**IEEE P802.15**

**Wireless Personal Area Networks**

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| Abstract | The CMD contains descriptions of the propagation characteristics and channel models of the operational environments relevant for the considered applications (e. g. data required to calculate link budgets) | |
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Document Overview

The CMD contains descriptions of the propagation characteristics and channel models of the operational environments relevant for the considered applications (e. g. data required to calculate link budgets)

The CMD will support the evaluation of the proposals submitted to P802.15.3d for consideration by the 15.3d task group.

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# Definitions:

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# Scope

This document details the characteristics of the air interface channels for the suite of applications described in the current revision of the 802.15.3d Application Requirements Document, 15-14-304-16-003d.

# Methodology

Descriptions of the applications and associated channel modeling parameters are listed in paragraphs 4-7.

## General Structure of the Channel Model

Structure of the CIR equation

## Multipath and Polarization Characteristics

Description of the ray-optical propagation paths and the considerartion of polarization characteristics by means of the Jones calculus

## Usage of the Channel Model in System Simulations

## General Channel Parameters

### Operating frequency band(s)

### Path loss model

### Antenna gain/pattern

## Scenario-Specific Channel Parameters

### Angular Dispersion

### Temporal Dispersion

### Other

# Close Proximity P2P Applications

## Environments

Regarding to the application requirement document [4.1] and the contribution on application usage [4.2], environments in where IEEE802.15.3d devices shall be operated can be defined. Two environments are characterized in this report. Table x1 summarizes the two characterized environments.

The scenario can be uniformed to line-of-sight (LOS) channel with transmission distance of a quite short range. Even for LOS scenario, we have to consider the case which metal chassis or metal cover exists on consumer electronics (CE) in which IEEE802.15.3d devices are implemented inside. That metal must be object for the path between the transmitter (TX) and the receiver (RX).

Table 1: A Table

|  |  |  |  |
| --- | --- | --- | --- |
| Channel Model | Scenario | Environment | Description |
| CMx | LOS | Kiosk  download |  |
|  |  |  |  |
| CMx | LOS  w/o Metal | File  exchange |  |
| CMx | LOS  w Metal | File  exchange |  |

## Channel Characterization

Close Proximity P2P (300 GHz):

Concerning the usage model of close proximity P2P wireless communications, the channel is assumed to be line-of-sight propagation in millimeterwave, 300 GHz band.

Generally, TSV model is introduced in millimeterwave PAN/LAN systems in IEEE802.15.3c and IEEE802.11ad operating both at 60 GHz. For proximity communications usage, reflections are observed inside terminals and at surface of terminals, etc. The channel model shall be modified to represent such propagation mechanisms and the frequency band at 300 GHz.

The channel model shall apply at least one of the several kinds of propagation depending on the antenna configurations.

### Path Loss

Molecular attenuation can be ignored because transmission distance along application usage is a short range of up to 50 millimeters.

### Power Delay Profile

### Fading Model

### Polarization

## Model Parameterization

### List of Parameters

The complete list of parameters used in this report can be summarize as follows:

1. *K*, K factor of Rice distributions for the first arrival path

2. , the cluster decay rate

3. initial decay between the first arrival path and delayed paths

The parameters are given in Table x.

### Model Parametrization

#### Kiosk Downloading

#### File exchange between device to device

## Other

# Intra-Device Communication

## Operating frequency band(s)

As envisaged in the ARD, the desired transmission rates for wireless intra-device communication reach up to almost 100Gbps. Furthermore, the use of frequency-domain and spatial multiplexing shall be possible. The operational environment is restricted to some 10cm and usually trapped by a device casing. Consequently, a huge frequency range might be exploited, for example between 270 GHz and 320 GHz.

## Intruductory Measurement Examples

### Measurement Methodology and General Channel Peculiarities

In the following, the peculiarities of the intra- device propagation channel shall be introduced by a set of measurementsin a board-to-board communication environment. The transmission channel consists of two antennas mounted on opposing surfaces at close proximity without any obstructions between the antennas. A sketch of this scenario is provided in Figure 1.



Figure 1: Board-to-board communication scenario (top view)  
Tx and Rx are mounted on opposing PCB surfaces (green)

With this configuration, a range of exemplary measurements has been performed to get a first insight in the channel characteristics. The measurements have been based on a setup comprising a vector network analyzer along with the necessary frequency extension modules to reach the frequency band between 270 GHz and 320 Ghz. Information regarding the setup and mechanical arrangement can be found in [5.1]. As seen in Figure 2 below, four configurations with diagonal antenna positioning have been measured. The measurements comprise two different box sizes *d* as well as two box setups, one including Printed Circuit Boards (PCB) at front- and backside and one without.

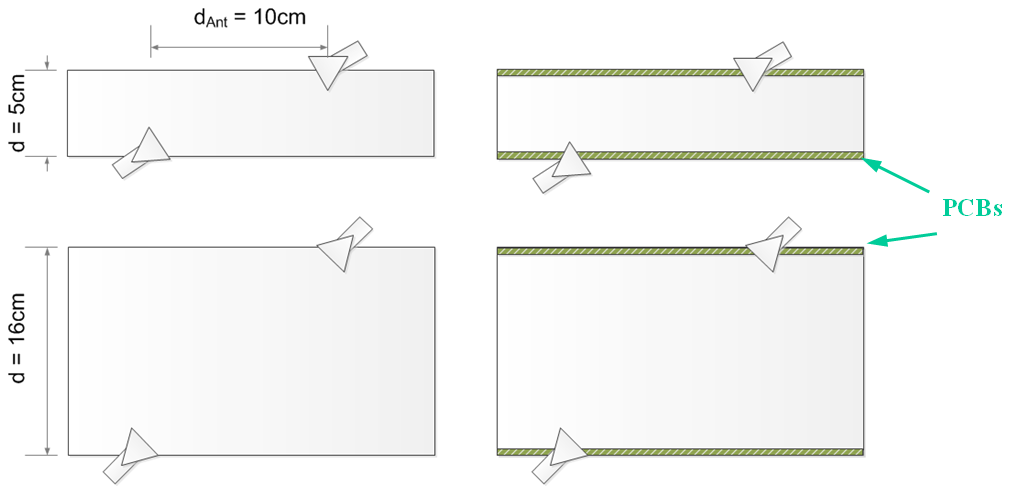


Figure 2: Measured board-to-board scenarios   
two box sizes (first and second row)   
full plastic or PCB-equipped box (left and right column)

In particular, the impact of printed circuit boards and the behaviour of the channel for the possible sub-bands have been investigated. Figure 3 exemplarily shows a measurement result over the full bandwidth along with the effects arising when only a sub-band of the complete channel is evaluated.

Figure 3: Measured channel transfer function (CTF) and channel impulse response (CIR)   
for the full frequency range (left) and two chosen sub-bands (middle and right)

The channel transfer function (CTF) over the complete bandwidth shows the typical profile of a strong propagation path interfering with some attenuated echoes. Its Fourier-Transform, the channel impulse response (CIR), reveals a strong peak corresponding to the direct path between Tx and Rx followed by the expected signal echoes from reflections inside the casing. It must be noted that the CIR is influenced by the leakage-effect introduced by the inverse Fourier Transform. Comparing the CIR of the full bandwidth to the CIR of the sub-bands band 1 between 270 GHz and 280 GHz and band 3 between 290 GHz and 300 GHz, a varying channel can be observed for the two bands. For band 1, the propagation channel seems to be almost free of echoes; the peaks seen in the full-bandwidth CTF are reduced almost to the FFT-leakage floor. In band 3, the reflections appear even stronger than in the original signal. This effect stems from the reflections at the plastic casing of the device. A signal reflected from a thin layer of plastic will interfere with itself due to two reflection processes at front- and backside of the plastic surface. Depending on the absolute frequency of the signal, these two reflection processes may add up constructively or destructively. A detailed investigation of the reflection and transmission behaviour at THz frequenies is found in [5.2] Thus, the same propagation path may lead to varying contributions to the total channel behaviour if different sub-bands are considered.

In the following, the CIRs obtained for the environments introduced in Figure 2 are presented. First, the result for the whole bandwidth is discussed. Subsequently, the results for sub-band 1 and sub-band 3 are presented.

|  |  |  |
| --- | --- | --- |
|  | Plastic Walls | PCB Walls |
| Small Box |  |  |
| Large Box |  |  |

Figure 4: Channel impulse responses for the full bandwidth between 270 GHz and 320 GHz

As introduced in the generic example in Figure 3, one strong main peak, corresponding to the direct transmission path between Tx and Rx, followed by a range of echoes from the casing walls is observed in all four cases. For the small box with plastic walls, the path loss of the main signal is as low as -20dB. In case of the large box, the path loss rises to about -30dB due to the additional propagation distance; furthermore, the far-field distance of the employed horn antennas is reached in the large box only. It can be observed that the path loss is around -30dB in case of the small box equipped with PCBs as well. This is due to the fact that the direct path between the antennas or, more precisely, the first Fresnel zone has been blocked by the building parts at the PCB surfaces. While the first echos arrive after around 1ns in the small box, the echoes in the large box arrive after 2 or more nanoseconds. The amplitude of the echo paths is only slightly influenced by the size of the box or the presence of PCBs.

|  |  |  |
| --- | --- | --- |
|  | Plastic Walls | PCB Walls |
| Small Box |  |  |
| Large Box |  |  |

Figure 5: Channel impulse responses for sub-band 1 between 270 GHz and 280 GHz

Comparing the impulse responses at full bandwidth to the impulse responses in sub-band 2 (Figure 5) and sub-band 3 (Figure 6), the lower temporal resolution of the impulse responses due to the smaller bandwidth of the sub-bands can be observed. It leads to a virtual pulse broadening which can be observed when comparing the impulse responses of the large box scenario with plastic walls. This effect is due to the missing temporal synchronization of the pulse delay to the time steps of the impulse responses; i.e. it can be compensated by receiver synchronization in a real transmission system.

|  |  |  |
| --- | --- | --- |
|  | Plastic Walls | PCB Walls |
| Small Box |  |  |
| Large Box |  |  |

Figure 6: Channel impulse responses for sub-band 2 between 290 GHz and 300 GHz

Apart from this, the behaviour of the main signal remains constant for both sub-bands when compared to the full bandwidth. The amplitude of the reflected paths varies clearly between the sub-bands for transmission inside the plastic boxes. For the small box, the multipath component at about 1ns after the main peak almost vanishes in sub-band 1. The same effect is observed for two multipath components at around 1.5ns after the main peak in the large box. Both multipath clusters are clearly present in sub-band 3. Looking at the scenarios with PCB walls, no significant difference exists between the sub-bands. This backs up the observation that the (systematically) varying channel behaviour is induced by the thin layers of the plastic casing rather than the PCB bulding parts.

### Significance of Scenario Definitions

It is assumed that the stochastic channel model under development will have varying statistical properties depending on the concrete operational environment. This assumption is based on the following observations from a measurement campaign comprising scenarios from two different operational modes for board-to-board communication. The operational mode Direct Transmission corresponds to the case of communication via a line-of-sight connection between a transmitter and a receiver mounted on two directly opposing surfaces. In the case of directed non-line-of-sight transmission, the signal is guided via a reflection inside the device due to the missing possibility of aligning the antennas. This could be the case if it is not possible to correctly align the antenna main lobes towards each other, for example, because building parts or edges of the casing are blocking the line of sight.

Two scenario realizations have been defined for each of the operational modes as depicted in Figure 7.

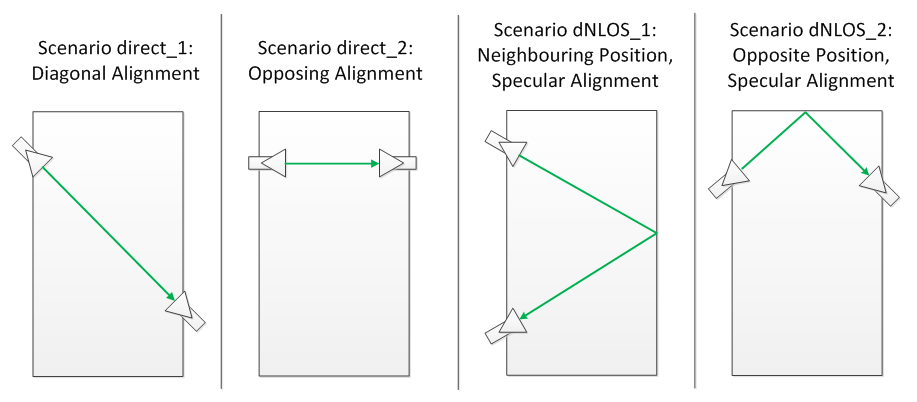


Figure 7: Scenario Definitions for the Operational Modes   
*Direct Transmission* (left) and directed *NLOS Transmission* (right)

For Direct Transmission, a diagonal positioning of Tx and Rx, corresponding to the scenario direct\_1, and a straight connection between directly opposing Tx and Rx, corresponding to scenario direct\_2, have been measured. For the mode of Directed NLOS Transmission, communication between two antennas mounted on the same surface via a guided reflection on the opposing wall, corresponding to scenario dNLOS\_1, and transmission between two opposing antennas via a reflection on a wall perpendicular to both antenna mounts, corresponding to scenario dNLOS\_2, have been measured.

Analoguous to 5.2.1, each scenario has been measured inside a large and a small environment, the dimensions of which can be found in [5.3]. Also, the environment was measured in two different configurations, with the first consisting of a full plastic environment and the second being equipped with two printed circuit boards at the front- and backside. This leads to a total number of four scenario realizations per scenario definition which are summarized exemplarily for scenario direct\_1 in Figure 2 in the above sub-chapter.

Figure 8 - Figure 11 show the measured CIRs for the scenario of Direct Transmission for all four scenario realizations. Each figure contains the measurement results from the first direct scenario in the top and the result from the second scenario in the lower sub-figure. Moreover, each scenario has been measured in two measurement runs that are plotted as a red and a green curve. The horizontal lines depict a threshold of -30dB below the strongest signal component; this threshold is used for the later on RMS delay spread calculations.



Figure 8: Measured CIRs of the Large Box with Plastic only   
Scenario *direct\_1* (top) , Scenario *direct\_2* (bottom)

For the large plastic box, it is observed that one dominant propagation path exists in the case of board-to-board communications with no obstructions. Its amplitude generally lies 20dB over that of the strongest echo path; most multipath components even vanish below the previously defined threshold.



Figure 9: Measured CIRs of the Large Box with PCBs   
Scenario *direct\_1* (top) , Scenario *direct\_2* (bottom)

When the scenario is equipped with printed circuit boards, it is observed that the general characteristics of the channel do not change. A clearly distinct main pulse remains visible while the amplitudes of the echo paths remain in the order of the -30dB threshold.



Figure 10: Measured CIRs of the Small Box with Plastic only   
Scenario *direct\_1* (top), Scenario *direct\_2* (bottom)

In a smaller environment, the echo clusters arrive earlier compared to the more spacious environment, thus the CIR ha s a temporally more compact form. The amplitudes of the echo paths remain at roughly the same level as ob served for the large environment.



Figure 11: Measured CIRs of the Small Box with PCBs   
Scenario *direct\_1* (top), Scenario *direct\_2* (bottom)

Again, inserting printed circuit boards into the environment does not much influence the channel behaviour. However, it must be noted that the amplitudes for the diagonal transmission in scenario direct\_1 drop from between -20dB and -30dB in Figure 10 to between -30dB and -40dB in Figure 11. This is most likely due to the fact that part of the first Fresnel Zone is blocked by building parts on the PCB surface in case of the narrow environment; however, no additional pulse broadening is observed from this.

Overall, the presence of printed circuit boards does not seem to have a significant impact to the direct line-of-sight communication channel; compared to the effects already observed for the plastic box, the multipath characteristics are not increased due to the insertion of PCBs.

As a figure of merit for the temporal characteristics of the LOS channel, Table 2 summarizes the RMS delay spreads that have been calculated from the measurements with respect to the abovely defined -30dB threshold.

Table 2: RMS Delay Spreads from the Direct Transmission Measurements

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Large ABS** | **Small ABS** | **Large PCB** | **Small PCB** |
| direct\_1, red | 0.241 ns | 0.019 ns | 0.036 ns | 0.126 ns |
| direct\_1, green | 0.164 ns | 0.113 ns | 0.020 ns | 0.065 ns |
| direct\_2, red | 0.197 ns | 0.097 ns | 0.215 ns | 0.099 ns |
| direct\_2, green | 0.089 ns | 0.107 ns | 0.225 ns | 0.110 ns |

One important characteristic of the presented values is their sensitivity regarding the level of the defined threshold. Comparing the delay spread values for scenario direct\_1 in the small box with ABS (green rectangle) to the values in the small box equipped with PCBs (red rectangle), it strikes that the value grows by a factor of six for the measurement corresponding to the green curve in FIGURE but shrinks by a factor of two for the measurement corresponding to the red curve when PCBs are inserted. Having a closer look at Figure 10 and Figure 11 reveals that this is due to the fact that some multipath components (marked with blue circles) exceed the defined threshold slightly while others don’t. Even though the overall characteristic of the impulse responses is the same in both cases, the calculated delay spreads suggest strong and also contradicting changes in the temporal channel behaviour. A consequence of this observations is that the channel model under development should be based on ray-tracing simulations and accompanied by verification measurements. Since there is no noise present in the case of simulations and the temporal position of the multipath components is exactly known, the definition of a threshold for e.g. delay spread calculations becomes obsolete.

Figure 12 - Figure 15 show the measured CIRs for the scenarios of Directed NLOS Transmission for all four scenario realizations.



Figure 12: Measured CIRs of the Large Box with Plastic only   
Scenario *dNLOS\_1* (top), Scenario *dNLOS\_2* (bottom)

Observing the results for the large environment, it is noticed that the main signal is clearly broadened due to the reflection on the plastic casing of the box. Apart from this significant difference to the LOS scenario, the multipath characteristics remain similar to the direct transmission case; it should however be noted that some rather strong multipath components are present in scenario dNLOS1.



Figure 13: Measured CIRs of the Large Box with PCBs  
Scenario *dNLOS\_1* (top), Scenario *dNLOS\_2* (bottom)

Inserting printed circuit boards into the environment may change the channel behaviour drastically for directed NLOS communications as seen in the above part of Figure 13. As the guided reflection takes place via a PCB surface now, the pulse broadening becomes more severe for the main pulse. In addition, the echo components increase in amplitude to la lavel of -5dB below the main signal. For scenario dNLOS\_2 the effects are much less significant as the reflection surface (short side-wall of the box) is still an ABS layer.



Figure 14: Measured CIRs of the Small Box with Plastic only   
Scenario *dNLOS\_1* (top), Scenario *dNLOS\_2* (bottom)

Looking at the results for the small boxes, it can be seen that, analoguous to the case of directed communications, the temporal structurce of the multipath components becomes more compact. For the main signal, a slight increase of the pulse broadening of the main pulse is observed compared to the large box measurement. This is due to the fact that a the larger reflection angle, resulting from the reduced distance between antennas and reflecting wall, leads to a longer path difference of the reflection processes at front- and backside of the reflecting plastic layer. Details regarding this behaviour can also be found in [5.2].



Figure 15: Measured CIRs of the Small Box with PCBs  
Scenario *dNLOS\_1* (top), Scenario *dNLOS\_2* (bottom)

From the measurement results of the small box equipped with PCBs, it becomes obvious that the impact of PCBs to the channel becomes less significant if the propagatio environments gets more narrow. However, a temporal spread of the main signal that stems from the scattering processes from the building parts throughout the board surface remains a main channel characteristic.

Concludingly, it is observed that the characteristics of directed NLOS communications vary significantly from those of the direct communications case. The guided reflection process impinges a pulse broadening of the main signal for both plastic and PCB guided reflections; moreover, the presence of scattering PCB surfaces has an impact on the temporal profile of the channel impulse response, especially in spacious environments.

Table 3 provides the results of the RMS delay spread calculations for the directed NLOS communication scenarios.

Table 3: RMS Delay Spreads from the Directed NLOS Transmission Measurements

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Large ABS** | **Small ABS** | **Large PCB** | **Small PCB** |
| dNLOS\_1, red | 0.367 ns | 0.099 ns | 0.758 ns | 0.122 ns |
| dNLOS\_1, green | 0.245 ns | 0.115 ns | 0.650 ns | 0.047 ns |
| dNLOS\_2, red | 0.072 ns | 0.036 ns | 0.026 ns | 0.027 ns |
| dNLOS\_2, green | 0.085 ns | 0.129 ns | 0.139 ns | 0.069 ns |

Under consideration of the measurement results presented in Chapters 5.2.1 and 5.2.2 a scientific base for the derivation of a stochastic channel model is established.

* The derivation of channel characteristics from measurements only leads to a number of issues, e.g. the presence of noise, the effects of IFFT leakage and the unknown position of multipath components in the measured signal. Thus, a ray-tracing approach is chosen for creating the channel statistics
* It has been shown that different operational modes lead to varying channel characteristics that need to be accounted for by separate channel statistics for separate use cases.

## Path loss model

## Antenna gain/pattern

## Scenario Definitions

### Direct Board-to-Board Communication

Transmission between two chips mounted on opposing surfaces

#### Angular Dispersion

#### Temporal Dispersion

#### Other

### Directed NLOS Board-toBoard Communication

Transmission between two chips with obstructed or without line of sight

#### Angular Dispersion

#### Temporal Dispersion

#### Other

### Chip-toChip Communication

Transmission between two chips mounted on the same surface

#### Angular Dispersion

#### Temporal Dispersion

#### Other

# Backhaul/Fronthaul

## Introductory Remarks

The mitigation of the high path loss at 300 GHz requires high gain antennas in the order of 40 dB at both sides of the link for a transmission distance of several hundred meters. This requires a LOS connection. In addition such high gain antennas are spatial filters, that supress multi path propagation at large. Fronthaul and backhaul links each require planning and some kind of coordination with national regulators. In IEEE 802. 15-15-0681-01-003d a simple worst case assessment for the required distance of objects to direct transmission path is illustrated. As long as these minimal distances are meta path loss model to evaluate the link budget is sufficient as an approximation.

## Path loss model

The relevant propagation mechanism in such an environment, which are contributing to increase the free space loss are described in [6.1]:

* Atmospheric gas attenuation
* Cloud and fog attenuation
* Rain attenuation

For terrestrial links it can be assumed that the link is operated below the height of clouds. The situation that a link penerates clouds may happen for example in some alpine regions with one transceiver at a high mountain, but it is unlikely, that ultra-high capacity links are required there. Therefore the attenuation by clouds may be less relevant. However, the influence of fog may be interest also for dense urban area.

### Calculation of the Overall Path Loss

The overall path loss at a distance d and a carrier frequency f can be modelled as:

(1)



where



### Specific Attenuation by Atmospheric Gases according to ITU-R P.676-10

Two methods are decribed in ITU-R P.676-10 [6.2]:

* A more detailed line –by-line calculation of gaseous attenuation
* A simplified method, based on curve-fitting of the line-by-line calculation agrees with the more accurate calculations to within an average of about ±10% at frequencies removed from the centres of major absorption lines. The absolute difference between the results from these algorithms and the line-by-line calculation is generally less than 0.1 dB/km and reaches a maximum of 0.7 dB/km near 60 GHz.

In the following the specific attenuation due to dry air and water vapour, is estimated using the simplified algorithms, valid for the frequency range 120 to 350 GHz:

The specific attenuation o due to dry air is calculated using the following equations:



(2)



(3)



(4)

Where *f*  frequency (GHz)

*rp* = *ptot*/1013, where *ptot* represents total air pressure

*rt* = 288/(273 + *t*)

*p*  pressure (hPa)

t  temperature (°C)

The specific attenuation w due to water vapour is calculated using the following equations:



(5)

(6)



(7)



(8)

where ρ is the water-vapour density (g/m3).

Exemplary result for the specific attenuation from 1 to 350 GHz at sea-level for dry air (p=1013 hPa, t=15°C) and water vapour with a density of =7.5 g/m3 (from [6.2])



Figure 7: Exemplary results for specific attenution due to dry air and water vapour

### Calculation Specific Attenuation R due to Rain according to ITU-R P. 838-3

The specific rain attenuation R is calculated according to according to ITU-R P. 838-3 [6.3]:

(9)



where:

*R* rain rate in mm/h

*k*  either *kH* or *kV* for horizontal and vertical polarization, respectively

α  either α*H* orα*V*. for horizontal and vertical polarization, respectively

Values for k and a for the frequencies 200, 300 and 400 GHz and horizontal/vertical polarization are given in Table 6.1

Table 6.1: Values for k and  in the frequency range 200-400 GHz

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Frequency (GHz) | *kh* | α*H* | *kV* | α*V* |
| 200 | 1.6378 | 0.6382 | 1.6443 | 0.6343 |
| 300 | 1.6286 | 0.6296 | 1.6286 | 0.6262 |
| 400 | 1.5860 | 0.6262 | 1.5820 | 0.6256 |

For linear and circular polarization, and for all path geometries, the coefficients in equation (9) can be calculated from the values given the previous table using the following equations



(10)

(11)



where  is the path elevation angle and  is the polarization tilt angle relative to the horizontal ( = 45° for circular polarization).

Typical rain rates for various rain intensities, which are required in equation (9) are listed in table 6.2.

Table 6.2: Typical rain rates [6.1, 6.4]

|  |  |  |
| --- | --- | --- |
| Type of Precipitation | Range of R (mm/h) | Intensity |
| Drizzle | R < 0,1 | Light |
| Drizzle | 0,1 < R < 0,5 | Moderate |
| Drizzle | R > 0,5 | Heavy |
| Rain | R < 2,5 | Light |
| Rain | 2,5 < R < 10 | Moderate |

Exemplary results for specific rain attenuation R at the carrier frequencies 200, 300 and 400 GHz are listed in Table 6.3

Table 6.3: Exemplary results for specific rain attenuation R

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| f/GHz | Horizontal Polarisation | | | Horizontal Polarisation | | |
| R/ mm/h | | | R/mm/h | | |
| 0,1 | 5 | 50 | 0,1 | 5 | 50 |
| 200 | 0,38 | 4,57 | 19,89 | 0,38 | 4,56 | 19,66 |
| 300 | 0,38 | 4,49 | 19,12 | 0,39 | 4,46 | 18,87 |
| 400 | 0,38 | 4,35 | 18,37 | 0,37 | 4,33 | 18,28 |

### Calculation of Attenuation due to Clouds and Fog

A calculation method is described in ITU-R 840-6 [6.5]:

The specific attenuation within a cloud or fog can be written as:

                dB/km (12)

where:

γ*c* : specific attenuation (dB/km) within the cloud

*Kl* : specific attenuation coefficient ((dB/km)/(g/m3))

*M* : liquid water density in the cloud or fog (g/m3).

At frequencies of the order of 100 GHz and above, attenuation due to fog may be significant. Typical water content for different fog types are listed in table 6.5.

Table 6.4: Typical liquid water density of fog types [6.5]

|  |  |
| --- | --- |
| Fog type | Typical liquid water density in g/cm3 |
| medium fog (visibility of the order of 300 m) | 0.05 |
| thick fog (visibility of the order of 50 m) | 0.5 |

A mathematical model based on Rayleigh scattering, which uses a double-Debye model for the dielectric permittivity ε ( *f*) of water, can be used to calculate the value of *Kl* for frequencies up to 1 000 GHz:

               (dB/km)/(g/m3) (13)

where *f* is the frequency (GHz), and:

 (14)

The complex dielectric permittivity of water is given by:

 (4)

 (15)

where:

ε0 = 77.66 + 103.3 (θ – 1) (16)

ε1 = 0.0671 (17)

ε2 = 3.52 (18)

θ = 300 / *T* (19)

with *T* the temperature (K).

The principal and secondary relaxation frequencies are:

*fp* = 20.20 – 146 (θ – 1) + 316 (θ – 1)2                GHz (20)

*fs* = 39.8*fp*                GHz (21)

In [6.6] some values for the average liquid water content of clouds are given, see table 6.5

Table 6.5: Liquid water content of cloud types [6.6]

|  |  |
| --- | --- |
| Cloud type | Average water content in g/cm3 |
| large cumulus | 2.5 |
| fair weather cumulus | 0.5 |
| Stratocumulus | 0.2 |
| Stratus | 0.2-0.3 |
| Altostratus | 0.2 |

## Antenna gain/pattern

In order to mitigate multipath propagation the applied antennas are required to have no side lobes wich are attenuated by less than 30 dB compared to the main antenna lobe. High gain antennas with very small HPBWs of some few degree, e.g. dish antennas, usually do not have any sidelobes.

## Scenario Definitions

### Xxx1

#### Angular Dispersion

#### Temporal Dispersion

#### Other

### Xxx2

#### Angular Dispersion

#### Temporal Dispersion

#### Other

### Xxx3

#### Angular Dispersion

#### Temporal Dispersion

#### Other











# Data Center

The wireless data center uses wireless data links to replace/complement the traditional cable connections, which brings various advantages e.g. high flexibility, low maintenance cost and favorable cooling environment. The high data rate requirement makes the THz technology a competitive candidate because of its high available bandwidth up to 50 GHz.

This document provides a realistic THz wireless channel model in a typical wireless data center scenario. The results presented here are based on [7.1] and [7.2].

As shown in Figure 7, the scenario consists of many server chassis (we assume the standard 1U rackmount chassis in this document), 4 walls and a roof (the 2 front walls and the ceiling are set invisible to illustrate the chassis). The stack height is assumed to be 1.8 m whereas the distance between 2 chassis in the x direction is 0 and in the y direction is 0.5 m. The transmitter (Tx) and the receiver (Rx) are marked as blue circles. A ray tracing simulator is applied to generate the THz channel model. Details of this ray tracing simulator are available in [7.3]. In our scenario, the material parameters of the wall and ceiling are taken from [7.3] whereas the chassis is assumed to be a perfect conductor. The floor is believed to absorb the signal. Using the ray tracing simulator calibrated for the frequency 300 GHz, the propagation channel can be obtained. In Figure 7, the propagation paths are illustrated as blue lines.

paper/figures/scenario.pdf

Figure 7: The data center scenario

## Propagation Path Types

Figure 8 illustrates the possible propagation path types. When the antennas are located on the chassis roof, the signal can be transmitted in a Line of Sight (LoS) path (type 1), or reflected on the ceiling (type 2). In case that Tx and Rx are placed on identical or adjacent chassis, the antenna can be mounted below the chassis roof (type 3) and the propagation path is either LoS or via a reflector to reduce the interference on the propagation path type 1 and 2.

**

Figure 8: Propagation path types

## Selection Between Path Types

When Tx and Rx are on identical or adjacent chassis, path type 3 would have advantage over type 1 and 2 because the lower antenna position produces less interference on other channels. If Tx and Rx are further departed therefore the antennas have to be placed on the chassis roof, type 2 is favorable if the propagation distance is limited whereas type 1 shows more advantage over a longer range. This selection is based on 2 considerations: 1) a shorter distance results in less free space propagation loss and therefore allows for additional reflection loss, 2) the elevation of path type 2 deviates from the horizontal direction more significantly with a shorter horizontal direction, therefore a vertically directive antenna would cause less interference on the horizontal LoS paths (because all the chassis have the identical size). We make the general suggestion that if the AoD/AoA elevation is at least 2 times the antenna Half Power Beam Width (HPBW) in the vertical direction away from the horizontal direction, type 2 has an advantage over type 1. The criterion should be adapted for every concrete scenario.

## Stochastic Channel Modelling

The stochastic channel modelling is based on massive ray tracing simulations. We choose a Tx position in the room corner (Tx 1) and in the room center (Tx 2) for propagation path type 1/2. For path type 3, we selected Tx and Rx positions randomly on identical or adjacent chassis.

Based on the simulation results, we derive a stochastic channel model in the following approach:

1. Determine number of propagation paths.
2. Assign a delay to each propagation path.
3. Determine the pathloss of each propagation path according to its delay.
4. Define the angular difference of each NLoS path to the LoS path.
5. Generate uniformly distributed phase for each path.
6. Generate frequency dispersion for each path.

In the following sections, we will explain the process step by step to obtain the stochastic channel model.

### Path Numbers

There is always 1 LoS path. The empirical distributions of the numbers of NLoS paths are presented in Table 1.

***Table 1 NLoS Path number distributions***

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Type 1/2, Tx 1 | | | | | | | | | | | | | | | | |
| Number of paths | 17 | | | 18 | | | 19 | | | | 20 | | | 21 | | |
| Probability (%) | 27 | | | 35 | | | 22 | | | | 15 | | | 1 | | |
| Type 1/2, Tx 2 | | | | | | | | | | | | | | | | |
| Number of paths | 16 | | 17 | | | 18 | | | 19 | | | 20 | | | 21 | |
| Probability (%) | 32 | | 29 | | | 12 | | | 16 | | | 8 | | | 3 | |
| Type 3 | | | | | | | | | | | | | | | | |
| Number of paths | 3 | 4 | | | 5 | 6 | | 7 | | 8 | | 9 | 10 | | | 11 |
| Probability (%) | 22 | 13 | | | 8 | 15 | | 8 | | 17 | | 8 | 6 | | | 3 |

### Delay distribution

Figure 9 illustrates the delay distributions. Note that the LoS delay is the absolute value whereas the NLoS delay is the relative delay, i.e. the difference between the NLoS delay and the corresponding LoS delay.

|  |  |  |
| --- | --- | --- |
| paper/figures/delay_distribution/delay_distribution_type12_1.emf  *(a) Type 1/2, Tx 1* | paper/figures/delay_distribution/delay_distribution_type12_2.emf  *(b) Type 1/2, Tx 2*  Figure 9: Delay distributions | paper/figures/delay_distribution/delay_distribution_type3.emf  *(c) Type 3* |

Table 2 lists the distribution types and the corresponding parameter values.

***Table 2 Delay distributions***

|  |  |  |
| --- | --- | --- |
| Path | Distribution | Parameters |
| Type 1/2, Tx 1, LoS | Normal distribution | μ=2.26x10-8, σ=8.76x10-9 |
| Type 1/2, Tx 1, NLoS | Negative EXP | λ=8.76x109 |
| Type 1/2, Tx 2, LoS | Normal distribution | μ=1.20x10-8, σ=4.56x10-9 |
| Type 1/2, Tx 2, NLoS | Normal distribution | μ=2.98x10-8, σ=1.79x10-9 |
| Type 3, LoS | Normal distribution | μ=1.80x10-8, σ=8.60x10-9 |
| Type 3, NLoS | Negative EXP | λ=4.92x107 |

### Delay-Pathloss Correlation

The delay has a positive correlation with the pathloss, as depicted in Figure 10. As in the last section, the pathlosses and delays for the LoS paths are absolute values whereas the NLoS carries relative pathlosses and delays. The definition of the relative pathloss is the pathloss of the considered path divided by the pathloss of the corresponding LoS pathloss.

|  |  |  |
| --- | --- | --- |
| *(a) Type 1/2, Tx 1* | *(b) Type 1/2, Tx 2*  Figure 10: Delay-pathloss distributions | *(c) Type 3* |
|  |  |  |

Table 3 illustrates the relationship between delay and pathloss. The subscript “r” stands for “relative”. The relationship between delay and path loss for the LoS paths can be completely described by the Friss equation. Therefore the random part is 0. For the NLoS paths, the additional loss due to reflections etc. contributes to the random part.

***Table 3 Delay-pathloss relationship***

|  |  |  |
| --- | --- | --- |
| Path | Deterministic part | Random part |
| Type 1/2, Tx 1, LoS | p=-20log10(d)-71.52 | σ=0 |
| Type 1/2, Tx 1, NLoS | pr=-0.294dr-17.44 | σ=4 |
| Type 1/2, Tx 2, LoS | p=-20log10(d)-71.52 | σ=0 |
| Type 1/2, Tx 2, NLoS | pr=-0.385dr-17.95 | σ=4 |
| Type 3, LoS | p=-20log10(d)-71.52 | σ=0 |
| Type 3, NLoS | pr=-0.429dr-30.30 | σ=6 |

With delays for every path available from the last section, the pathloss can be derived from Table 3.

### Pathloss-angle Correlation

The simulation shows some certain degree of correlation between pathloss and the angular difference between the considered NLoS path and the corresponding LoS path. This correlation is important because it has impact on the spatial filtering performance of the directive antennas. The relative probabilities of antenna angles as a function of path loss are depicted in Figure 11 and the numbers are listed in Table 4.

|  |  |  |
| --- | --- | --- |
| *(a) Type 1/2, Tx 1* | *(b) Type 1/2, Tx 2*  Figure 11: Relative Probabilities of Antenna Angle as a Function of Path Loss | *(c) Type 3* |
|  |  |  |

Table 4: Relative Probabilites of Antenna Angles versus Path Loss

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Type 1/2, Tx 1 | | | | | | | | |
| Relative pathloss (dB) | | | | | | | | |
| Angular difference (°) | -70 | -60 | -50 | -40 | -30 | -20 | -10 | 0 |
| 0 | 0.000 | 0.000 | 0.054 | 0.062 | 0.065 | 0.014 | 0.257 | 0.000 |
| 10 | 0.000 | 0.000 | 0.023 | 0.029 | 0.082 | 0.067 | 0.274 | 0.360 |
| 20 | 0.000 | 0.000 | 0.000 | 0.020 | 0.052 | 0.061 | 0.031 | 0.360 |
| 30 | 0.000 | 0.118 | 0.008 | 0.058 | 0.113 | 0.082 | 0.120 | 0.280 |
| 40 | 0.000 | 0.000 | 0.000 | 0.031 | 0.084 | 0.055 | 0.067 | 0.000 |
| 50 | 0.000 | 0.000 | 0.023 | 0.036 | 0.039 | 0.084 | 0.036 | 0.000 |
| 60 | 0.000 | 0.118 | 0.078 | 0.016 | 0.030 | 0.131 | 0.016 | 0.000 |
| 70 | 0.000 | 0.059 | 0.085 | 0.062 | 0.047 | 0.178 | 0.000 | 0.000 |
| 80 | 0.000 | 0.000 | 0.109 | 0.102 | 0.131 | 0.090 | 0.000 | 0.000 |
| 90 | 0.000 | 0.059 | 0.132 | 0.122 | 0.080 | 0.027 | 0.023 | 0.000 |
| 100 | 0.000 | 0.059 | 0.070 | 0.049 | 0.049 | 0.033 | 0.031 | 0.000 |
| 110 | 0.249 | 0.059 | 0.078 | 0.049 | 0.039 | 0.027 | 0.029 | 0.000 |
| 120 | 0.000 | 0.059 | 0.062 | 0.067 | 0.026 | 0.023 | 0.020 | 0.000 |
| 130 | 0.249 | 0.176 | 0.101 | 0.084 | 0.026 | 0.020 | 0.022 | 0.000 |
| 140 | 0.249 | 0.000 | 0.047 | 0.067 | 0.025 | 0.019 | 0.015 | 0.000 |
| 150 | 0.249 | 0.235 | 0.062 | 0.062 | 0.032 | 0.017 | 0.013 | 0.000 |
| 160 | 0.000 | 0.059 | 0.039 | 0.027 | 0.027 | 0.027 | 0.015 | 0.000 |
| 170 | 0.000 | 0.000 | 0.016 | 0.029 | 0.029 | 0.027 | 0.019 | 0.000 |
| 180 | 0.000 | 0.000 | 0.016 | 0.026 | 0.024 | 0.019 | 0.013 | 0.000 |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Type 1/2, Tx 2 | | | | | | | | |
| Relative pathloss (dB) | | | | | | | | |
| Angular difference (°) | -70 | -60 | -50 | -40 | -30 | -20 | -10 | 0 |
| 0 | 0.053 | 0.000 | 0.026 | 0.017 | 0.054 | 0.015 | 0.021 | 0.000 |
| 10 | 0.053 | 0.000 | 0.000 | 0.017 | 0.070 | 0.027 | 0.041 | 0.051 |
| 20 | 0.053 | 0.000 | 0.053 | 0.044 | 0.093 | 0.045 | 0.079 | 0.039 |
| 30 | 0.053 | 0.000 | 0.053 | 0.048 | 0.075 | 0.123 | 0.100 | 0.000 |
| 40 | 0.053 | 0.000 | 0.026 | 0.065 | 0.074 | 0.089 | 0.108 | 0.100 |
| 50 | 0.053 | 0.000 | 0.026 | 0.072 | 0.050 | 0.065 | 0.121 | 0.248 |
| 60 | 0.053 | 0.000 | 0.053 | 0.075 | 0.060 | 0.056 | 0.137 | 0.129 |
| 70 | 0.053 | 0.000 | 0.132 | 0.140 | 0.055 | 0.035 | 0.165 | 0.000 |
| 80 | 0.053 | 0.000 | 0.184 | 0.130 | 0.051 | 0.117 | 0.085 | 0.003 |
| 90 | 0.053 | 0.748 | 0.145 | 0.106 | 0.093 | 0.065 | 0.034 | 0.039 |
| 100 | 0.053 | 0.000 | 0.066 | 0.072 | 0.039 | 0.054 | 0.023 | 0.071 |
| 110 | 0.053 | 0.000 | 0.000 | 0.027 | 0.043 | 0.053 | 0.020 | 0.058 |
| 120 | 0.053 | 0.000 | 0.053 | 0.041 | 0.056 | 0.056 | 0.012 | 0.058 |
| 130 | 0.053 | 0.000 | 0.092 | 0.068 | 0.045 | 0.034 | 0.013 | 0.039 |
| 140 | 0.053 | 0.000 | 0.039 | 0.041 | 0.046 | 0.035 | 0.012 | 0.045 |
| 150 | 0.053 | 0.250 | 0.026 | 0.010 | 0.030 | 0.029 | 0.013 | 0.026 |
| 160 | 0.053 | 0.000 | 0.000 | 0.000 | 0.028 | 0.041 | 0.005 | 0.058 |
| 170 | 0.053 | 0.000 | 0.000 | 0.014 | 0.023 | 0.031 | 0.007 | 0.019 |
| 180 | 0.053 | 0.000 | 0.026 | 0.014 | 0.016 | 0.027 | 0.006 | 0.019 |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Type 3 | | | | | | | | |
| Relative pathloss (dB) | | | | | | | | |
| Angular difference (°) | -70 | -60 | -50 | -40 | -30 | -20 | -10 | 0 |
| 0 | 0.062 | 0.045 | 0.000 | 0.000 | 0.000 | 0.000 | 0.003 | 0.002 |
| 10 | 0.000 | 0.091 | 0.049 | 0.054 | 0.005 | 0.006 | 0.000 | 0.000 |
| 20 | 0.125 | 0.136 | 0.024 | 0.027 | 0.005 | 0.004 | 0.000 | 0.000 |
| 30 | 0.062 | 0.091 | 0.024 | 0.000 | 0.016 | 0.000 | 0.004 | 0.003 |
| 40 | 0.000 | 0.091 | 0.073 | 0.000 | 0.033 | 0.013 | 0.006 | 0.006 |
| 50 | 0.000 | 0.136 | 0.000 | 0.000 | 0.030 | 0.006 | 0.047 | 0.028 |
| 60 | 0.000 | 0.000 | 0.049 | 0.000 | 0.025 | 0.011 | 0.013 | 0.006 |
| 70 | 0.000 | 0.000 | 0.000 | 0.054 | 0.027 | 0.032 | 0.003 | 0.047 |
| 80 | 0.000 | 0.000 | 0.122 | 0.000 | 0.019 | 0.015 | 0.131 | 0.069 |
| 90 | 0.000 | 0.091 | 0.439 | 0.675 | 0.692 | 0.877 | 0.780 | 0.820 |
| 100 | 0.000 | 0.182 | 0.049 | 0.000 | 0.005 | 0.004 | 0.004 | 0.001 |
| 110 | 0.062 | 0.000 | 0.049 | 0.081 | 0.033 | 0.000 | 0.001 | 0.002 |
| 120 | 0.125 | 0.091 | 0.073 | 0.000 | 0.033 | 0.002 | 0.000 | 0.005 |
| 130 | 0.187 | 0.000 | 0.024 | 0.081 | 0.027 | 0.004 | 0.003 | 0.009 |
| 140 | 0.062 | 0.000 | 0.024 | 0.027 | 0.025 | 0.000 | 0.003 | 0.001 |
| 150 | 0.187 | 0.000 | 0.000 | 0.000 | 0.016 | 0.000 | 0.000 | 0.000 |
| 160 | 0.062 | 0.045 | 0.000 | 0.000 | 0.005 | 0.006 | 0.000 | 0.000 |
| 170 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.019 | 0.000 | 0.000 |
| 180 | 0.062 | 0.000 | 0.000 | 0.000 | 0.003 | 0.000 | 0.001 | 0.000 |

The angular difference can be determined given the pathloss from the last section.

### Phase and Frequency Dispersion

The phase can be safely assumed to be uniformly distributed. The frequency dispersion can be described by

where f0 and g0 are the reference frequency and the channel gain at the reference frequency, respectively.























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