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## **Channel characteristics of an indoor multiuser environment**

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## *Abstract*

*High data rate MIMO communications in a multiuser environment is one of the goals for future wireless systems. The paper discusses an extensive experimental study at 5.8 GHz of a wideband (100 MHz) multi-antenna multiuser system. The environment is a large office environment with standard furniture and equipment and with active users either operating a laptop with four antennas or a body-worn 4-element patch antenna. The access point antenna is an 8 element circular array of vertically polarized dipole elements, the array being positioned near the ceiling in the middle of the room or at the end of the room.*

*The propagation is dominated by diffuse scattering with a resulting exponential decay impulse response, and as described elsewhere, the tail of the response is independent of position in the room and independent of the type of antenna, both for the slope and the power level.*

*The narrowband power distributions have an interesting new property. The distributions averaged over all antennas is Rayleigh, but there are significant deviations to both sides, to the Rice side and to the multiple scattering side, up to 5 dB at the 1% level. The orientation of the users with respect to the access point has a small impact on the mean power level, with up to 3 dB additional shadowing when the back is towards the access point. The correlations between signals from the antennas on one array and between arrays are small. The capacity of the arrays is almost independent of antenna and location for fixed SNR, but considerable variation due to varying mean power as a result of different distances and environments.*

## *Introduction*

The indoor environment is still of significant interest for future wireless systems, especially with multiple users demanding the same access to the limited spectrum. In some previous publications [1, 2] we have addressed the propagation issues and the derivation of a suitable wideband channel model. This was based on extensive measurements with planar arrays (16 \* 32 elements), and the main experimental and theoretical results are cited in the following section. It should be noted that there were some scaling errors in [1], which have been corrected in [2].

In the present document a more realistic situation is treated with an 8 element circular array of vertically polarized dipoles as an access point, and user antennas either 4 dipole elements connected to the lid of a laptop or a compact array of 4 patch antennas on a body worn antenna. Apart from presenting the key propagation results also the capacities of these rank 4 MIMO systems are discussed.

## *Outline of Room Electromagnetics*

Room Electromagnetics is developed in analogy with Room Acoustics [3], a well established discipline based on random, diffuse radiation due to scattering from rough walls or inventory. The wavelengths are typically of the same order, in the cm range, the main difference between them being material properties and polarization. Thus we should expect many of the same concepts to carry over.

With an input source power of  $S(t)$  Watt the power balance in the room is given by (1) , where the input power is balanced by the increase in energy density per second and the losses at the walls,

$$S(t) = V \frac{dW}{dt} + \frac{c\eta A}{4} W \quad \text{Watt} \quad (1)$$

with  $c$  being the velocity of light. This agrees with the standard equation for room acoustics [3], except that here the velocity of sound is replaced by the velocity of light.  $V$  is the volume of the room,  $A$  the total area including all walls, floor and ceiling,  $W$  the energy density,  $\eta$  an effective absorption coefficient of the walls.

For a steady state situation we find the final energy density, uniformly distributed in the room,

$$W_0 = \frac{4S}{c\eta A} \quad (2)$$

and the decay rate of exponential decay

$$W = W_0 e^{-t/\tau} \quad (3)$$

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

An example of the results from the earlier measurements is given in Figure 1.

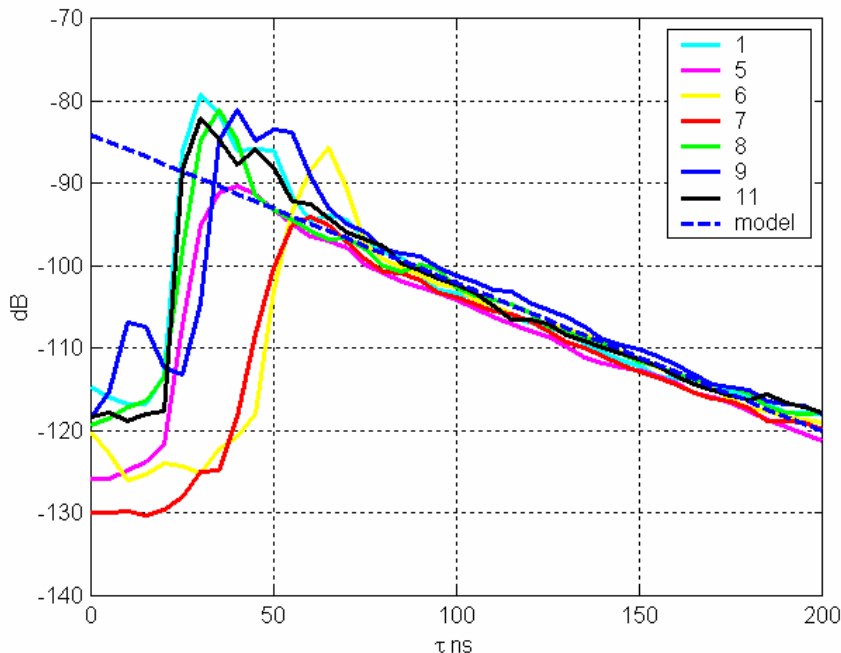


Figure 1. Average power delay profiles at various positions in the room normalized to a back-to-back measurement in delay and power. Access point #1. Measurements performed with planar arrays.

It is noted that there is a certain delay until the start of the impulse depending on the distance from the access point. There is a certain overshoot in the beginning depending on local conditions, and finally an exponential decay, which is the same everywhere, in rate and in magnitude. In the present case we can derive a decay of 0.18 dB/ns corresponding to a time constant of 24 ns. This represents an upper bound on the average delay spread. It is also a consequence of the theory that the radiation in the tail is randomly distributed in angle, which in antenna terms means a directivity of one. It is then possible to derive the mean received narrowband power (or the link gain) as

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

### *The environment and user activities*

The measured data used in the current work is obtained using a MIMO channel sounder operating at a carrier frequency of 5.8 GHz. The sounder uses the correlation principle, and measures 16 transmit channels simultaneously, where each transmit branch uses a 1 W power amplifier. On the receive side eight channels were measured in parallel, and using 1:4 switching each branch is extended so that in total 32 receive channels are measured. Additional information about the sounder is available in [4]. The full complex 16x32 MIMO channel is measured in a time-triggered way at a rate of 60 Hz. In a post-processing procedure the measurements are compensated for the sounder system response and the bandwidth is limited to about 100 MHz.

The measurements were made on the down-link (DL) using two access points (APs) each with 8 elements arranged in a circle and mounted on a wooden pole at about 2.1 m above the floor, close to the ceiling. AP1 denotes the array located near the middle of the room, while AP4 was near one of the end walls, see Figure 2. In the figure the dashed lines indicate light partitions of height about 1.8 m and the double lines indicate wooden bookshelves which are standing on the floor and of the same height as the partitions. Although the APs are higher than the partitions not all of the mobile station (MS) positions have optical view of the APs.

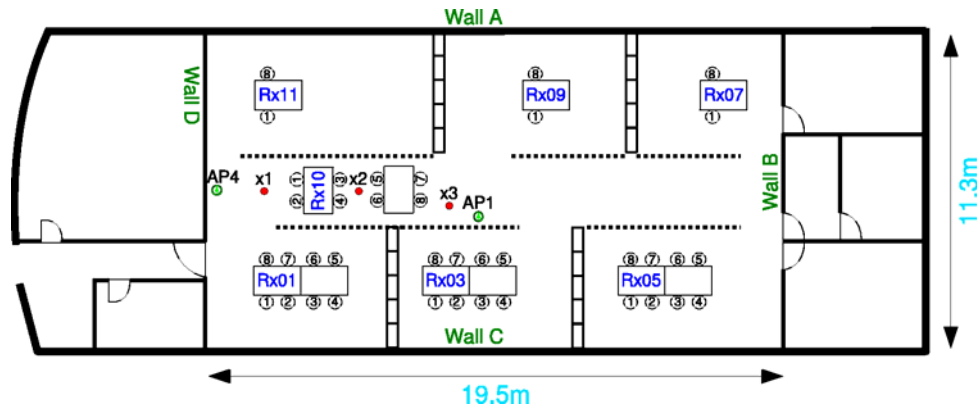


Figure 2: Overview of the measurement site.

Two types of MS arrays are considered. The first type is designed to mimic an array built-in a laptop. Henceforth this is called a 'laptop array.' The other type of array consists of four patches at the corners of a square of size about 3 by 3 cm, which is mounted on the chest of a person. The two array types are illustrated in Figure 3.

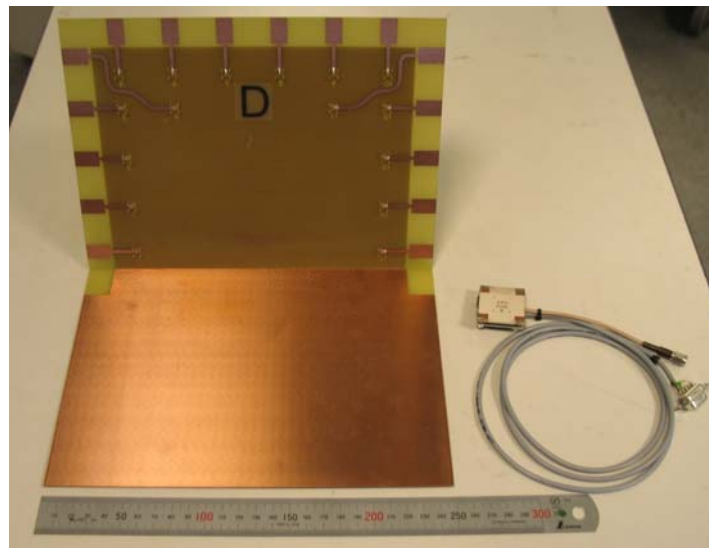


Figure 3: The two arrays used at the MSs.

In total eight MS arrays are measured simultaneously and organized in four identical pairs of arrays, consisting of a body mounted array and a laptop array. Each pair was then associated with a different person. During the measurements described in the following the body mounted array is always on the user's chest on a smock, except for the 'Free' measurement series where the user leaves the smock hanging on the chair, as described below.

Using the four pairs of arrays, labelled MS-a, MS-b, MS-c, and MS-d, a series of measurements was carried out in different scenarios. However, the following only describes the cases relevant for the current work.

The measurements are organized around the table positions Rx01, Rx03, and Rx05, shown in Figure 2. Around each table a number of seats are defined shown in the sketch as encircled numbers. In the so called 'small separation series' all the four users are located in the vicinity of each other, around the same table. The individual measurements may be described by different combinations of *Location*, *Orientation*, and *Type*, where *Location* is either of the above mentioned table positions.

The *Orientation* is any of the following:

- 'Back.' All MSs are in line, with the users sitting with the back towards the APs and facing Wall-C.
- 'Front.' All MSs are in line, with the users sitting with the front towards the APs and facing Wall-A.
- 'Face.' One pair of MS sitting in line are facing another pair of MS sitting on the other side of the table.

The *Type* is one of the following:

- 'Static.' The MS remains static in location and the nearby environment does not change. During the measurements the users of the MSs sit down at the table and simulate work at the laptops by "typing" or other types of movements nearby the MS.
- 'Moving.' All the laptop arrays are moved by the hands of the respective users, near the table top and in a small area close to the static position. The near environment of the MSs is static.
- 'UsrMovFB.' This is the same as the 'Static' measurement, except that during the measurement the MS-a user moves to the other side of the table while carrying the laptop array, starting from sitting position at Rx#.1 and to sitting position at Rx#.8. The other users simulate typing/work, as in the 'Static' type.
- 'UsrMovBF.' Similar to the 'UsrMovFB' but in the reverse direction, so that the measurement starts with all MSs in the 'Back' orientation.
- 'ExtMov.' This type is carried out as the 'Static' type of measurement, except that during the measurement a person is walking in a circle around the table with the users.
- 'Free.' All users leave the laptop array on the table and the smock with the body worn device hanging on the chair. At the beginning of the measurement the users are standing behind the chair and starts walking; user of MS-a/MS-d: clockwise, user of MS-b/MS-c: counter-clockwise.

## Wideband aspects

The average impulse responses for the new antennas including persons operating the laptops or wearing the antennas follow the same trend as above. An example is given in Figure 4 a and b for the cases where the persons are facing the access point from position #5

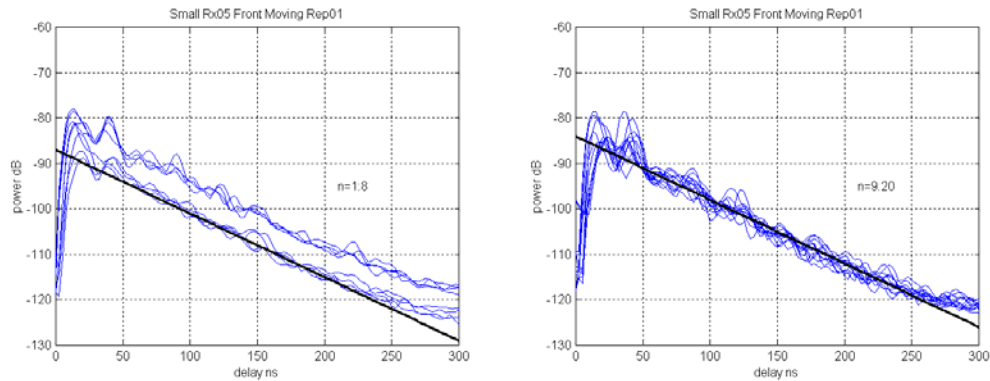


Figure 4 Average impulse responses for a) laptops and b) bodyworn.

The results of fig. 4 are for position 5, but the results are very similar for other positions and scenarios, and the decay rate is exactly the same everywhere. The lower power levels for the Laptop antenna in Fig 4a is probably due to the difference in polarization, since these antennas are horizontal. The decay rate is now 0.14 dB/ns compared to 0.18 dB/ns for the other antennas in the same room. The reason is the inhomogeneous distribution of wall losses, like windows, making a small dependency on the wall losses of the radiation patterns. The approach to a floor at late delays is due the finite dynamic range of the measurement equipment, and thus not a propagation phenomenon.

## Narrowband aspects

### Power distributions

The distributions in Figure 5a are typical examples for all cases. On average for all antennas the distribution is close to Rayleigh, but there are significant deviations. On the one side there are more Rician like distributions which is natural, and on the other side the distributions are worse than Rayleigh. The access point array is also surrounded by scatterers, and Fig 5b shows the distribution of the paths from the various elements to one antenna at the user. The mean values are different and the distributions are different, partly due to the directional element pattern of the array. When averaging over the distributions in Fig 5b the results are those of Figure 5a. A model involving mutual scattering has been suggested in a previous COST paper [5], and more recently analyzed by Salo [6]. The header part of the impulses will often carry the main part of the energy and thus have a major impact on the narrowband power. For the tail all the distributions will be Rayleigh.



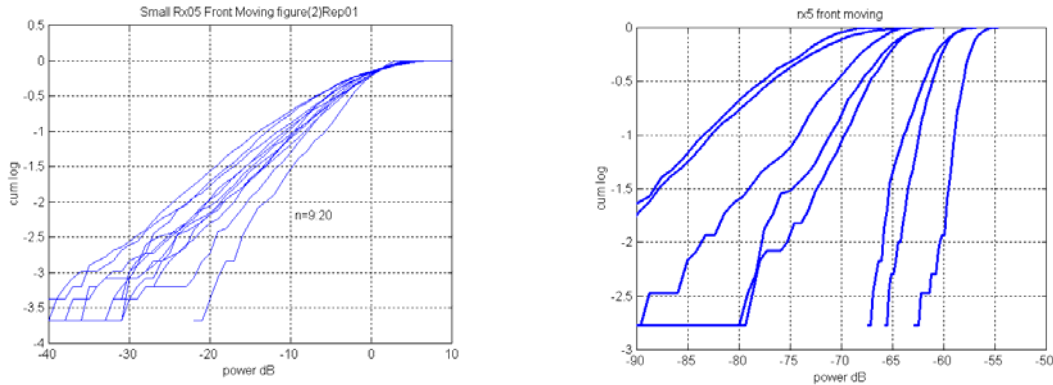


Figure 5 a) Distributions at position 5 for different receive antennas when moving the laptops around averaged over all transmit antenna and user movements b) Distributions for the eight transmit antennas to user antenna #9.

Figure 6 shows two more distributions, for the ‘static’ case and for the ‘free’ case following the same general pattern.

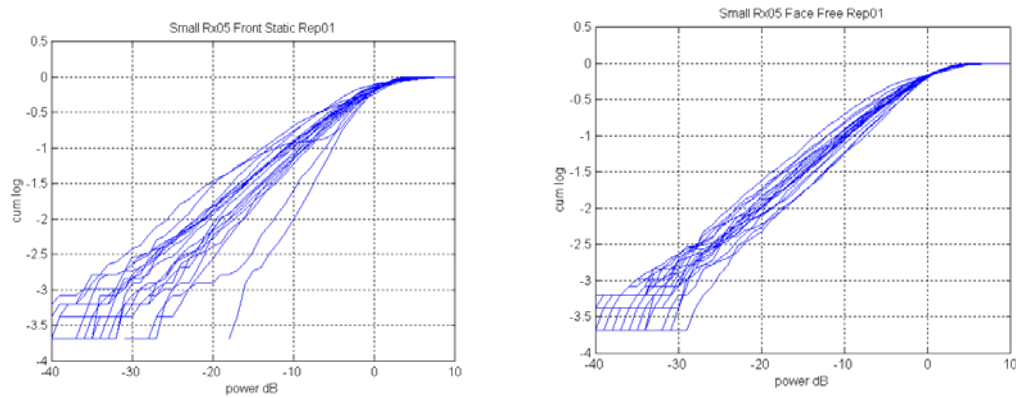


Figure 6 a) ‘Static’ case b) ‘Free’ case

### Mean Power

From eq. 4 we can find the mean power level (for any antenna) in the room at steady state. Using the appropriate numbers (volume, area, decay time) we find  $\eta=0.40$  and a mean narrowband power (link gain incl. antennas) of  $-65.2$  dB. For the impulse in question with a width of 20 ns the steady state is not quite reached, but it is close. Distance also plays a role. As can be seen from Figure 1, the impulses at positions far away arrived later to the tail, some energy has been lost already, and the mean power is less. For the positions 1, 3 and 5 the mean powers are given in Table 1.

The power levels at positions near the access point are clearly dominated by the non-diffuse part, being about 10 db higher, while the values for position 5 are close to the theoretical

value. It is noteworthy that the average distribution is Rayleigh for all situations, even those where a strong direct Ricean component is expected. The reason is that the distances between the antennas are larger than the reverberation distance [1, 2].

Positions and scenarios	Mean Power dB
Rx1 Front Moving	-57.6
Rx1 Back Moving	-60.5
Rx3 Front Moving	-55.2
Rx3 Back Moving	-56.0
Rx5 Front Moving	-63.8
Rx5 Back Moving	-63.9
Rx5 Free	-65.0
Rx5 Static	-64.0

Table 1 Mean power at different positions and orientations.

The distribution of mean powers among the individual antenna is indicated in Figure 7 for position 5 (front).

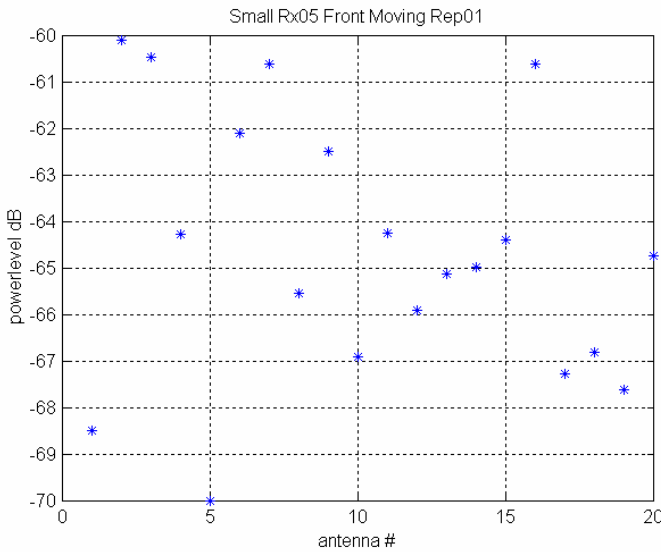


Figure 7. Distribution of mean powers among individual antennas. #1:4 laptop 1, #5:8 laptop 2, #9:20 body worn antennas in groupings of four.

Again it is noted that the horizontally polarized antennas have lower mean powers (# 1, 4, 5, 8).

### Correlations and Capacity

Correlations between antennas for one user influence the achievable capacity, and correlations between users' antennas would mean more difficulty in interference rejection. An example of correlations between all twenty antennas is shown in Figure 8. The correlations

shown are absolute values of complex correlations. The position and orientation is #3 with front towards the access point, and it is the worst situation as far as correlation is concerned.

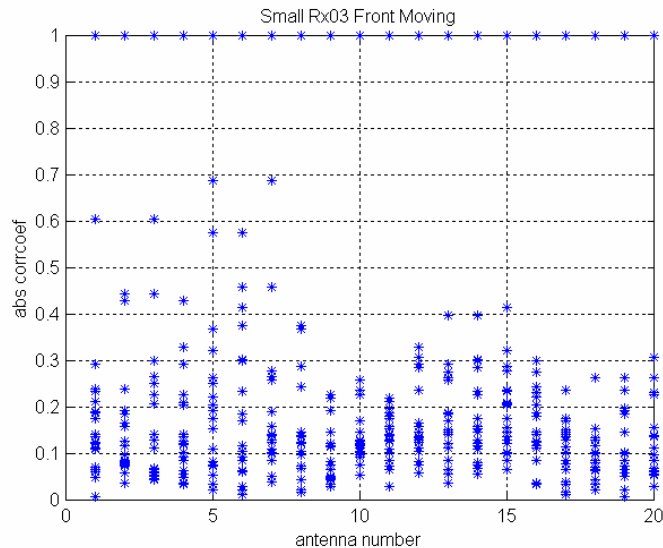


Figure 8. Absolute value of complex correlations between antenna signals for position #3 Front. . #1:4 laptop 1, #5:8 laptop 2, #9:20 body worn antennas in groupings of four.

The overall level is low, less than 0.3, and in those situations where the correlations are higher, they are between antennas in one array, which means that the between-user signals are highly decorrelated.

The capacity is calculated for the downlink situation in two ways, first as the mean capacity for an assumed SNR of 20 dB in all cases, second as the mean capacity for a fixed transmit power with 20 dB SNR at a reference antenna (antenna no 1). In both cases the capacities are calculated for a uniform distribution of power among the transmit antennas with no channel information at the transmitter, no water filling. The mean values over all 5 arrays at different locations and situations are shown in Table 2. It is clear that the richness is almost the same in all situations (column 3) and fairly close to the theoretical Rayleigh case of 25.2 b/s/Hz, which indicates that the correlations have not had a major impact, and that the Ricean part of the signals also is of minor importance for the capacity.

In contrast the mean power level has a major impact (column 4), where the range is from 18.9 to 32.4 b/s/Hz and the values are highly correlated with the mean power. This agrees with earlier measurements in the same room, the mean power is the major determinant [1].

Positions and scenarios	Mean Power dB	Mean capacity, SNR=20dB,b/s/Hz	Mean capacity, Fixed power ,b/s/Hz
Rx1 Front Moving	-57.6	23.2	28.7
Rx1 Back Moving	-60.5	23.8	25.8
Rx3 Front Moving	-55.2	23.5	32.4
Rx3 Back Moving	-56.0	23.5	29.8
Rx5 Front Moving	-63.8	22.8	20.7
Rx5 Back Moving	-63.9	22.5	21.1
Rx5 Free	-65.0	23.0	18.9
Rx5 Static	-64.0	22.6	19.9

Table 2. Mean powers, mean capacities for fixed SNR, and mean powers for fixed transmit power.

## Conclusion

A situation with multiple users in a large office like room has been explored from a propagation and antenna point of view. The users are in most situations sitting at a table and simulating using a laptop, which are furnished with four dipole like antennas around the rim of the lid. The users are also wearing compact antennas with four patch antennas. The access point is an eight element circular array of dipole like antennas, vertically polarized.

Earlier measurements in the same room with planar arrays established the validity of an ‘acoustics like’ theory named ‘room electromagnetics’ with the following results. For a 100 MHz bandwidth at 5.8 GHz the mean power delay profiles consisted of a header and a tail, where the tail had exponential decay with a decay rate depending on the room properties (size, wall absorptions) and not on the antenna type and positions. The header energy would vary depending on local properties in the room, distance and antenna directivities. For the present measurements with different antennas the same overall principles apply as well, although with a slightly different decay rate due to the inhomogeneous wall properties and windows. The theory also predicts the mean energy assuming that all the energy is diffuse and randomly propagating. The level agrees well with the measured values.

It is interesting to observe that the distribution of the narrowband power is close to Rayleigh in the mean, independent of a seemingly strong line-of-sight contribution. For the individual paths the distribution may have Rice-like properties or multiple scattering properties with outage levels worse than Rayleigh, depending on the averaging. We conclude that most of the distances are larger than the reverberation distance, signifying that the random energy will dominate over the deterministic one. The simulated ‘typing’ at the laptops creates sufficient scattering to create Rayleigh-like distributions.

The correlations between the antenna signals are in general low, both for those belonging to the same array, and for those on different persons, even though the persons are shielding the signal from certain directions. This is expected for diffuse radiation, which in the multiple scattering situation will have directions of arrival uniformly distributed over space. It is also in agreement with the capacity calculations, where the capacity for fixed SNR is almost constant independent of the situation, i.e. the multipath richness is uniformly distributed. The header energy, part of the total energy, is not uniformly distributed as discussed above for the mean power. The capacity for fixed transmit power therefore shows significant variability, where the highest capacity is found where the mean power is highest.

The influence of the persons and their movements is small, the greatest one being a 3 dB shielding of mean power.

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