HORIZON 2020

	Deliverable ID: D4.3	Preparation date: 24 February 2020
	Milestone: final proposed	
	Title: **Initial Characterisation of Systems**	
Terahertz based Ultra High Bandwidth Wireless Access Networks	Editor/Lead beneficiary (name/partner): Johannes Eckhardt / TUBS	
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	Approved by: PSC	

Dissemination level		
PU	Public	x
CO	Confidential, only for members of the consortium (including Commission Services)	

Revisions

Version	Date	Author	Organisation	Details
1.0	31.01.19	Johannes Eckhardt	TUBS	structure and first chapters added
2.0	18.02.10	Johannes Eckhardt	TUBS	Final proposed
3.0	25.02.19	Thomas Kürner	TUBS	Small Changes included

The research leading to these results has received funding from the EU H2020 under grant agreement n° 761579.

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Executive summary

This deliverable presents the extensive measurement campaign carried out in June 2019 in the data center of Dell EMC in Ireland by the Technische Universität Braunschweig and some recent results. At first, some general information is presented as well as the classification of the measurement setups. The general characterisation measurements focus on universal propagation effects in the data centre whereas the Top-of-Rack measurements emulate a realistic data transmission scenario. Two measurement methods are used for each class. The point-to-point measurements have a fixed setup where the transmitter and receiver are mounted on top of tripods. The full-omni rotational measurements use a rotation unit to scan the whole horizontal plane and allow in this way a spatial analysis of the channel. The recent results prove that a communication at 300 GHz in a data centre in general is possible from the channel's perspective. Due to difficulties with the calibration process, the analysis shown in this document is limited to setups where the above mentioned intrinsic impulse response of the channel sounder does not influence the results. The optimisation of the calibration process is currently in progress both in TERAPOD and other THz projects. An update of the results will be included in D4.4.

1 Introduction

1.1 Summary

This deliverable presents the extensive measurement campaign carried out in June 2019 in the data center of Dell EMC in Cork/Ireland by the Technische Universität Braunschweig and some recent results. At first, some general information is presented as well as the classification of the measurement setups. The general characterisation measurements focus on universal propagation effects in the data centre whereas the Top-of-Rack measurements emulate a realistic data transmission scenario. Two measurement methods are used for each class. The point-to-point measurements have a fixed setup where the transmitter and receiver are mounted on top of tripods. The full-omni rotational measurements use a rotation unit to scan the whole horizontal plane and allow in this way a spatial analysis of the channel. The recent results prove that a communication at 300 GHz in a data centre in general is possible from the channel's perspective.

1.2 Structure of this document

The deliverable is organised as follows: Chapter 2 presents some general background information and the measurement equipment. From chapter 3 to chapter 5 the individual measurement setups are described in detail. Chapter 6 shows recent results of the evaluation process, and chapter 7 finally concludes the deliverable.

1.3 Relationships with other deliverables

The content presented in this document relates on the following deliverables:

- D2.1 – Initial Requirements and Scenario Specification

1.4 Contributors

The following partners have contributed to this deliverable:

- Johannes Eckhardt, TUBS
- Tobias Doeker, TUBS
- Thomas Kürner, TUBS

1.5 Acronyms and abbreviations

B2B – Back-to-Back measurement

DC – Data Centre

FO – Full-Omi 360° rotational measurement

FSPL – Free space path loss

GC – General Characterisation measurement

ISI – intersymbol interference

LOS – line-of-sight

MPC – Multipath component

NLOS – non line-of-sight

P2P – Point-to-Point

PAS – Power Angular Spectrum

PDP – Power Delay Profile

RX – receiver

ToR – Top-of-Rack

TX – transmitter
TZC – Time Zero Calibration

2 Measurement Campaign

The integration of wireless links in a Data Centre (DC) raises the need for appropriate channel models in the sub-mmWave range in order to adapt the communication system to its environment. Therefore the WP4 T4.2 aims at developing these channel models based on ray-tracing simulations and measurements. The information obtained from measurements is a necessary and indispensable component for the development of realistic channel models. This deliverable presents the measurement campaign that was performed in the Dell EMC Research Data Centre in Cork, Ireland and the TSSG Data Centre in Waterford, Ireland by the Technische Universität Braunschweig and the recent evaluation results.

The measurement campaign started the 31st May 2018 and finished the 21st June 2018. The ultra-wide band (UWB) sub-mmWave channel sounder and the necessary support equipment were transported in a van and via ferry from Braunschweig to Cork and Waterford.

Since the rack represents the basic unit from the data centre operator point of view, the measurement setups were classified into two categories, the inter-rack communication and the intra-rack communication. The inter-rack communication is then further divided into general characterisation measurements (GC) and top-of-rack measurements (ToR) as shown in Figure 1 Classification of measuremFigure 1 .

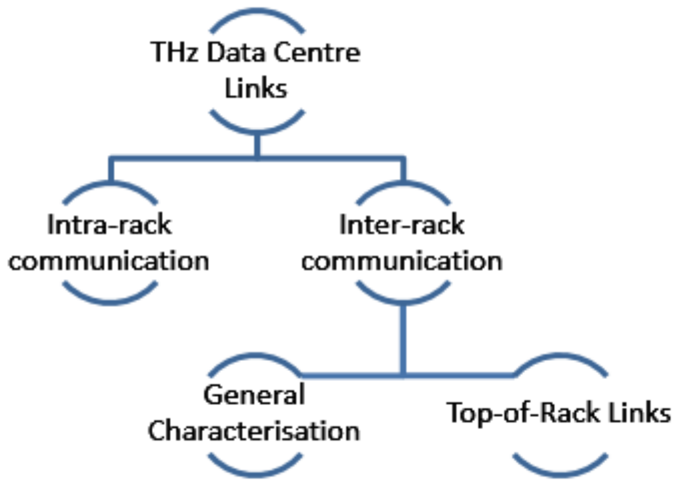

Figure 1 Classification of measurements

The GC measurements aim at investigating general propagation characteristics in the DC, especially the electromagnetic properties of the racks. These measurements will be used to calibrate and validate raytracing simulations. In contrast, the ToR measurements emulate a real data transmission scenario on the top of DC racks quantifying the radio channel for wireless DC applications. For each inter-rack scenario, measurements were performed in a Point-to-Point (P2P) configuration and a Full-Omni 360° (FO) rotational measurement. More than 26 different measurement setups were performed where the main groups are listed in Table 1.

The Dell EMC Research Data Centre is a thermally efficient data centre where the racks are allocated in rows. Plastic curtains separate the cold air that is streamed out of the floor into the DC, and the hot air which comes out of the back of the racks. To have a fixed reference for all measurements in the data centre, a coordinate systems was defined and the whole environment, like the position of the racks, all TX positions, RX positions were documented in reference to this coordinate system. A map of the data centre was drawn that enables the creation of a 3D model of the data centre. That model will be used to perform ray tracing simulations as part of WP4 T4.2.2.

The measurements were performed with the UWB real-time sub-mmWave channel sounder. It consists of a base unit, a control laptop and several UWB transmitters (TX) and receivers (RX) that are equipped with sub-mmWave frontends. The base unit distributes a 9.22 GHz clock signal to all TX and RX via a multi-function cable of 10 m length to guarantee a time stable operation. A pseudo random test sequence with a bandwidth of approximately 8 GHz is generated in the TX and converted to a centre frequency of 304 GHz. The signal is then transmitted via horn antennas and received by the RX. After the down conversion the received signal is sampled using the subsampling principle with a factor of 128. The cross correlation is performed offline on the control computer in order to calculate the time variant impulse response of the radio channel. More information on the channel sounder can be found in [1].

Every time the channel sounder is switched on, two types of calibration need to be done. The first type is a time zero calibration (TZC), where the relative delay between the individual UWB nodes is measured. The second type is the back-to-back calibration (B2B) that measures the intrinsic impulse response of the channel sounder system. Therefore TX and RX are connected via waveguides as shown in Figure 2. The intrinsic impulse response is then compensated by deconvolution in the post processing. However, due to probably nonlinear effects and phase shifts caused by setup change, the calibration process needs some further improvement.

Figure 2: Back-to-Back configuration for the calibration

Table 1: List of measurement setups

Name	Type	Characteristic	Duration	Location
GC	FO	Long distance, cold aisle	12 h	Dell
GC	FO	Short distance, cold, aisle, vertical polarisation	12 h	Dell
GC	FO	Short distance, cold aisle, horizontal polarisation	12 h	Dell
GC	FO	Long distance, hot aisle	12 h	Dell
GC	P2P	Reflection and transmission meas.	8 h	Dell
ToR	FO	Same aisle, vertical polarisation	12 h	Dell
ToR	FO	Adjacent aisle, vertical polarisation	12 h	Dell
ToR	FO	Adjacent aisle, horizontal polarisation	12 h	Dell
ToR	FO	Next to adjacent aisle, horizontal pol.	12 h	Dell
ToR	FO	Next to adjacent aisle, vertical pol.	12 h	Dell
ToR	P2P	Transmission and interference meas.	8 h	Dell
Intra-rack	P2P	Various distances / numbers of servers	8 h	Dell
ToR	P2P	Various distances / heights	8 h	TSSG
GC	P2P	Various angles, vertical polarisation	8 h	TSSG

Name	Type	Characteristic	Duration	Location
GC	P2P	Various angles, horizontal polarisation	8 h	TSSG

3 General Characterisation Measurements

3.1 Point-to-Point Measurements

In the P2P measurements one TX and one RX are used. Both are mounted on top of a tripod and aligned according to the prepared measurement setup. The position and the orientation as well as a short description are documented. 512 to 2048 impulse responses are saved to increase the signal-to-noise ratio (SNR). For this setup high gain antennas with a gain of 26 dBi and a half power beam width (HPBW) of 8° are used. The first GC P2P measurement characterises the reflection of the floor and the ceiling. Therefore TX and RX are placed in the main aisle and the direct path is measured that serves as a reference measurement as shown in Figure 3. Then the elevation of TX and RX is adjusted such that the specular reflection from the floor and the ceiling are measured. This will give a reference for the raytracing simulation that will be performed in WP4 T2.2.2.

Figure 3: Reference measurement of the floor and ceiling reflection

The second GC P2P measurement looked at the reflection and the transmission effects of the plastic curtains. Therefore TX and RX were placed in the same aisle pointing to the same direction. In the radar like measurement mode the reflection from the individual rows of curtain were investigated as presented in Figure 4.

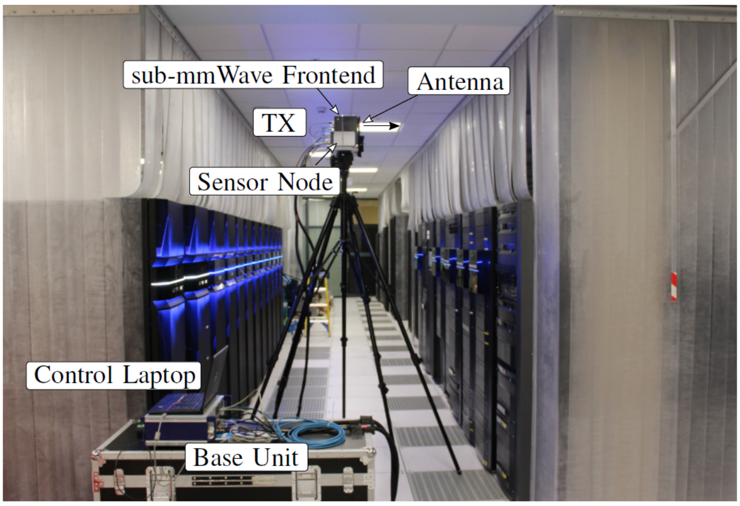

Figure 4 : Reflection measurement of the plastic curtains

The maximum transmission measurement was performed by placing the TX and RX in a distance of 10.7 m with four rack rows in between. The last GC P2P configuration realises transmission between TX and RX in a non-line-of-sight (NLOS) condition via a reflector. This measurement investigates how transmission in a DC under an NLOS condition can be made possible. TX and RX point towards the specular reflection point of the neighbouring row as shown in Figure 5. A metal reflector is placed at the specular reflection point to compare the reflections on the front of the racks to the reflection on a metal plate. In a similar scenario TX and RX are placed in adjacent aisles and a connection is realised via a first order reflection on a metal plate.

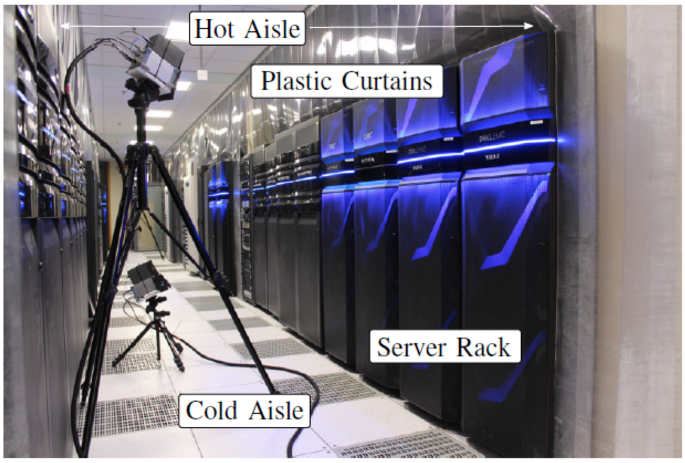

Figure 5: GC P2P setup to investigate NLOS transmission

3.2 Full-Omni Rotational Measurements

The FO measurements use two automatic rotation units to turn TX and RX stepwise with a selectable step size. In this way the whole horizontal plane can be sampled and spatial analysis of the channel becomes possible. The FO measurements use the same antenna as the GC P2P measurements with a gain of 26 dBi and a HPBW of 8° and last 12 h each. Therefore the angular step is set to 8°, too. The individual measurement setups are listed in Table 2. The identifiers are explained as follows: long (l), short (s) measurement distance; cold (c), hot (h) aisle temperature; vertical (v), horizontal (h) polarisation. Figure 6 shows the GC FO scv setup.

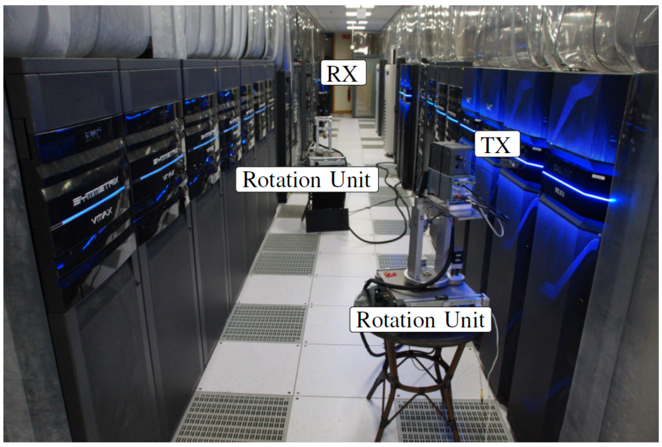

Figure 6: GC FO scv measurement setup

Table 2: List if GC FO setups

identifier	d/m	$\vartheta_{\mathrm{TX}}/°\mathrm{C}$	$\vartheta_{\mathrm{RX}}/°\mathrm{C}$	polarisation
GC FO lcv	12.52	26.6	26.6	vertical
GC FO scv	3.66	26.6	26.6	vertical
GC FO sch	3.66	26.6	26.6	horizontal
GC FO lhv	12.47	30.4	30.4	vertical

4 Top-of-Rack Measurements

4.1 Point-to-Point Measurements

In contrast to the earlier mentioned GC measurements, the ToR setups emulate data transmission in a realistic scenario. The space above the racks offers the least obstructed area in the DC and is therefore appropriate for wireless data transmission. Furthermore, the majority of the data traffic between racks passes the top-of-rack switch which is located at the top of the rack. This enables an easy interface to the present rack architecture. The TX is placed on top of a rack at the end of an aisle. The RX is placed on top of the adjacent rack in the same aisle and TX and RX are oriented towards each other as shown in Figure 7. For every measurement the distance between TX and RX is increased by one rack until the distance reaches the maximum distance of interest of 10 m as defined in D2.1. TX is placed on the adjacent row of racks and the measurements are repeated for the different distances, now with TX and RX on adjacent rows.

Figure 7: Setup of the ToR P2P measurements

In the case of many links operating in parallel in a DC, the question of interference between those links becomes important. In theory, the antenna diagram acts as a spatial filter and reduces the interference as long as the transmitters are located in different spatial directions. The antenna diagram should contain all information on the received power of interference. Nevertheless, interference measurements have been performed to validate this assumption. The difference to the setups described above is shown in the fact that TX is oriented to a virtual receiver in the same row of racks whereas RX is oriented towards TX to measure the incident power from this foreign TX. A schematic view of the measurement setup is shown in Figure 8.

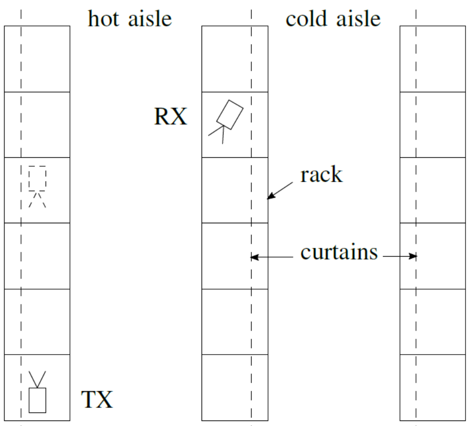

Figure 8: Schematic top view of the P2P interference setup

4.2 Full-Omni Rotational Measurements

The FO measurements have the same purpose as described in section 3.2. The characterisation of the whole horizontal plane above the racks gives the possibility to analyse the propagation channel in time and in space for this application case. The rotation units are lifted to a height of the antenna of 2.10 m whereas the standard rack height is 1.90 m. Measurements are performed for a configuration where TX and RX are in the same aisle, TX and RX are in adjacent aisles (see Figure 9) and TX is shifted one aisle further to the next to adjacent aisle. The detailed configurations are listed in Table 3 with the following explanations: same aisle (sa), adjacent aisle (aa), next to adjacent aisle (ntaa); vertical (v), horizontal (h) polarisation.

Figure 9: Setup of the ToR FO aav measurement

Table 3: List of ToR FO setups

identifier	d/m	$\vartheta_{\mathrm{TX}}/°\mathrm{C}$	$\vartheta_{\mathrm{RX}}/°\mathrm{C}$	polarisation
ToR FO sav	3.68	26.6	26.6	vertical
ToR FO aav	4.56	30.4	26.6	vertical
ToR FO aah	4.56	30.4	26.6	horizontal
ToR FO ntaav	7.33	21.9	26.6	vertical
ToR FO ntaah	7.33	21.9	26.6	horizontal

5 Intra-Rack Measurements

The intra-rack communication deals with the second category of wireless data transmission in a DC where data transmission takes place from one server to another server in the same rack. For the reason of space limitations, only P2P measurements were possible in this scenario. The main interest is the investigation of the influence of the number of servers and the distance between TX and RX. Measurements have been performed for a short distance of 0.32 m (see Figure 10 left), a medium distance of 0.64 m (see Figure 10 middle) and a long distance of 1.00 m between TX and RX (see Figure 10 right). At least one server, and up to six servers, were placed in between TX and RX. The impulse response were recorded for 17 different configurations.

Figure 10: setup of the intra-rack measurements with one server, four servers and six servers

6 Recent Results

Since the measurement campaign covers a high number of different scenarios, the most important results and effects will be presented here. Some of these results will be presented in [2]. Due to difficulties with the calibration process, the temporal analysis is limited to setups where the above mentioned intrinsic impulse response of the channel sounder does not influence the results. The optimisation of the calibration process is currently in progress both in TERAPOD and other THz projects. An update of the results will be included in D4.4.

The use cases defined in D2.1 are based on the assumption that the radio channel in a DC is static. The evaluation of the time-variant power delay profile (PDP), the squared absolute value of the impulse response, presented in Figure 11 shows that this assumption can be confirmed. For a static scenario the radio channel does not change over the absolute time in a DC.

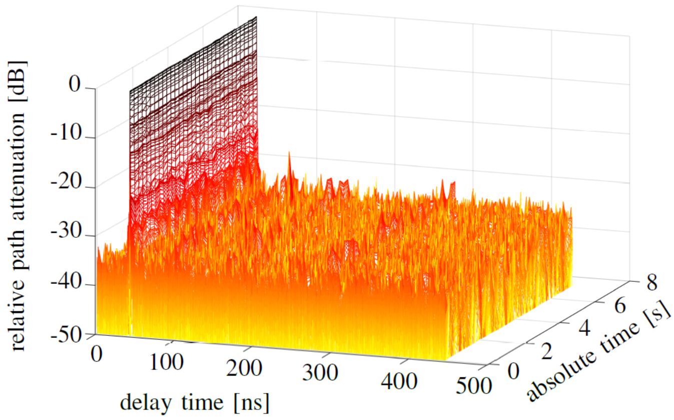

Figure 11: Normalised time-variant PDP of the GC FO lcv direct path measurement

The high path attenuation is a major challenge in the design process of a communications system in the THz range. The evaluation of all direct path measurements of the FO measurements shows that for a line-of-sight (LOS) scenario the absolute path attenuation corresponds well to the formula of the free space path loss (FSPL) given by

$$G_{\mathrm{FSPL,dB}} = 20\log_{10}\left(\frac{\lambda}{4\pi\, r}\right)$$

with λ denoting the wavelength and r denoting the distance between TX and RX. This relation is visualised in Figure 12 that also shows a maximum error of 2.95 dB.

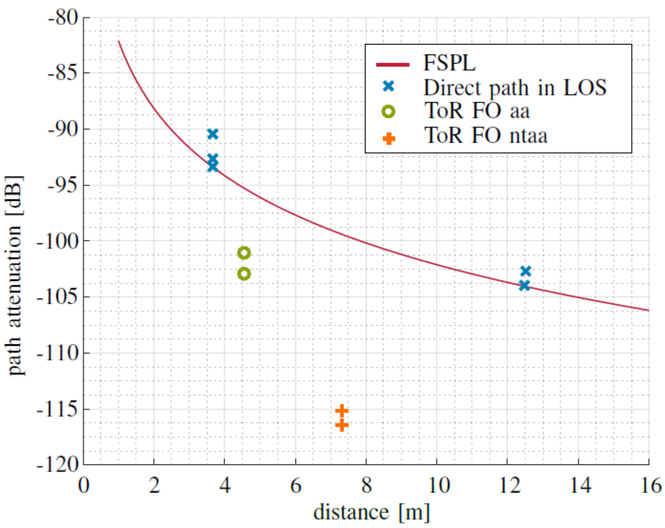

Figure 12: Absolute path attenuation of all FO direct path measurements

The red line shows the FSPL as a function of the distance, the blue crosses illustrate all direct paths in a LOS scenario, the green circles represent the ToR FO aa measurements and the orange plus the ToR FO ntaa measurements. The ToR FO aa and the ToR FO ntaa, being measurements in a non-line-of-sight (NLOS) scenario, show an additional attenuation of 7 dB for each row of curtains between TX and RX. However, the absolute path attenuation stays in a range where data transmission with directive antennas is feasible.

The influence of the plastic curtains has further been investigated in the GC P2P reflection measurement. TX and RX where placed in the same aisle with the same orientation in a distance of 0.28 m as shown in Figure 13. The PDP obtained from this measurement is presented in Figure 14. It demonstrates well three characteristic peaks with a delay of 6.62 ns, 34.36 ns and 47.09 ns, respectively, which correspond to twice the distance of the next three rows of curtains. The maximum absolute error in the distance is given by 0.046 m.

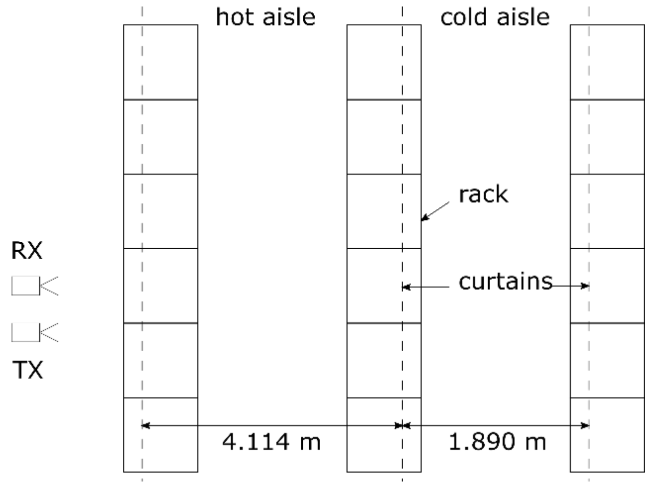

Figure 13: Schematic view of the GC P2P reflection measurement

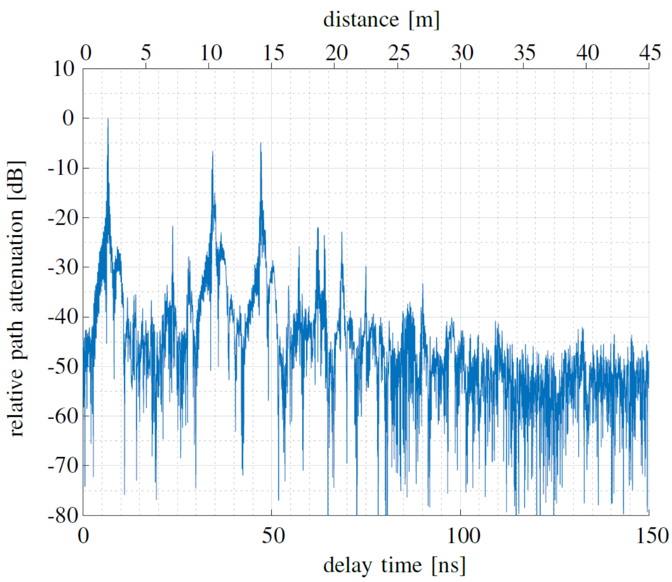

Figure 14: PDP of the GC P2P reflection measurement

A second reflection measurement, where TX and RX pointed towards the specular reflection point of the first row of curtains with an incidence angle of 8°, showed that the reflected power highly depends on the angle between the wave vector and the normal to the curtains. The power reflected by the first row increased by 9.2 dB, whereas the power reflected by the second and the third row decreased by 11.4 dB and 17.7 dB, respectively. The presented P2P measurements prove good correlation between the DC's geometry and the obtained results. This fact encourages the use of raytracing tools for the simulation of the wave propagation in DC as planned in T4.2.2.

The correlation of the measurement data and the environment is also reflected in the spatial analysis of the FO measurements. The power angular spectrum (PAS) plots the received power normalised to the maximum received power as function of the angle of arrival (AoA) and the angle of departure (AoD) which are organised clockwise. The direct path is arranged at the AoA and the AoD of 0° and 0°, respectively. A comparison of the GC FO lcv, where TX and RX are set to a distance of 12.52 m, and the GC FO scv with a distance of 3.66 m in the same aisle is shown in Figure 15. For a better comparison, the PAS of the GC FO lcv is also normalised with respect to the maximum of the GC FO scv. It can be seen that the power is more focused around the direct path and for the longer distance whereas the PAS for the short distance shows a bigger spread. This observation agrees with the change in the geometry since the scenario is stretched for the longer distance and the propagation paths depart and arrive at smaller angles.

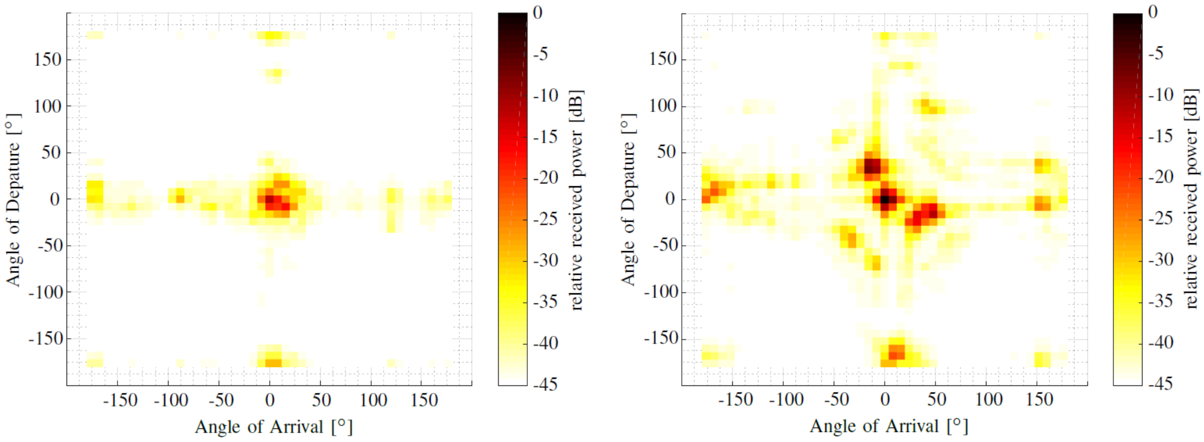

Figure 15: Normalised PAS of the GC FO lcv (left) and GC FO scv (right)

Also the ToR FO measurements show interesting aspects such as the ToR FO sav measurement in Figure 16. In this setup TX and RX are located in the same aisle. Besides the direct path, a strong component at AoD 40° and AoA -16° with -3.3 dB occurs which might be caused by a reflection at a higher rack or a column of concrete. In combination with an antenna with significant side lobes as currently exist for antenna arrays with beam steering in the THz range, these multipath components (MPC) can cause intersymbol interference (ISI) in the case that the side lobes and the MPC match. Though directive antennas make the communication system robust against ISI, the encounter of both effects threatens the performance of high-performance communication systems and needs further investigations.

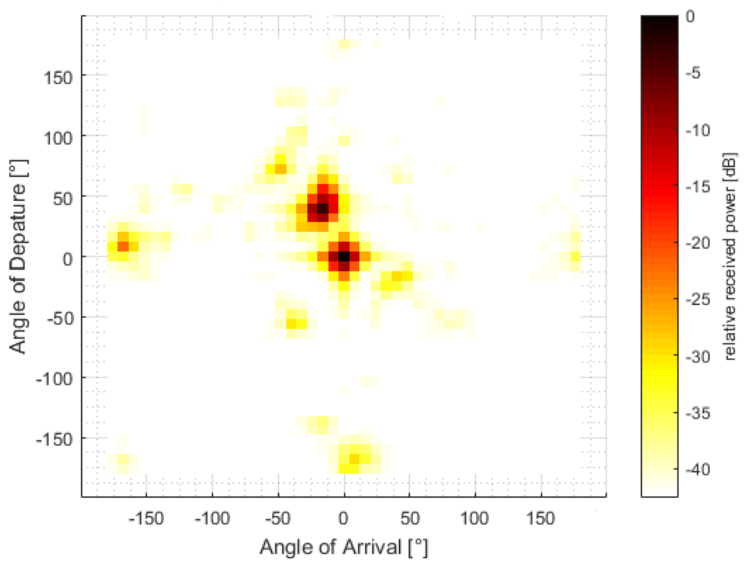

Figure 16: Normalised PAS of the ToR FO sav measurement

FO measurements have been performed for vertical and horizontal polarisation, since polarisation effects have an influence on the propagation. Figure 17 compares the PAS of the ToR measurements where TX and RX are located in two adjacent aisles. The most obvious difference is the much broader spectrum for the horizontal polarisation. This difference is due to the antenna pattern of the used standard gain horn with a gain of 26 dBi. Its simulated gain is plotted in Figure 18. The antenna has much higher side lobes in the E-plane which broaden the MPC in the PAS. However, some paths, which exists for the vertical polarisation, are not part of the horizontal polarised channel as for example at AoD 112° and AoA -80° or at AoD -152° and AoA 0°.

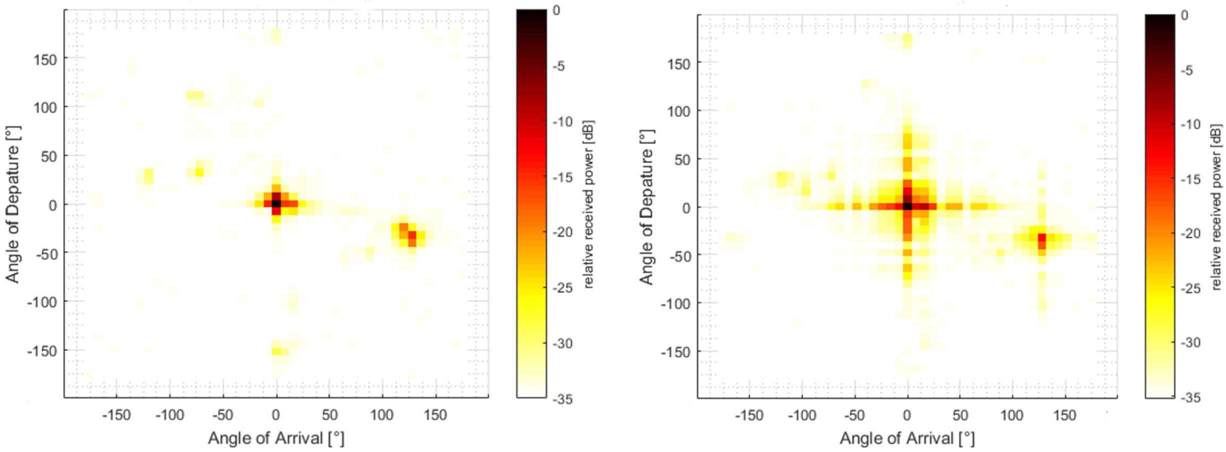

Figure 17: Normalised PAS of the ToR FO aav (left) and the ToR FO aah (right)

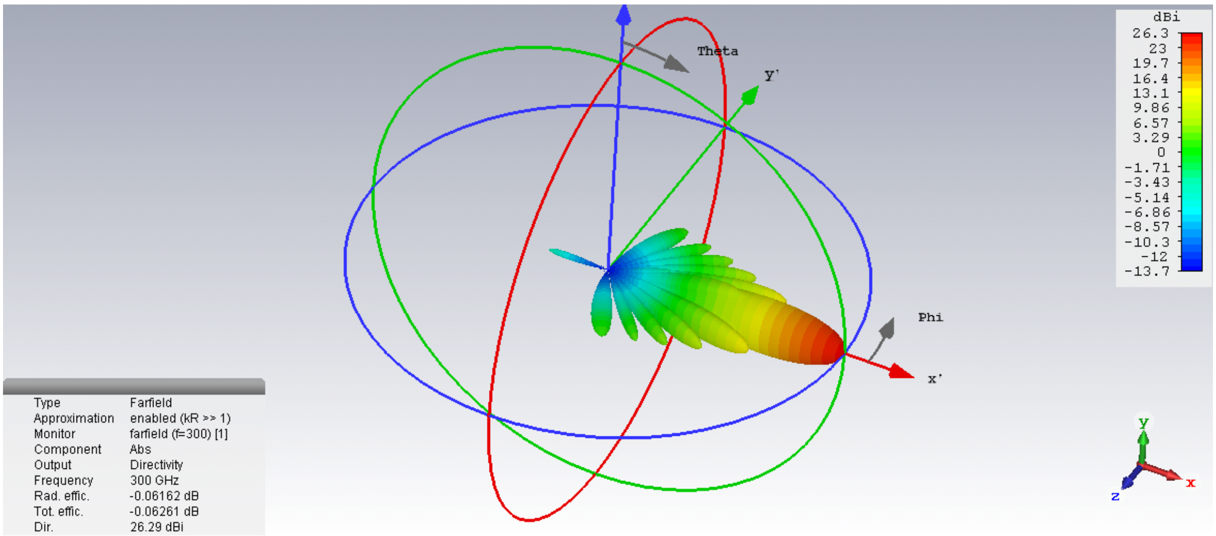

Figure 18: CST Simulation of the used 25 dBi standard gain horn

These effects will be investigated in the channel modelling and channel simulation based on ray tracing algorithms in T4.2.2. To perform ray tracing simulations, a 3D model of the environment is required. Both DCs have been mapped during the measurement campaign and a first simplified model of the Dell EMC Research Data Centre was created. The model accuracy is assumed to be in the order of magnitude of a centimetre. Figure 19 visualises the model and shows the rows of racks and the plastic curtains that separate the hot and cold aisles. The 3D model will be refined in TERAPOD and the final version will be presented in D4.4 along with the 3D model of the second data center where measurements took place. Depending on the simulation results, the required level of detail will be found.

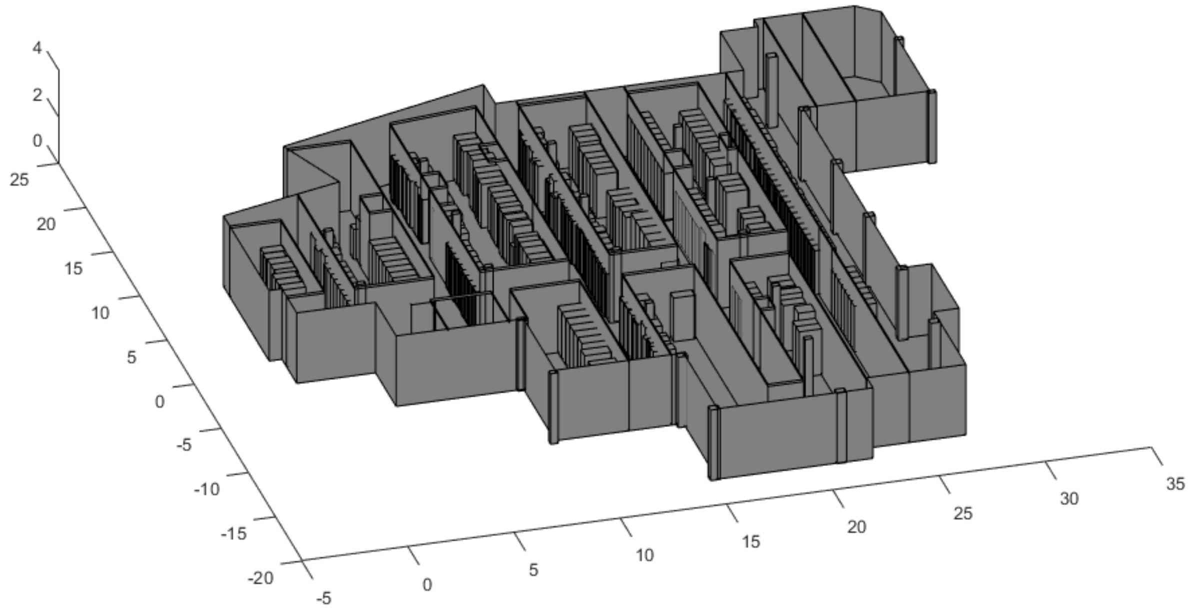

Figure 19: Illustration of the 3D model of the Dell EMC Research Data Centre

7 Conclusion/Further work

This deliverable gives a comprehensive description of the measurement campaign that was performed in Ireland by the Technische Universität Braunschweig in June 2018. The terminology of inter-rack and intra-rack with general characterisation and top-of-rack measurements is explained. The individual measurement setups with point-to-point setups and the full-omni rotational measurements are presented. The measurements prove that the radio channel is static and that the free space path loss describes well the path attenuation in a non-obstructed environment. The analysis of the measurements shows good agreement between the measurement results and the data centre environment and reasonable propagation paths. In conclusion, it can be said that data transmission is possible in a data centre from the channel point of view.

In the next step, the temporal and spatial channel characteristics will be evaluated in more detailed and the channel propagation will be simulated via ray tracing. The same evaluation and modelling will take place for the measurement campaign, which was performed in the second data center at TSSG Waterford/Ireland.

We would like to thank our partners Dell EMC and TSSG for the possibility to perform the measurement campaign in their data centres. Special thanks belong to the whole team of the Dell EMC Research Data Centre and the TSSG Data Centre for their support.

References

[1] S. Rey, J. M. Eckhardt, B. Peng, K. Guan, and T. Kürner, “Channel sounding techniques for applications in thz communications: A first correlation based channel sounder for ultra-wideband dynamic channel measurements at 300 GHz,” in Proceedings of the 9th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), Nov 2017, pp. 449–453.

[2] J. M. Eckhardt, T. Doeker, S. Rey, T. Kürner, “Measurements in a Real Data Centre at 300 GHz and Recent Results”, accepted for publication in Proc. European Conference on Antennas and Propagation, Krakow(Poland), April 2019