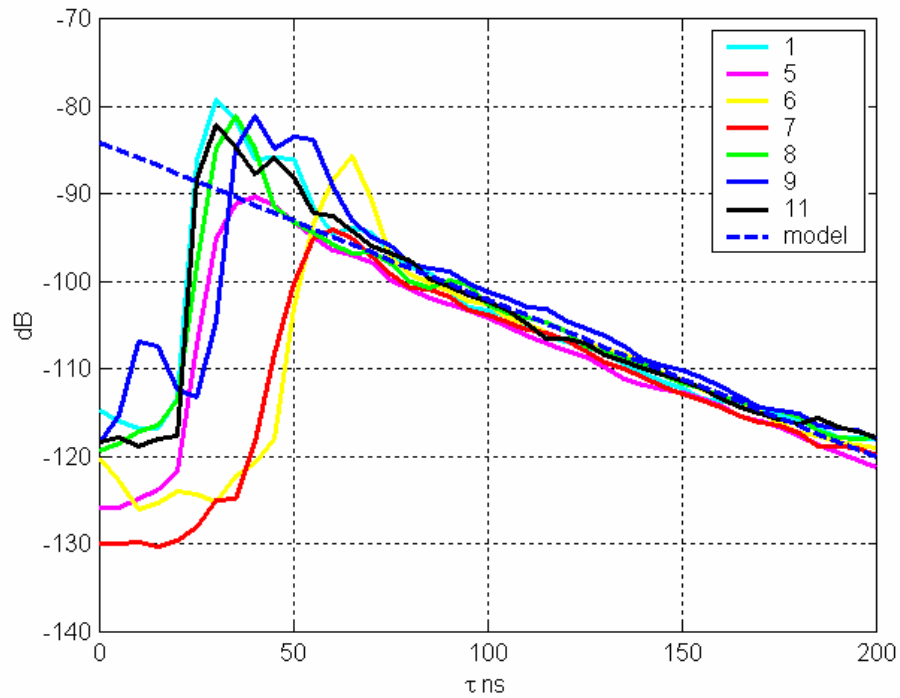


Figure 7 Average power delay profiles for all positions except # 2, 3 and 4 (dashed lines in figure 6). Dashed line theoretical reverberation model

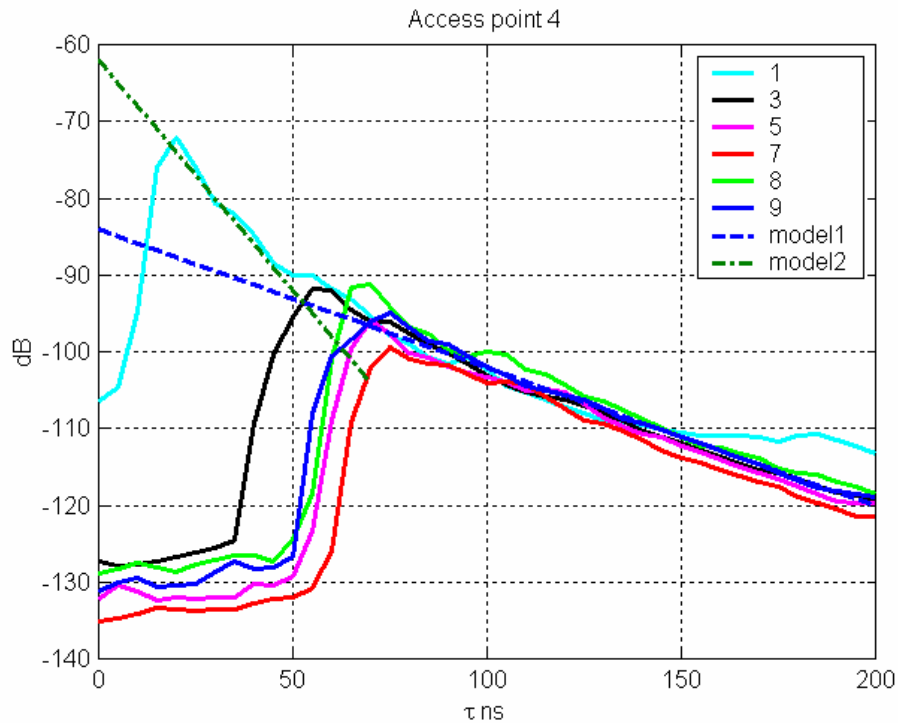


Figure 8 Average power delay profiles for access point 4 near the end wall (Fig.1)

6. Measured 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 depends on the position in the room is due to the fact that the antenna directivities vary. The true geometrical distances from the access point to all the user locations are shown in Figure 9 together with the calculated reverberation distances. It is noted that for locations 2,3, and 4 the true distances are much smaller than the reverberation distances (position 10 was not measured). This then is the explanation of the Ricean distribution at these points, they are so close that the direct path dominates over the diffuse fields.

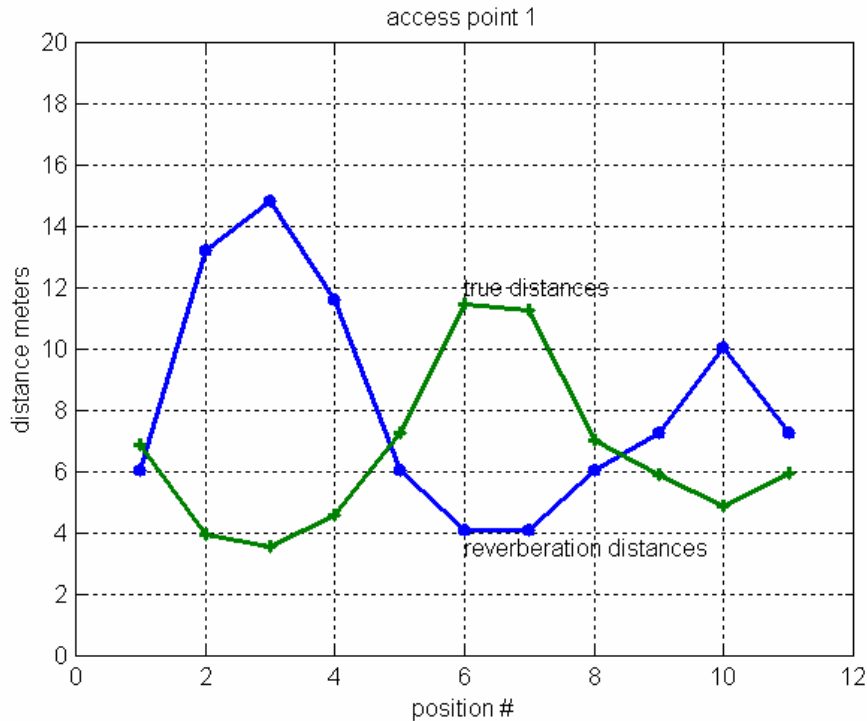


Figure 9. True distances and reverberation distances for the different locations

7. Discussion

Measurements of the average power delay profiles in a typical large office environment have shown that the decay rate of the tail is governed by the overall dimensions of the room and an average absorption coefficient. Not only the decay rate but also the power levels are the same all over the room in the tail of the response. At each location the peak of the impulse arrives with some delay related to the distance, and the energy builds up in the beginning based on the possible line-of-sight and the local scattering from objects and walls, depending also on local shadowing. This part of the energy is important for the communication process, but is not treated in detail here. The remaining part of the impulse, our main concern, is governed by the completely random, chaotic process where the whole room is filled with energy, leading to a constant energy density all over for the same delay. This process is fully developed after a delay of 75 ns (corresponding to 22 m in distance) and continues until the signal drowns in noise. The level and slope of the tails is also independent of the access point (transmitter) position. There is some evidence of a dual-slope case for close positions near the end of the room, but the final slope is the same.

The simple scalar theory of acoustic reverberation in a room with lossy walls agrees well with microwave measurements. This gives a single parameter that characterizes the room, the effective absorption coefficient, which in our case was close to 0.5. In reality it is an

average figure including possibly also some losses inside the room. It would be of interest to find this parameter for other types of room, since it is so simple. The decay rate of the tail is a constant around 0.18 dB/ns corresponding to a time constant of 24.1 ns in the exponential decay. Since the delay spread of the total impulse is reduced by the presence of the non-diffuse part, we may note that this time constant is an upper bound on the rms delay spread. The main difference from the acoustical case apart from material parameters is polarization. This is not considered here, since both transmitting and receiving antennas were vertically polarized.

The reverberation distance signifies the distance between the transmitter and the receiver antennas below which the direct ray dominates. In the present room it turns out that for three positions (2, 3, and 4) the real distance is much shorter than the reverberation distance. For these locations the power has a Rice distribution with a K-factor of 9 dB. For all other locations the distribution is close to Rayleigh as would be expected in a chaotic, random field, independent of whether they have line-of-sight to the transmitter or not.

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Bios

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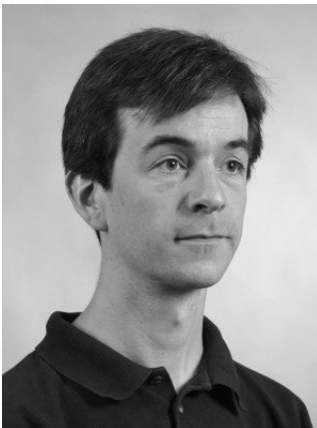


Jørgen Bach Andersen received the M.Sc. and Dr.Techn. degrees from the Technical University of Denmark (DTU), Lyngby, Denmark, in 1961 and 1971, respectively. In 2003 he was awarded an honorary degree from Lund University, Sweden. From 1961 to 1973, he was with the Electromagnetics Institute, DTU and since 1973 he has been with Aalborg University, Aalborg, Denmark, where he is now a Professor Emeritus.

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Professor Andersen is a Life Fellow of IEEE and a former Vice President of the International Union of Radio Science (URSI) from which he was awarded the John Howard Dellinger Gold Medal in 2005.

Jesper Ødum Nielsen



Jesper Ødum Nielsen received his master's degree in electronics engineering in 1994 and a PhD degree in 1997, both from Aalborg University, Denmark. He is currently employed at Department of Communication Technology at Aalborg University where his main areas of interests are experimental investigation of the mobile radio channel and the influence on the channel by mobile handset users. He has been involved in channel sounding and modeling, as well as measurements using the live GSM network. In addition he has been working with handset performance evaluation based on

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Gert Frølund Pedersen



Gert Frølund Pedersen was born in 1965. He received the B.Sc. E. E. degree, with honour, in electrical engineering from College of Technology in Dublin, Ireland, and the M.Sc. E. E. degree and Ph. D. from Aalborg University in 1993 and 2003. He has been employed by Aalborg University since 1993 where he is now Professor for the Antenna and Propagation group. His research has focused on radio communication for mobile terminals including Antennas, Diversity systems, Propagation and Biological effects. He has also worked as consultant for developments of antennas for mobile terminals including the first internal antenna for mobile phones in 1994 with very low SAR, first internal triple-band antenna in 1998 with low SAR and high efficiency, small and highly efficient headset antenna in 2004 and various antenna diversity systems rated as the most efficient on the market. Recently he has been involved in establishing a method to measure the communication performance for mobile terminals that has been used as basis for 2G and 3G standard where measurements also including the antenna are needed. The measurement technique is currently used in mobile terminals for beyond 3G terminals including several antennas to enhance the data communication.

Gerhard Bauch, Senior Member, IEEE



Gerhard Bauch received the Dipl.-Ing. and Dr.-Ing. degree in Electrical Engineering from Munich University of Technology in 1995 and 2001, respectively, and the Diplom-Volkswirt degree from Fern Universität Hagen, Germany, in 2002. In 1996, he was with the German Aerospace Center (DLR), Oberpfaffenhofen, Germany. From 1996-2001 he was member of scientific staff at Munich University of Technology (TUM). In 1998 and 1999 he was visiting researcher at AT&T Labs Research, Florham Park, NJ, USA. In 2002 he joined DoCoMo Euro-Labs, Munich, Germany, where he is currently manager of the Advanced Radio Transmission Group. Since October 2003 he has also been an adjunct professor at Munich University of Technology (TUM). He received the best paper award of the European

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His research interests include channel coding, turbo processing, multihop transmission, ad-hoc networks and various aspects of signal processing in multi-antenna systems (MIMO).

Markus Herdin



Markus Herdin works as a senior development engineer for signal processing and FPGA design at Rohde & Schwarz in the Test Systems for Wireless Network Optimization group. He received his Dipl. Ing. degree in mobile communications from the Vienna University of Technology, in 2001. He continued his research towards a PhD in the mobile communications group at the Institute of Communications and Radio-Frequency Engineering, Vienna University of Technology. His research areas covered multiuser detectors for UMTS, mutual interference of Bluetooth and WLAN, MIMO channel measurements and MIMO channel characterization. After finishing his PhD in 2004, he joined DoCoMo

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