Technische Universität Braunschweig

Institut für Nachrichtentechnik

THz Communications – An Option for Wireless Networks Beyond 5G?

Prof. Dr.-Ing. Thomas Kürner

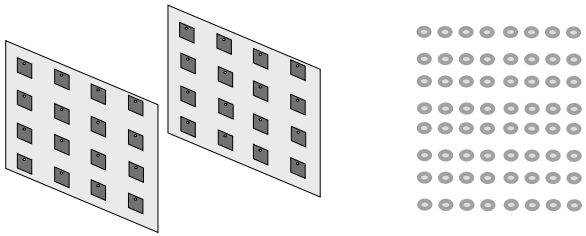
Keynote Speech, EuCNC 18, Ljubljana, 19 June 2018

Outline

1. **Introduction to THz Communications**
2. Propagation Characterisation
   - Measurements and Modeling of Indoor Propagation
   - Terahertz Intra-Device Propagation Channel
3. Ultra-high Data Rate Transmission with steerable antennas @300 GHz
4. Standardisation, Regulation and THz Communications @H2020
5. Conclusion

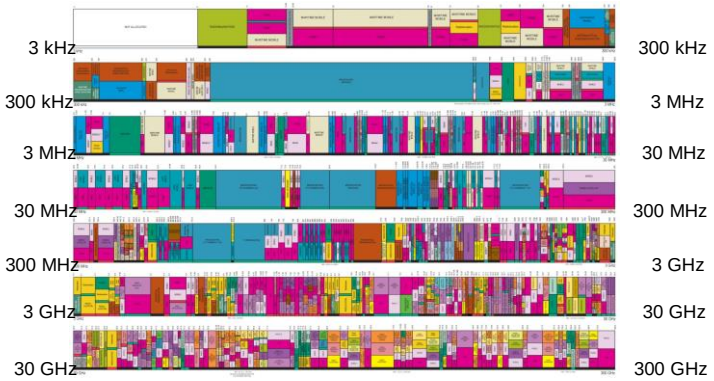
What are the possibilities to achive ultra high data rates?

Option 1:
Using already allocated Spectrum at 60 GHz



- limited bandwidth (~ 7 GHz)
- complex transmission schemes
- massive MIMO

Option 2:
Exploiting new Spectrum beyond 275 GHz



- Bandwidth > 20 GHz
- simple transmission schemes
- high-gain antennas

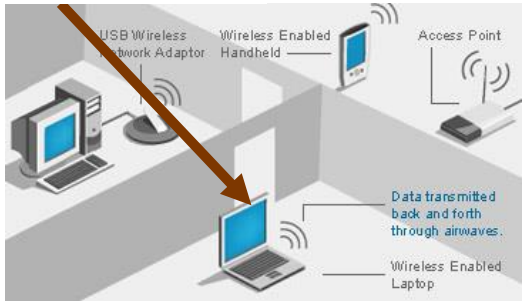
Brief Introduction to THz communications

- **THz characteristics**
  - Huge bandwidths (50+ GHz) are available at THz frequencies (300 GHz – 3 THz)
  - THz components become available to emit 0-10 dBm at 300 GHz
  - Simple modulation schemes (QPSK) are suitable for high data rates (100+ GBit/s)
  - High path losses: free space path loss of ~100 dB at 300 GHz for 10 m
  - High directive (~25 dBi) antennas required for most applications
  - Atmospheric windows of ~50 GHz (attenuation due to resonance of molecules in the air, >2 dB/km)

- **Challenges**
  To make THz communications happen a couple of challenges have to be met:
  - Channel models for the envisaged applications are required
  - RF front-ends and antenna concepts have to be developed
  - Appropriate base band transmission techniques need to be defined
  - Standards have to be developed and regulatory issues have to be resolved

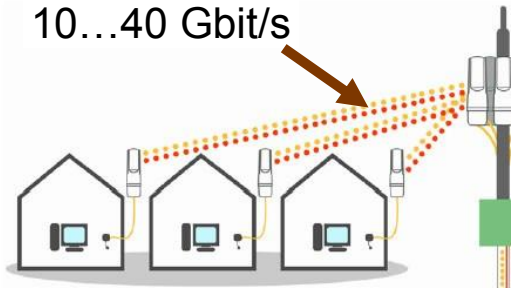
Possible Applications for THz Communications

10...100 Gbit/s



(1) THz WPANs/WLANs

10…40 Gbit/s



(2) Wireless data to home

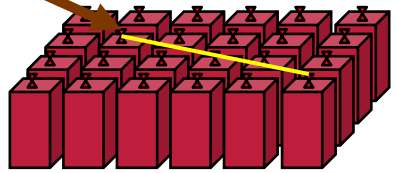
10...20 Gbit/s

(3) Kiosk downloads

10..100 Gbit/s

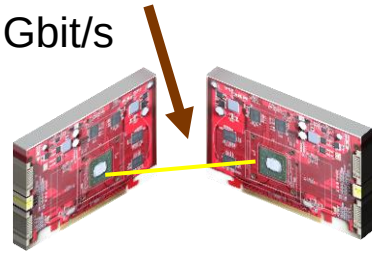
(4) Backhaul/Fronthaul links

10...100 Gbit/s



(5) Wireless Links in Data Centers

10...100 Gbit/s



(6) Intra-Device Communication

Kürner, T. ;Priebe, S., Towards THz Communications - Status in Research, Standardization and Regulation, Journal of Infrared, Millimeter, and Terahertz Waves, Volume 35, Issue 1, January 2014, pp. 53-62

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   - **Measurements and Modeling of Indoor Propagation**
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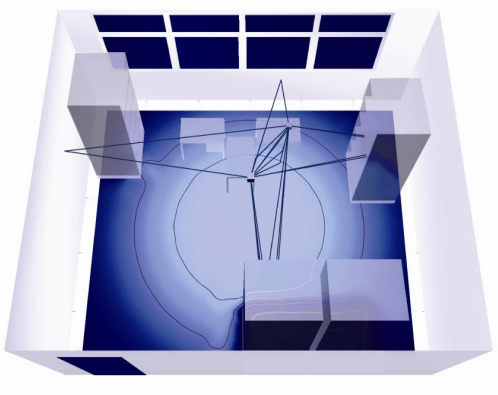
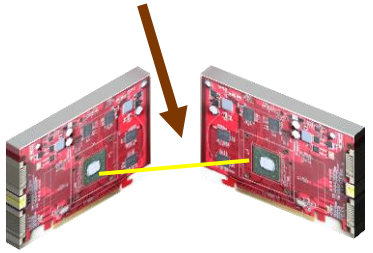
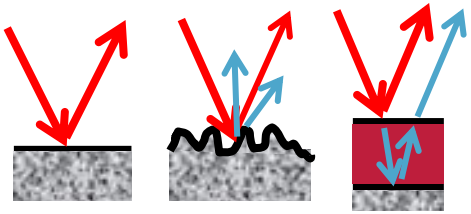
Motivation

- A wireless communciation system, which is going to be operated in a
  - new frequency band or
  - a new application environment or
  - in both
- triggers activities in channel characterisation and channel modelling
- channel measurements are always the first step

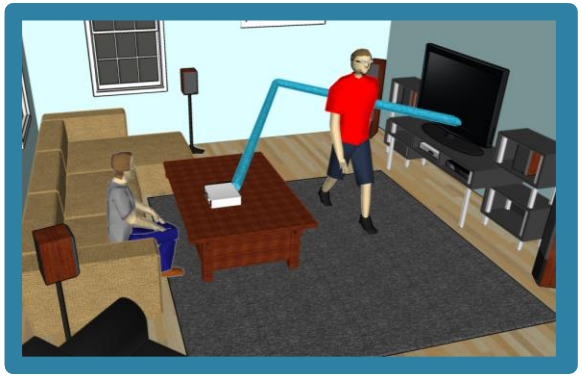




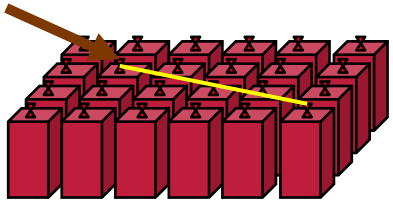
Intra-Device Communication



Indoor Communication & Impact of Building Materials



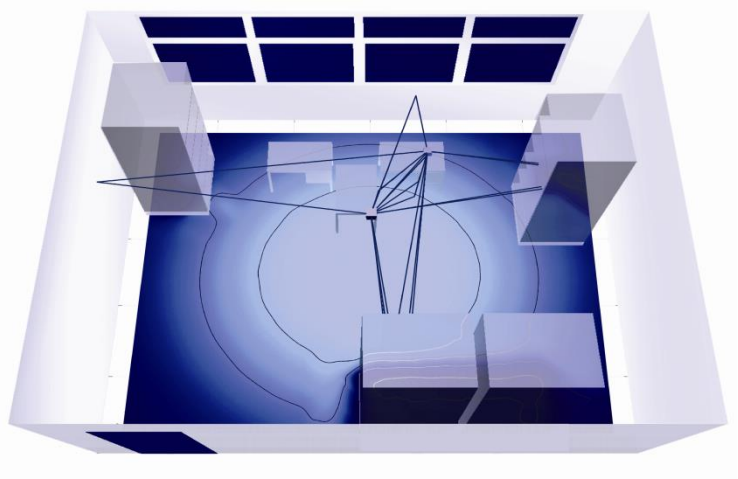
Dynamic environments in combination with high gain antennas



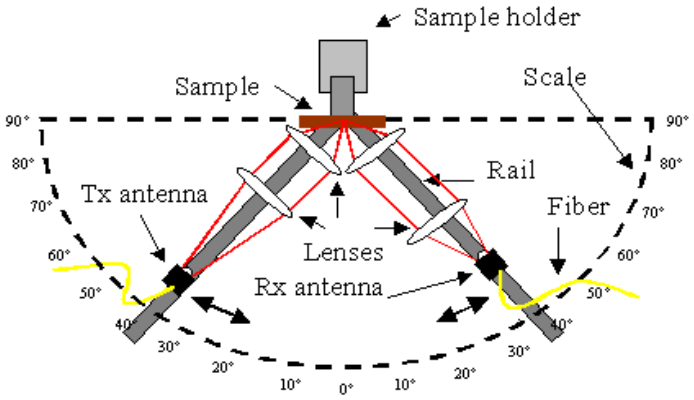
Wireless Links in Data Centers

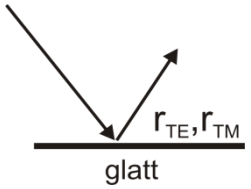
Modelling the Indoor Propagation Channel

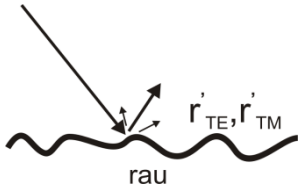
- As at 60 GHz Ray-tracing is well-suited to model the propagation channel beyond 300 GHz in indoor environments
- Proper modelling of reflection and scattering processes for typical building materials required:
  - Reflection on smooth surface
  - Scattering on rough surface
  - Reflection on multi-layer objects



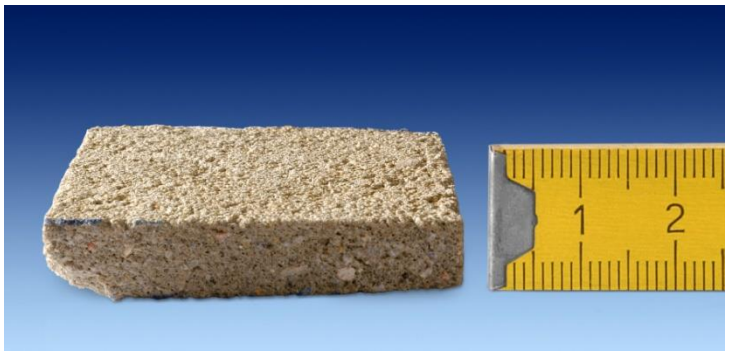
Rough Surface Scattering in Specular Direction







Scattering on Rough Surfaces

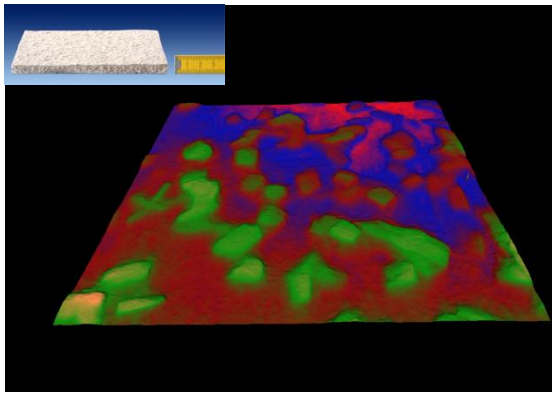


plaster

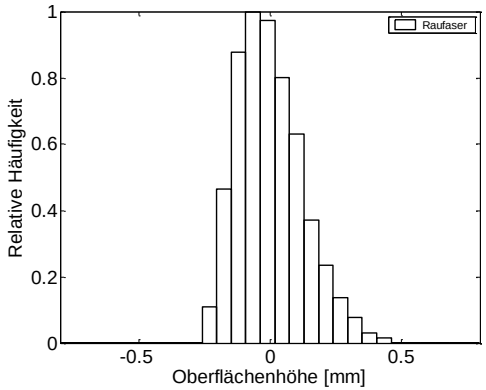
Raufaser wallpaper

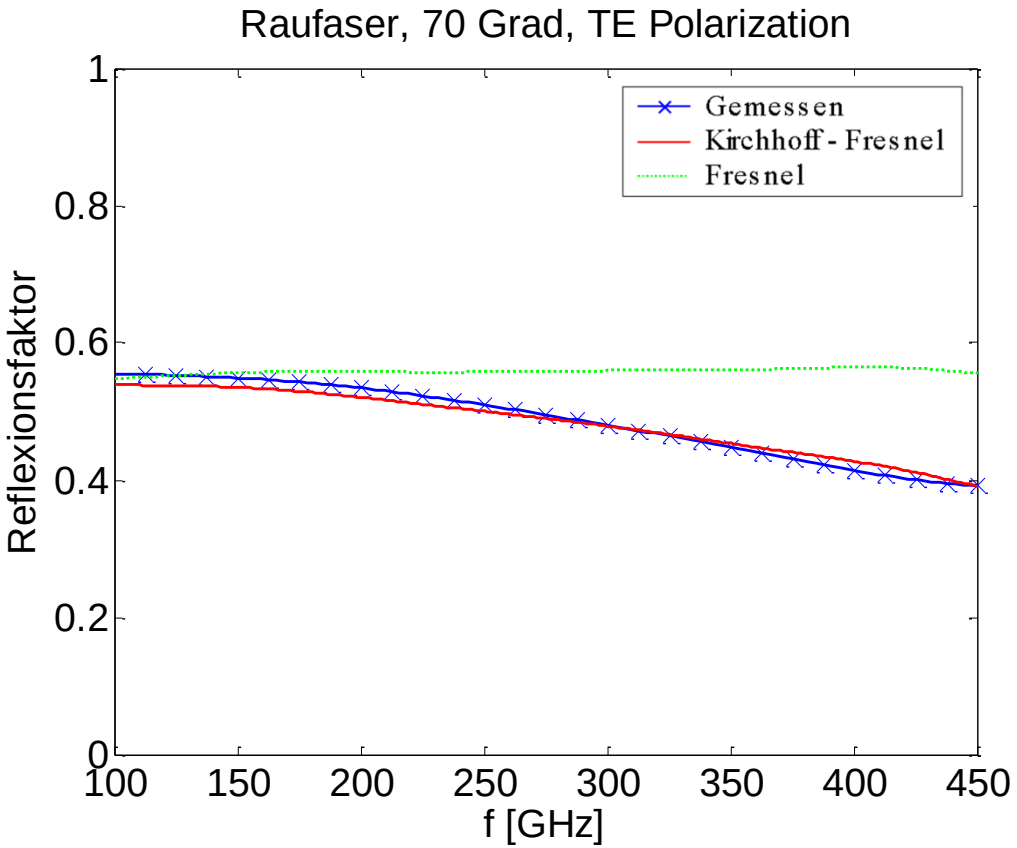
Piesiewicz, R.; Jansen, C.; Mittleman, D.; Kleine-Ostmann, T.; Koch, M.; Kürner, T.; Scattering analysis for the modeling of THz communication systems; IEEE Trans. on Antennas and Propagation, Vol. 55, No. 11, November 2007, pp.3002-3009

Rough Surface Scattering in Specular Direction



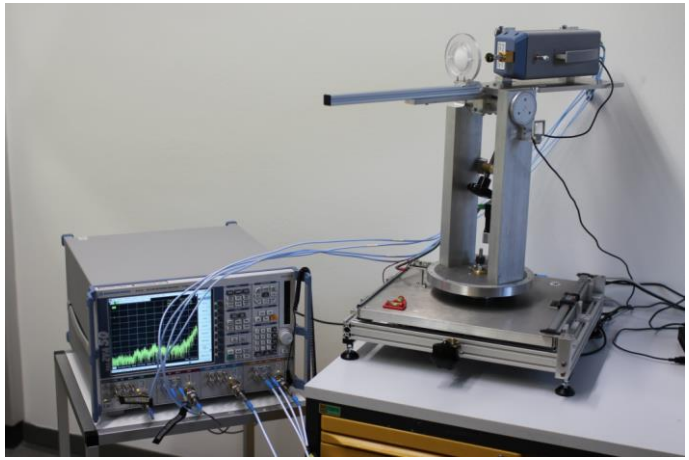
Measured Surface Properties of Raufaser

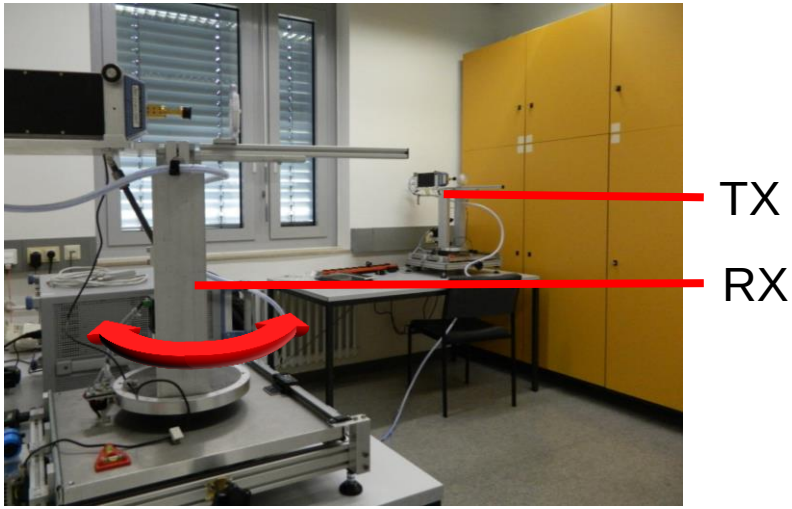




Measuring Spatial Channel Characteristics

- Vector Network Analyzer Rohde & Schwarz ZVA50 with frequency extensions ZVA-Z325
- Measurements in the frequency range 275-325 GHz
- Antennas: Standard gain horn combined with focusing Polyethylen lense

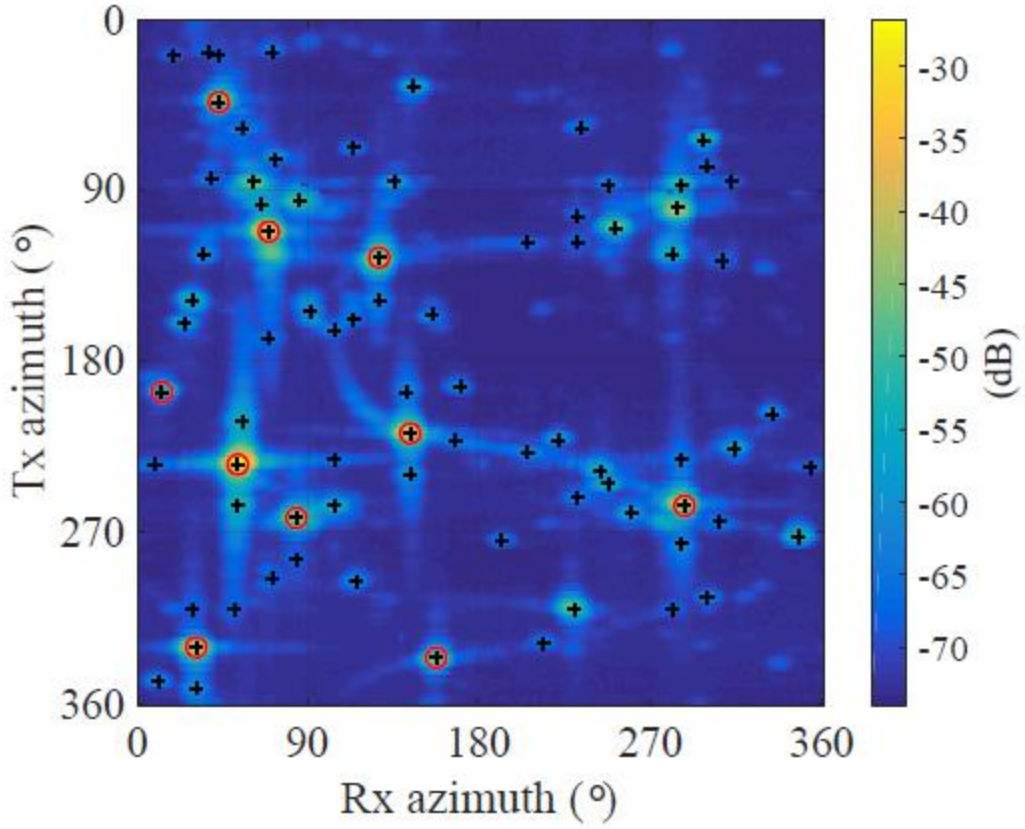




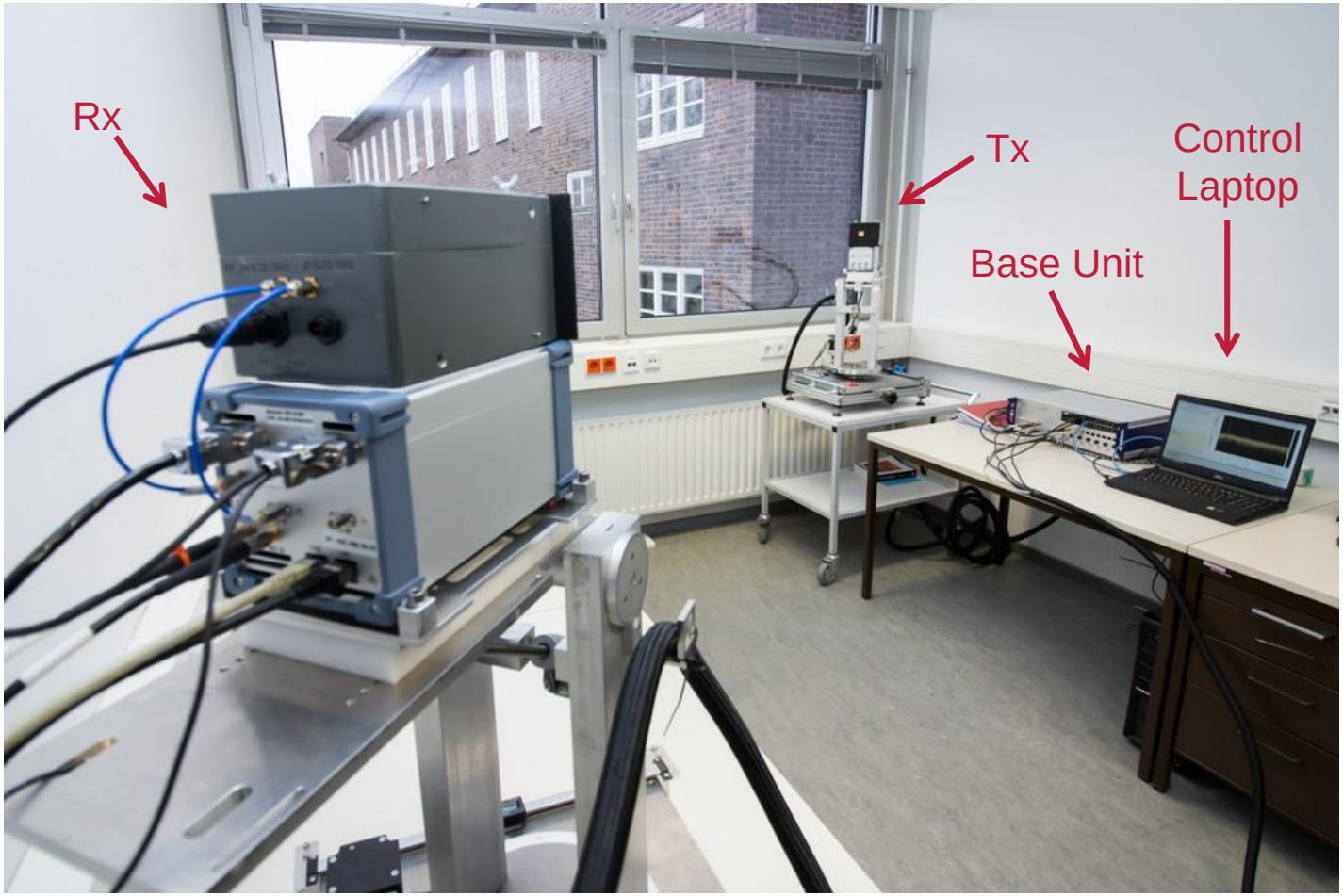
Measurement parameter	Value
Frequency	275 - 325 GHz
Angular resolution	2°
Dynamic range	145 dB
Measurement duration for one position (360° x 360°)	90 h

Sebastian Priebe , Marius Kannicht , Martin Jacob and Thomas Kürner, Ultra Broadband Indoor Channel Measurements and Calibrated Ray Tracing Propagation Modeling at THz Frequencies, Journal of Communications and Networks, December 2013, Vol. 15, No. 6, pp.547-558,

Comparison between measured and (ray launching) predicted AoA



TUBS‘ M-Sequence UWB Channel Sounder



S. Rey, J. Eckhardt,. Peng, K. Guan, T. Kürner, Channel Sounding Techniques for Applications in THz Communications, 2nd Workshop on THz Communications (THZCOM) at the 9th International Congress on Ultra Modern Telecommunications and Control Systems, 8 November 17, 5 pages

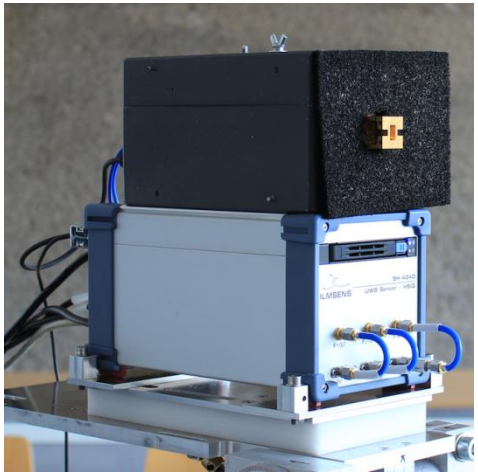
M-Sequence UWB Channel Sounder

Parameter	Value
Clock Frequency	9.22 GHz
Bandwidth	approx. 8 GHz
Chip duration	108.5 ps
M-sequence order	12
Sequence length	4095
Sequence duration	444.14 ns
Subsampling factor	128
Acquisition time for one CIR	56.9 µs
Measurement Rate	17,590 CIR/s
Center Frequencies	9.2/64.3/304.2 GHz
SISO/MIMO	up to 4x4

Set-Up for a Measurement Campaign at Multiple Frequencies. Set Up of the three Bands

Sensor node with frequency extension and antenna

Double ridged horn antenna for 9 GHz

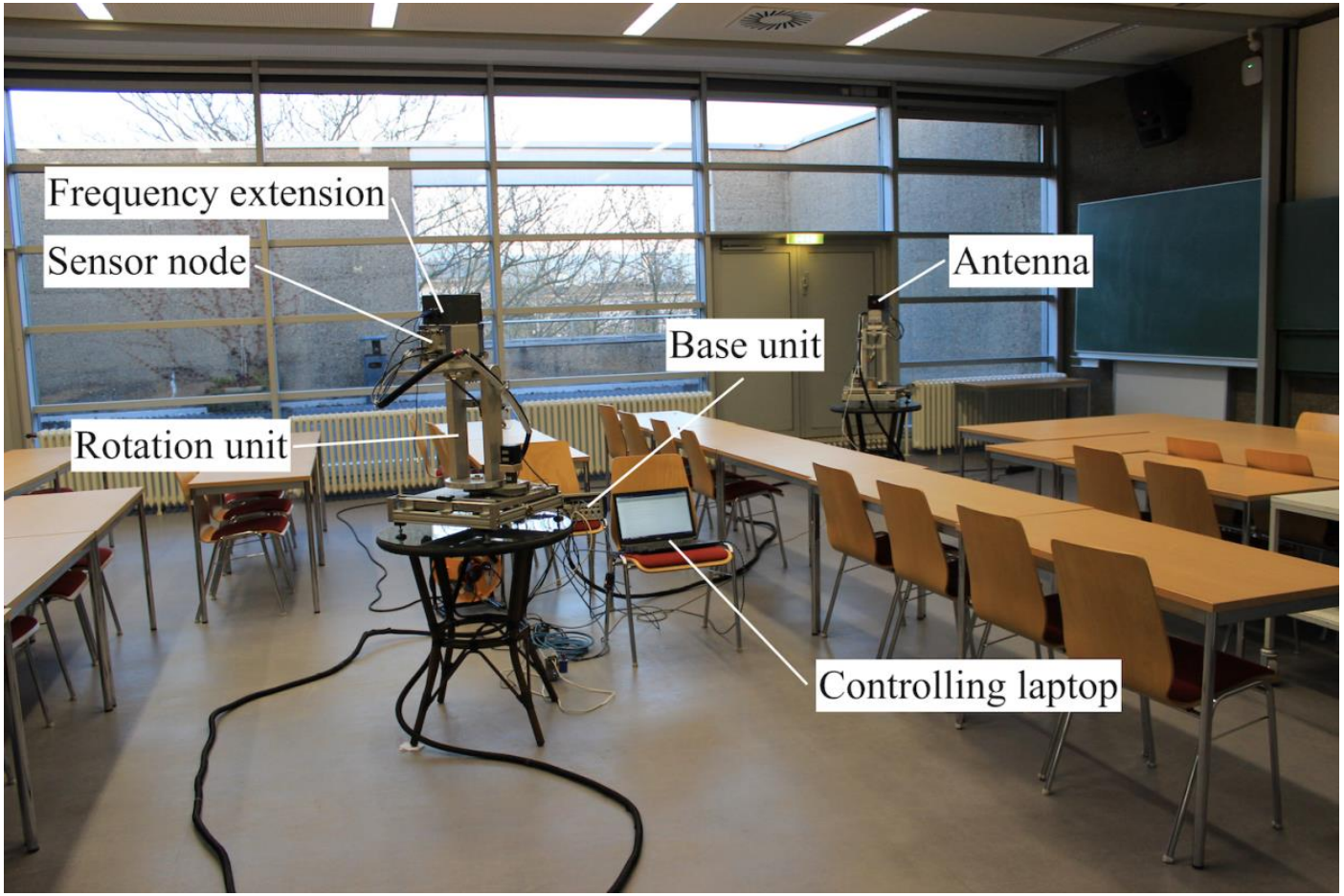


Horn antenna for 60 GHz

Horn antenna for 300 GHz

T. Kürner, B. Peng, K. Guan, S. Rey, Multi-Frequency Measurements at 9, 64 and 304 GHz using an Ultra-Wideband Channel Sounder, IEEE 802.15 IG Thz, oc. 15-17-0588, Orlando, November 2017

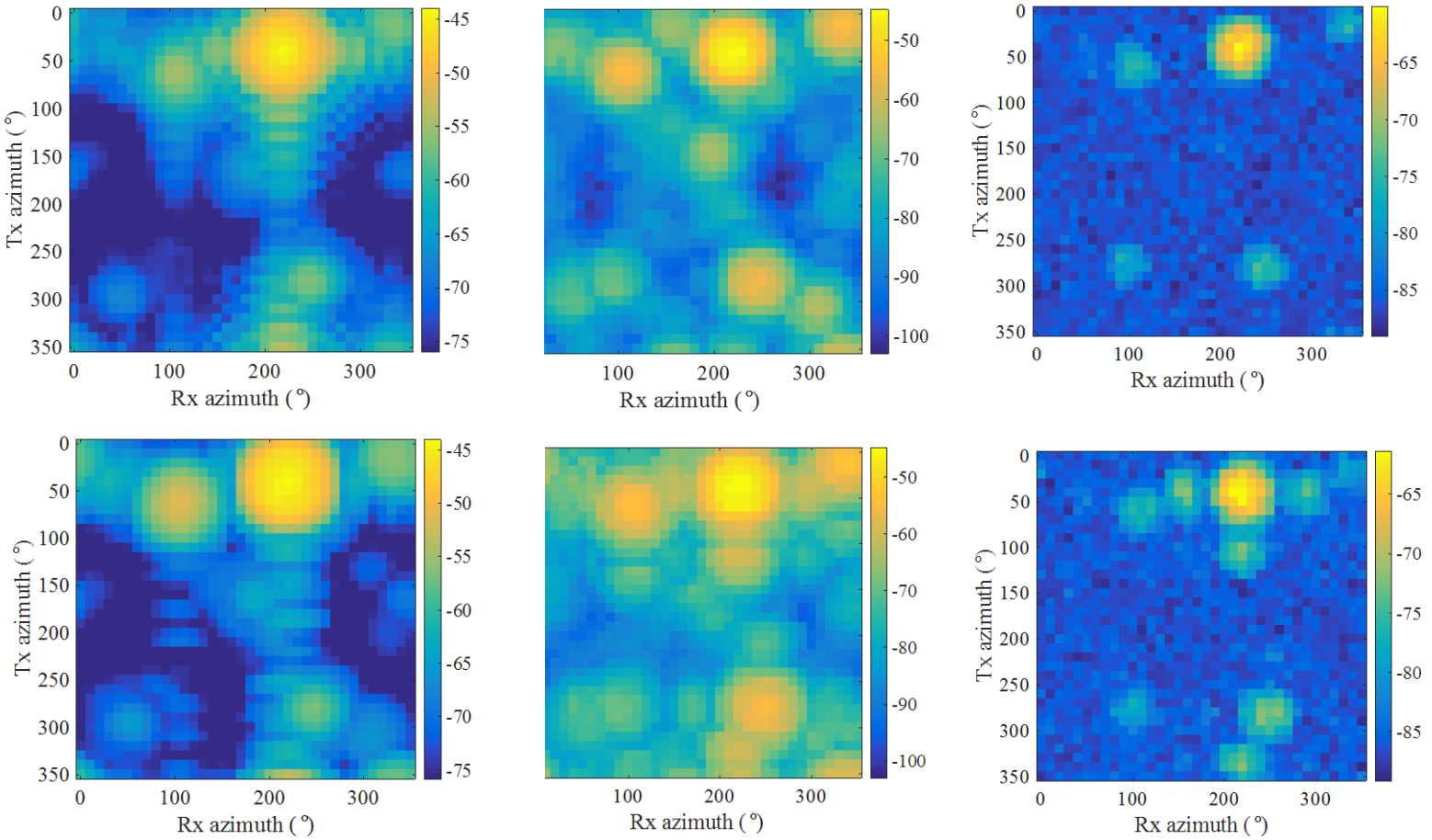
Measurement Scenario (Lecture Room)



Measured Power Angular Spectra

Horizonatl polarization

vertical polarization

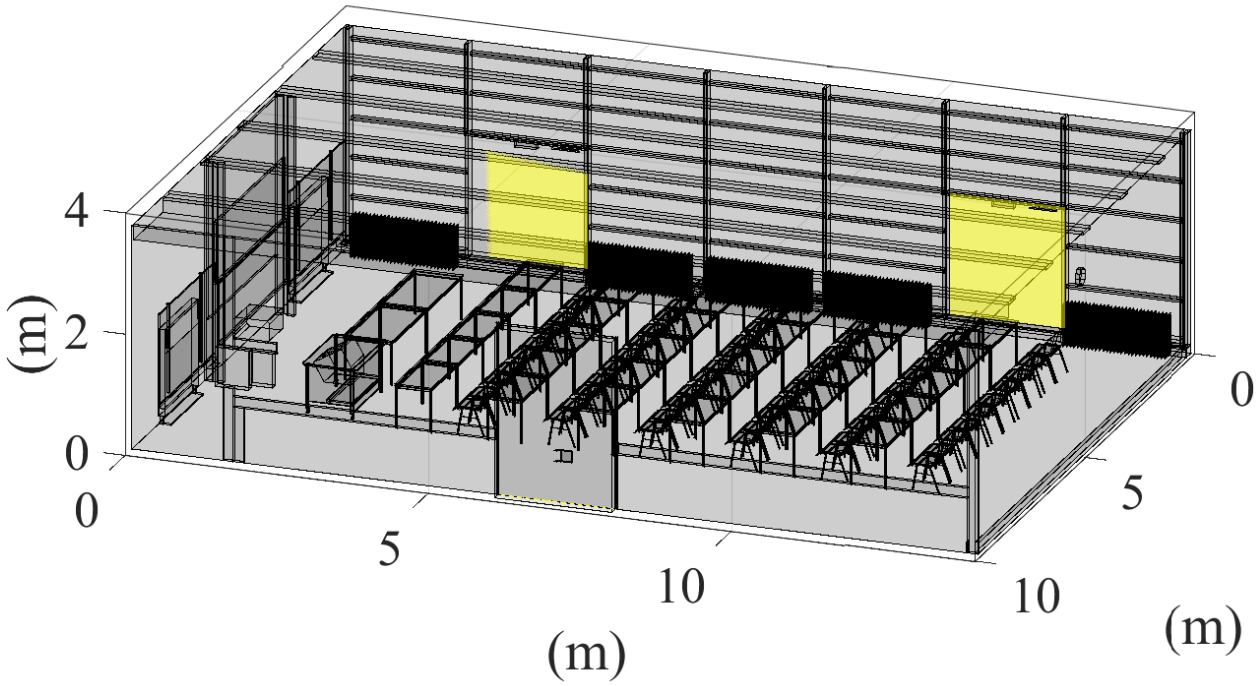


9 GHz

60 GHz

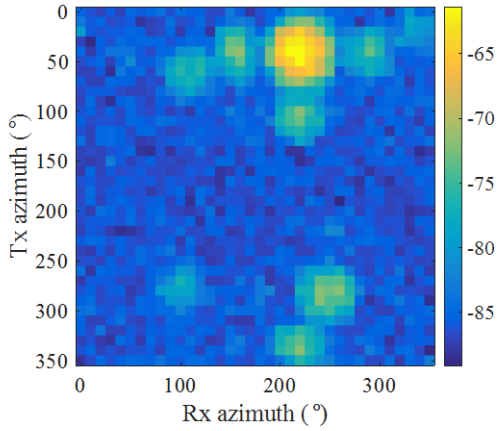
300 GHz

Simulation Scenario

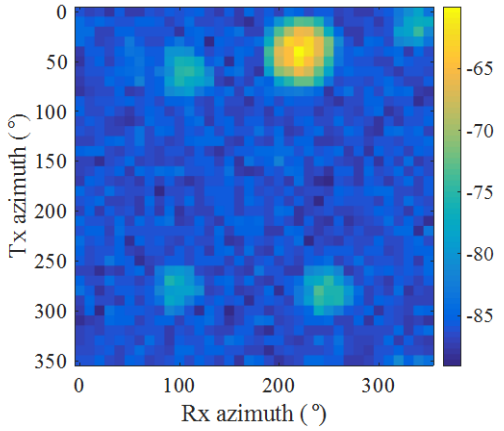


Simulations have been performed using Ray Launching in a 3D model of the lecture room

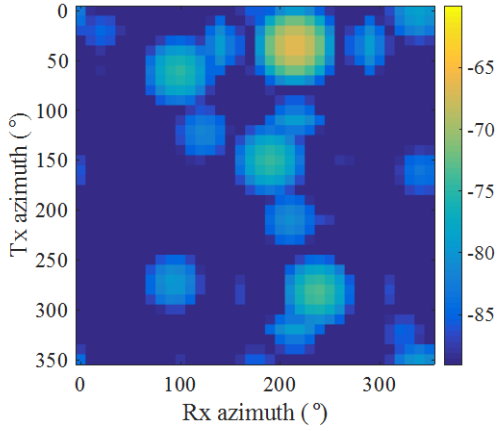
Measured vs. Simulated Power Angular Spectra at 300 GHz



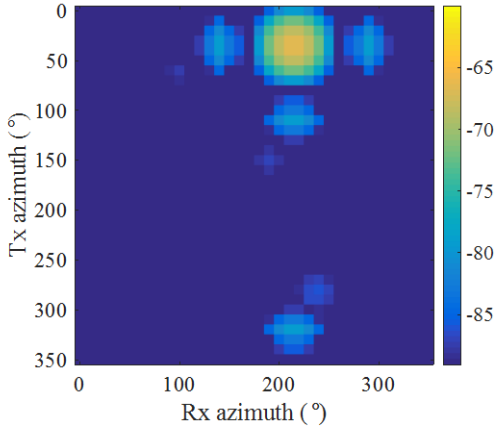
Measured, vertical polarization



Measured, horizontal polarization



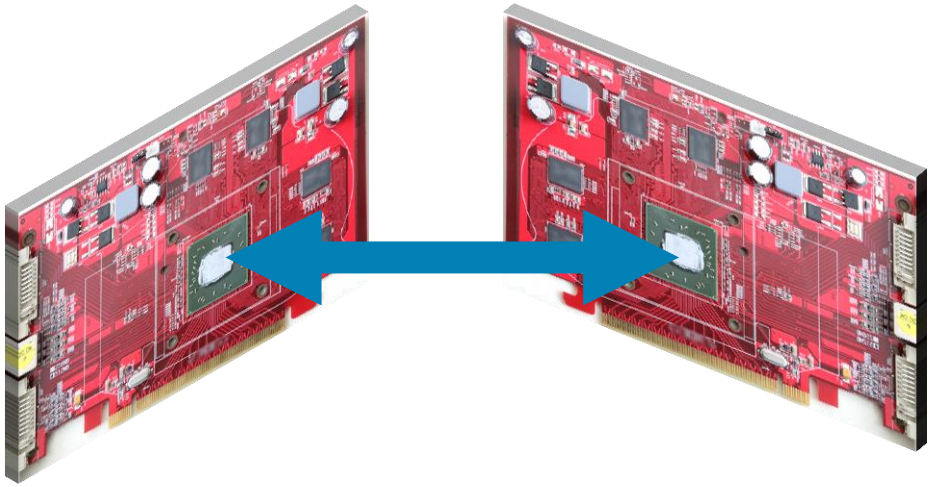
Simulated, vertical polarization



Simulated, horizontal polarization

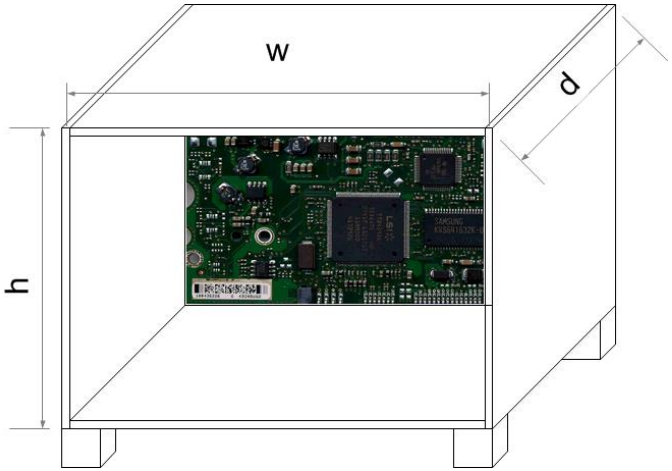
Intra-Device Communications at THz-Frequencies

- Short wave lengths of several millimeters and less enable **intra device communications** from chip to chip with integrated antennas.
- Need to investigate the propagation characteristics **with typical structures and materials** for intra devices links
- Development of appropriate **propagation models** and **software design tools**



Intra Device Channel – Full Wave Analysis vs. Ray Tracing

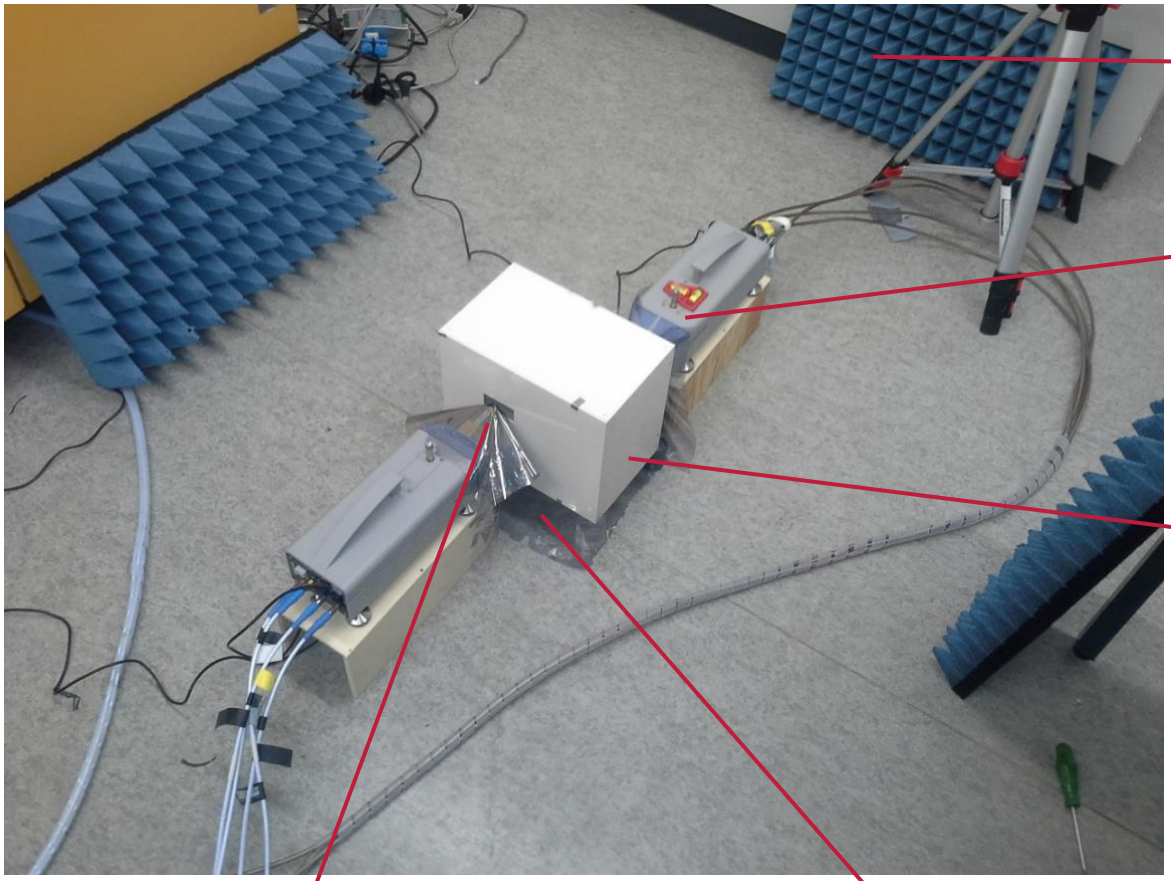
- The intra-device environment comprises many features of the order of the wavelength and the antennas are often placed in the vicinity of these objects
- The use of widely applied high-frequency approximations such as ray tracing reaches its limitations.
- Due to the short wavelength full-wave methods reach their limits in terms of run-time and memory requirements



Scenario	Size of Scenario [in cm]	Simulation run time[2]	Memory requirements [GByte]
Scenario as presented in the following slides	13x1x0.5	3 h	3.6
Medium scenario for intra-device communcation	20x20x20	108d[1]	2900[1]

[1]extrapolated data [2]Computer with 4 CPUs, 3.4 GHz clock and 32 GB RAM

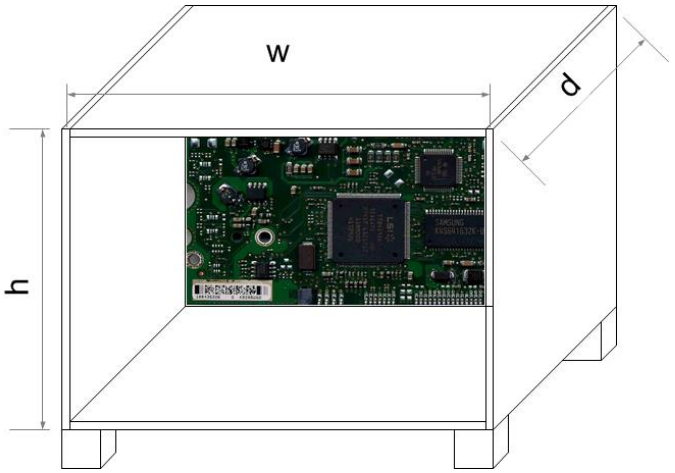
Propagation Research – Measurement Example



Absorbers

Rohde & Schwarz ZVA50 with Frequency Extensions ZVA-Z325

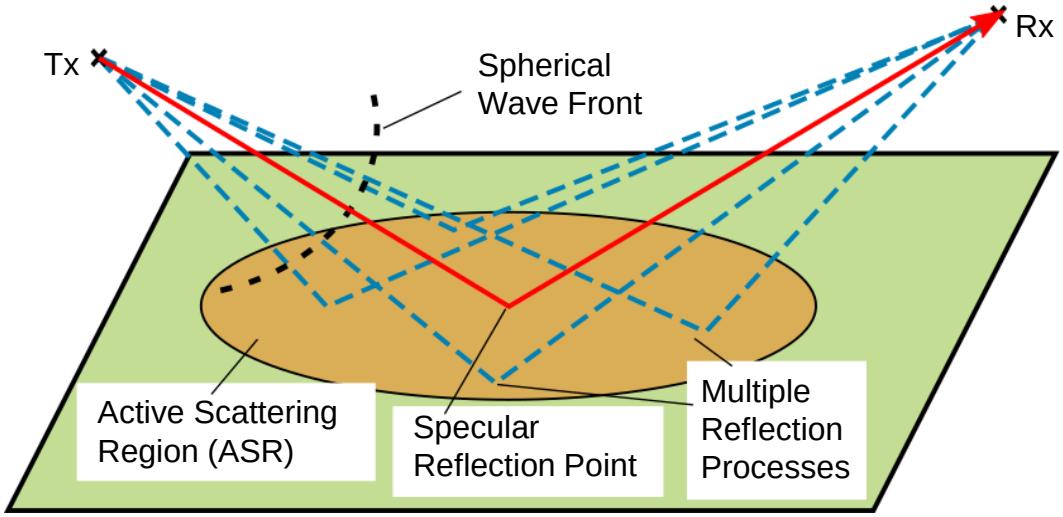
Mock-Up:

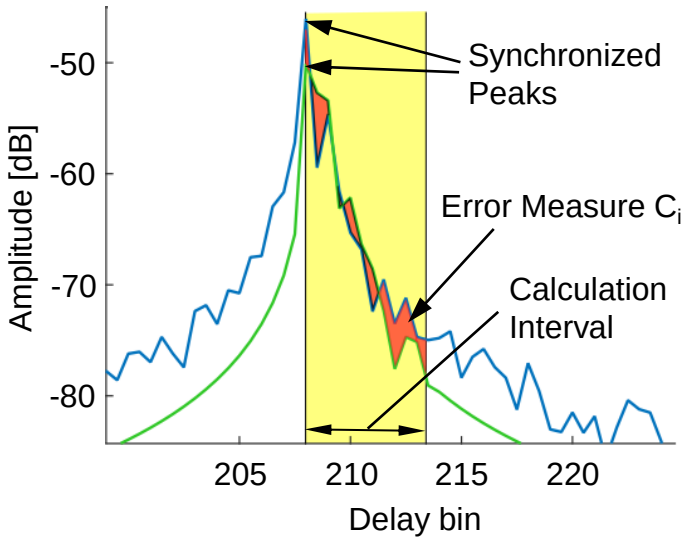


Standard Gain Horns

Absorbing Foil

Propagation Research – PCB Model





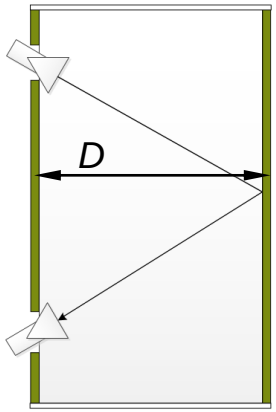
- Superposition of **multiple reflection processes** throughout the surface in an area (ASR) **around the specular reflection** point
- Summation of field components after evaluation with antenna patterns yields **CTF of cluster**
- **Single ray-tracing step** for every PCB interaction
- ASR size, scatterer density, base reflectivity and local amplidute modifier are governed by **four model parameters**
- The parameters are determined based on measured results using **simulated annealing**

A. Fricke, T. Kürner, “A model for the reflection of terahertz signals from printed circuit board surfaces”, EuCAP 2017

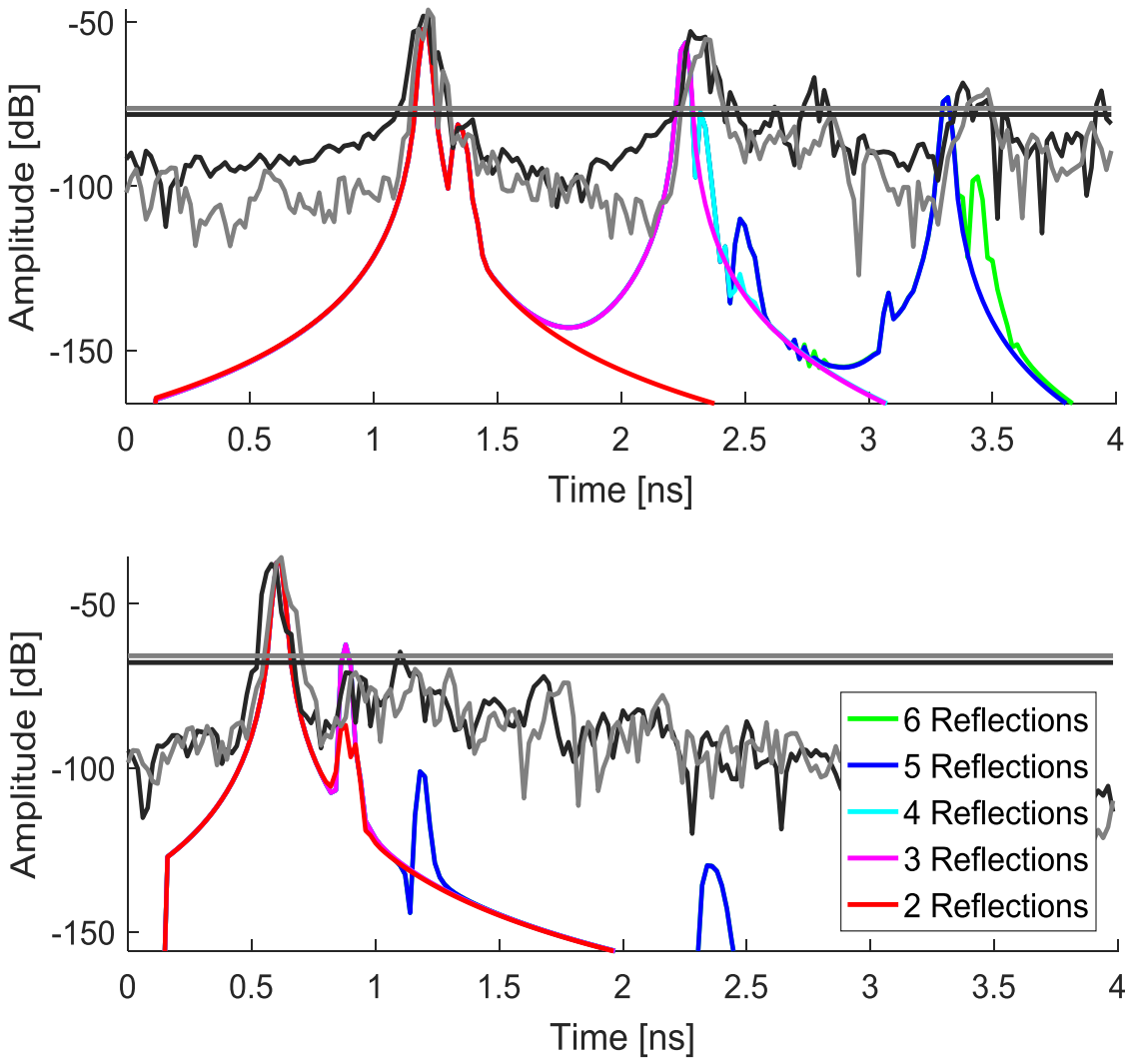
Propagation Research: Complete Channel

- For illustration, the **directed NLOS** scenario has been simulated using the PCB model

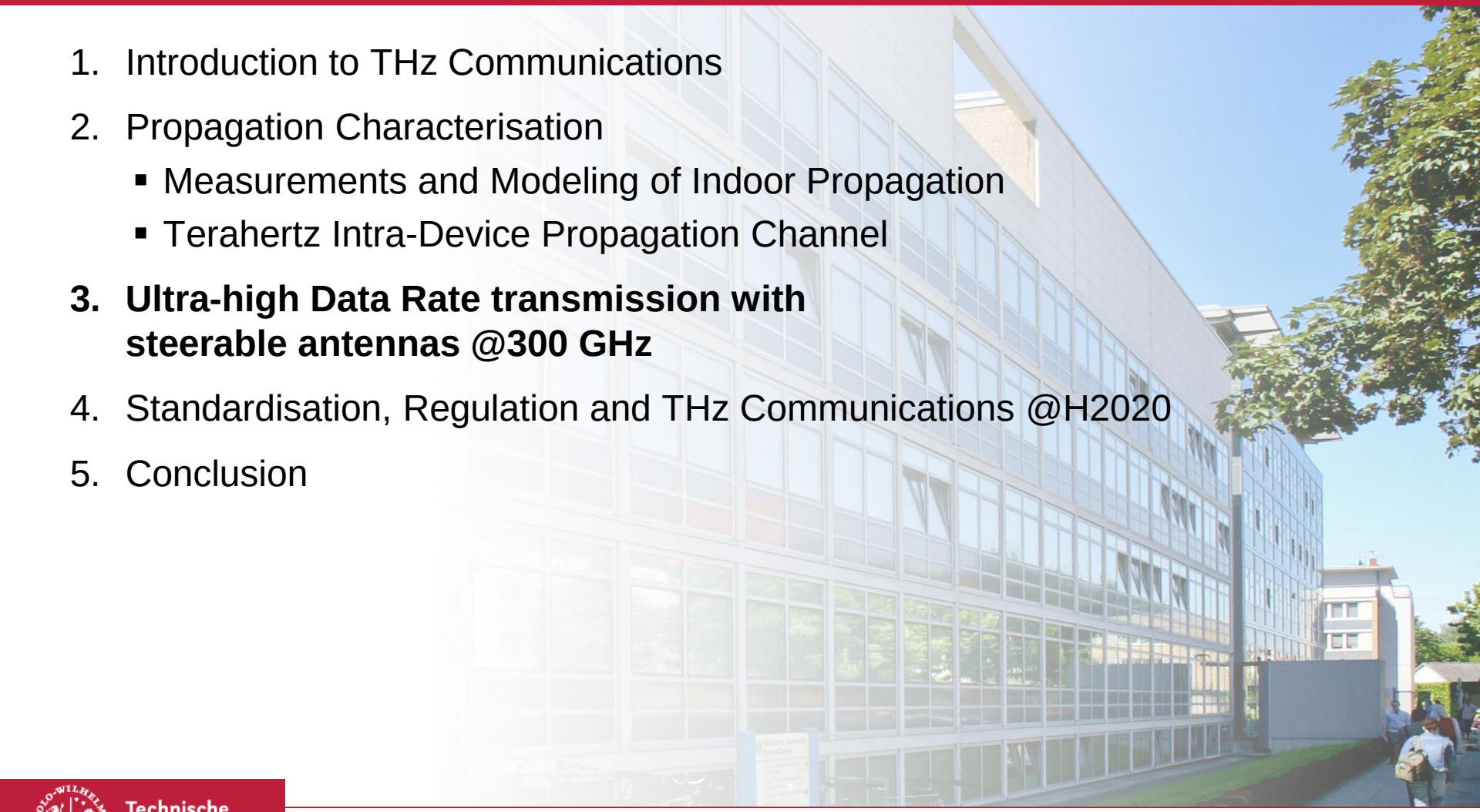
Scenario dNLOS_1:
Neighbouring Position,
Specular Alignment



- The depth ***D* is 16cm** for the large (top) **and 5cm** for the small (bottom) environment
- For both first-order and higher-order reflections, the **amplitude agreement is very good**



Outline



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5. Conclusion

TERAPAN – SISO-Link

- Collaboration project (University of Stuttgart, Fraunhofer IAF, TU BS)
- 35nm GaAs mHEMT
- Fully integrated **300 GHz transmitter & receiver MMICs**
- Compact high performance waveguide modules
- Link budget

  -4.0 dBm transmit power

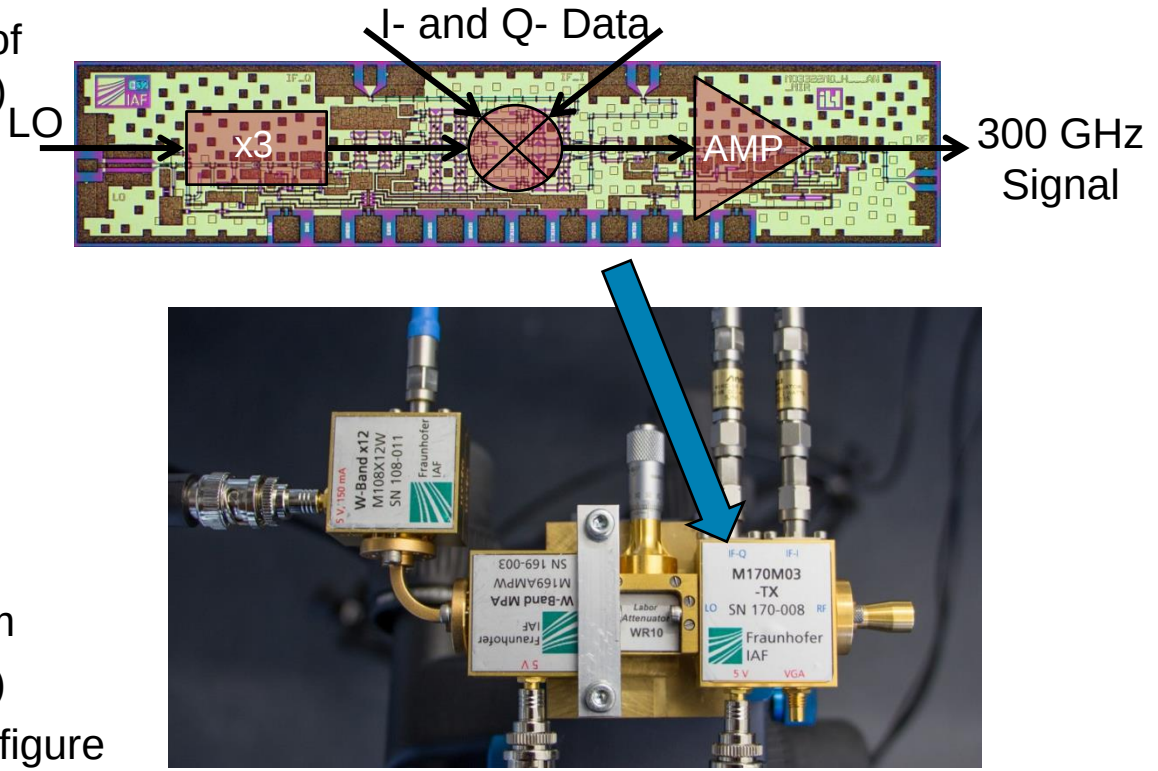
  +24.2 dBi horn antenna gain (Tx)

  -88.0 dB free space path loss 2 m

  +24.2 dBi horn antenna gain (Rx)

  -(-59.2 dB) receiver noise (noise figure 6.7 dB, 64 GHz bandwidth)

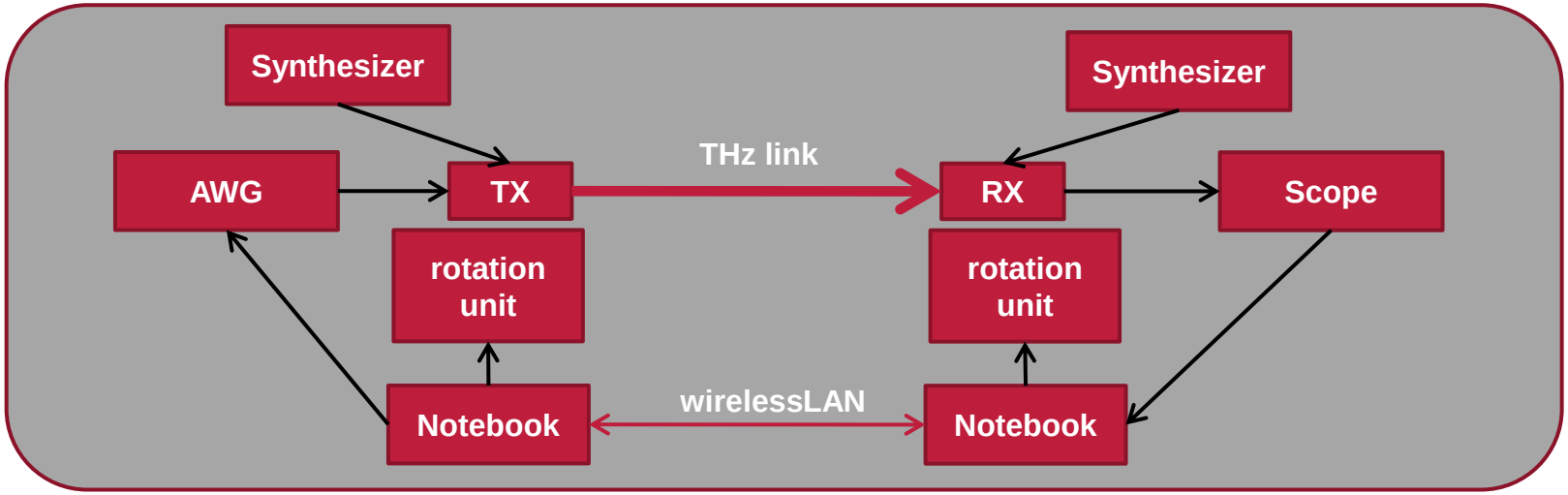
  = **15.6 dB SNR**



- Successfully demonstrated 64 Gbit/s data transmisson with QPSK (limited by measurement equipment and linearity)

Rey, S.; Dan, I.; Merkle, T.; Tessmann, A.; Kallfass, I.; Kürner, T.:*TERAPAN –Towards a 100 Gbit/s Point-to-Point Link with Electronic Beam Steering Operating at 300 GHz. IEEE COMSOC MMTC* Communications – Frontiers, Vol. 11, No. 1, S. 8-11, 2016.

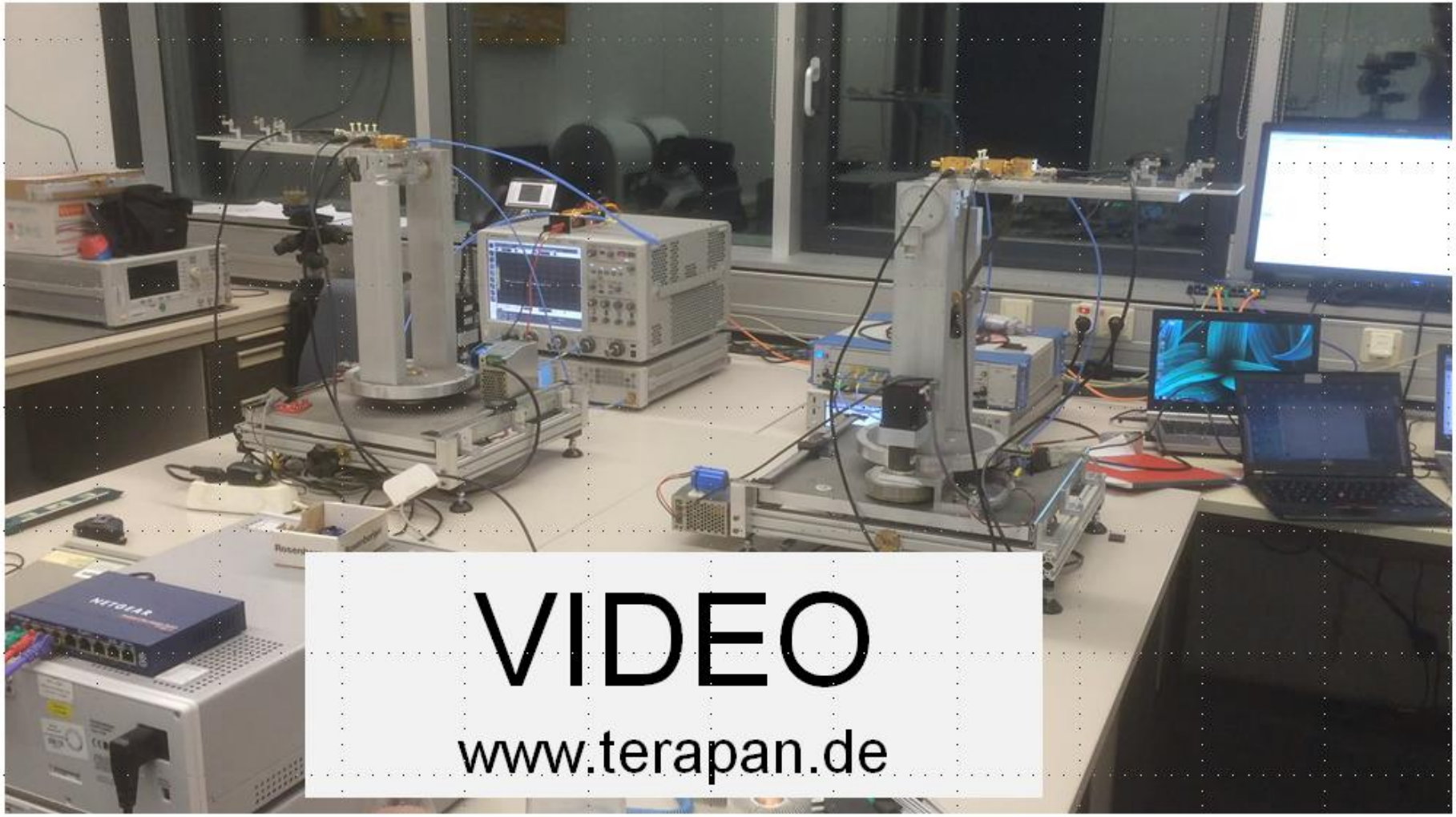
Setup of the TERAPAN demonstrator



- **1st Demonstrator (March 2015)**
  - 1st generation of chip design
  - mechanical beem steering (horn antennas with 25 dBi gain)

- **2nd Demonstrator (October 2016)**
  - optimised 2nd gen. of chip design
  - electronic beam steering

… and the fully working demonstrator

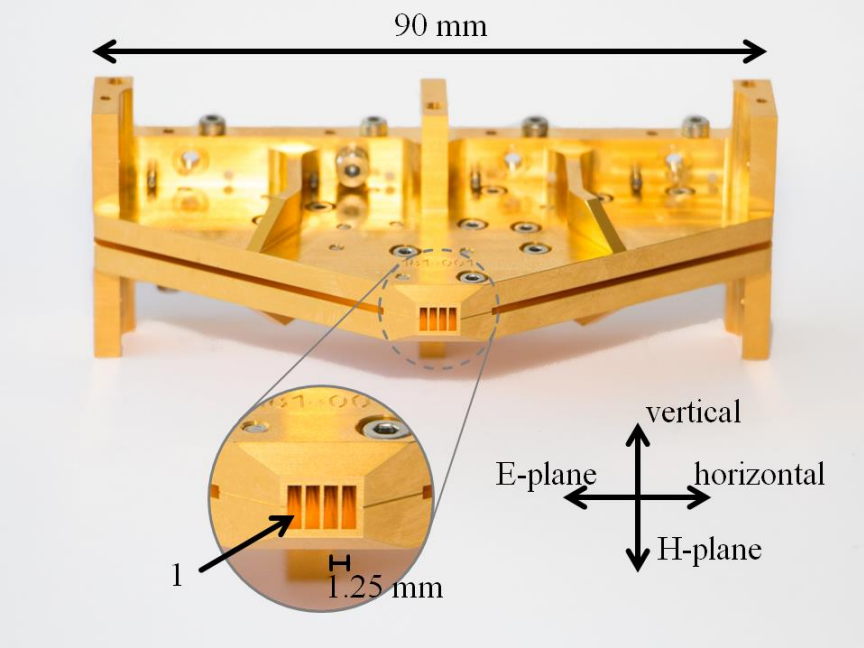


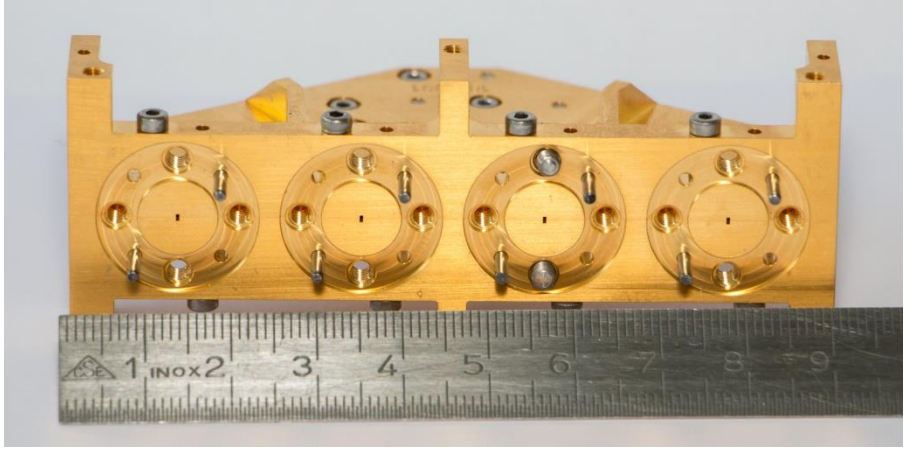
Targets for the Antenna Design fo electronic Beamsteering

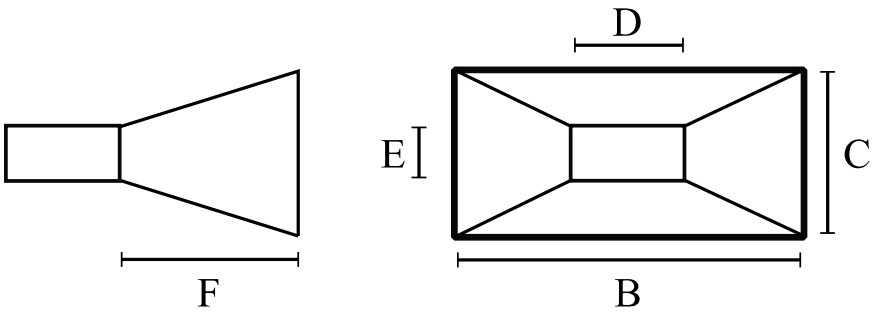
- Max. **4 channels**
  - Max. number of available AWG channels
  - Enough for beam steering demonstration
- Standard **WR-3 wave guide flange** for each element
  - Easier characterization of components
  - Practical reasons (easy exchange in case of defect, etc)
  - Flexibility
- Operational frequency range 275 to 325 GHz
- At least a **gain of 20 dBi** (whole array), 14 dBi single element
  - SISO-link used 24.2 dBi horn antenna
  - Transmitter: 20 dBi (array gain) + 6 dB (4 channels with the same power)
- Linear array in one dimension
  - Narrower main lobe
  - Better steering capabilities than 2x2
- Manufacturability

S. Rey, T. Merkle, A. Tessmann, T. Kürner, A Phased Array Antenna with Horn Elements for 300 GHz Communications, Proc. International Symposium on Antennas and Propagation, Okinawa/Japan, October 2016,

Phased Array Antenna consisting of 4 Elements

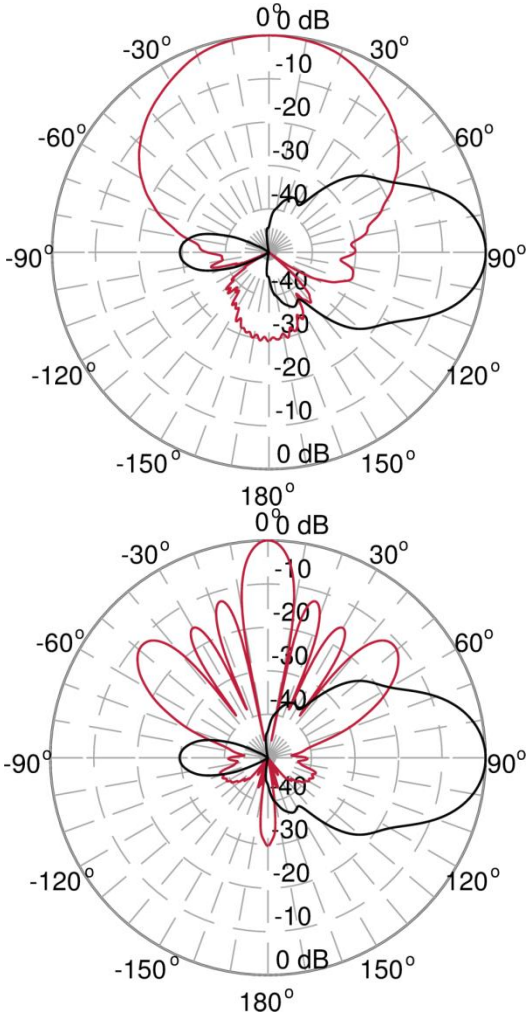






Parameter	Size
B	3.0 mm (horn width)
C	1.0 mm (horn height)
D	0.8640 mm (WR3)
E	0.4320 mm (WR3)
F (flare)	3.577 mm
spacing	1.25 mm= C + 0.25 mm

Simulated Antenna Pattern – Single Element and Array

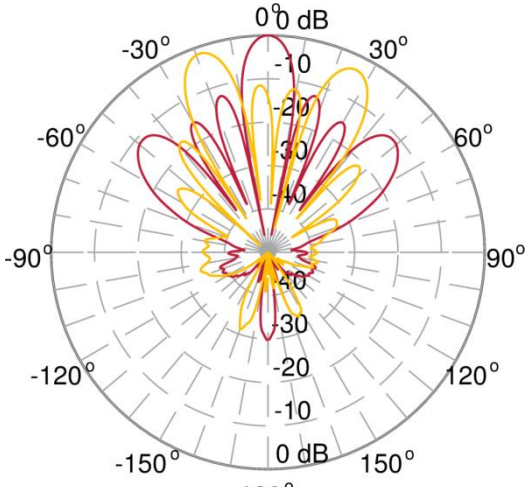


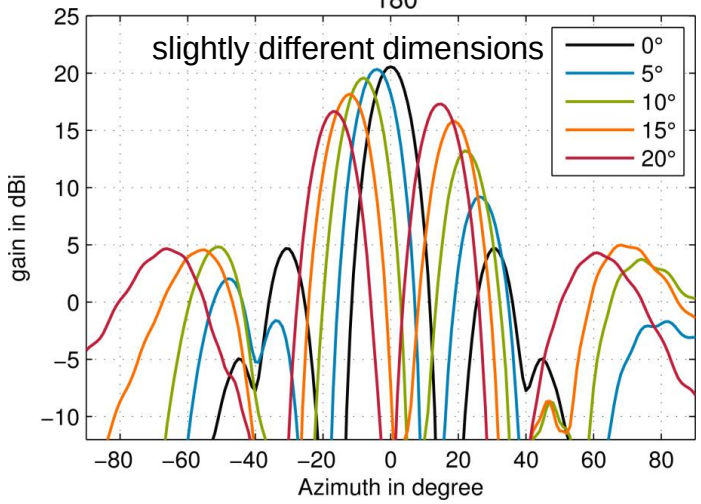
- Single (inner) horn
  - **14.8 dBi gain**
  - 50.0° horizontal HPBW (along width)
  - 23.6° vertical HPBW (along height)
- Outer elements
  - -0.2 dB less gain; Horizontal HPBW approx. 2° wider
- Average S11 of -25.7 dB; max. -22.7 dB

- Array
  - **20.7 dBi gain**
  - 10.3° horizontal HPBW (along width)
  - 23.6° vertical HPBW (along height)

- All values for 300 GHz with Time Domain Solver of CST Microwave Studio
  - For 275 GHz 19.9 dBi, 11.3°, 24.9°
  - For 325 GHz: 21.4 dBi, 9.5°, 22.3°

Beam Steering and Grating Lobes



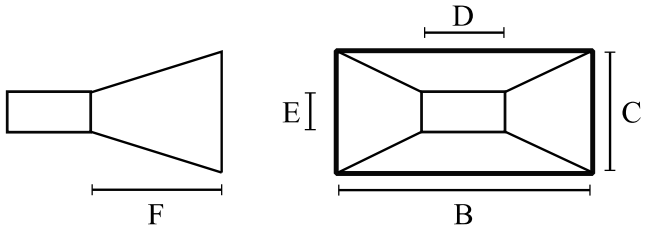


- Phase increment for a target angle α

$$\delta = -\frac{2\pi}{\lambda} r_x \sin\alpha$$

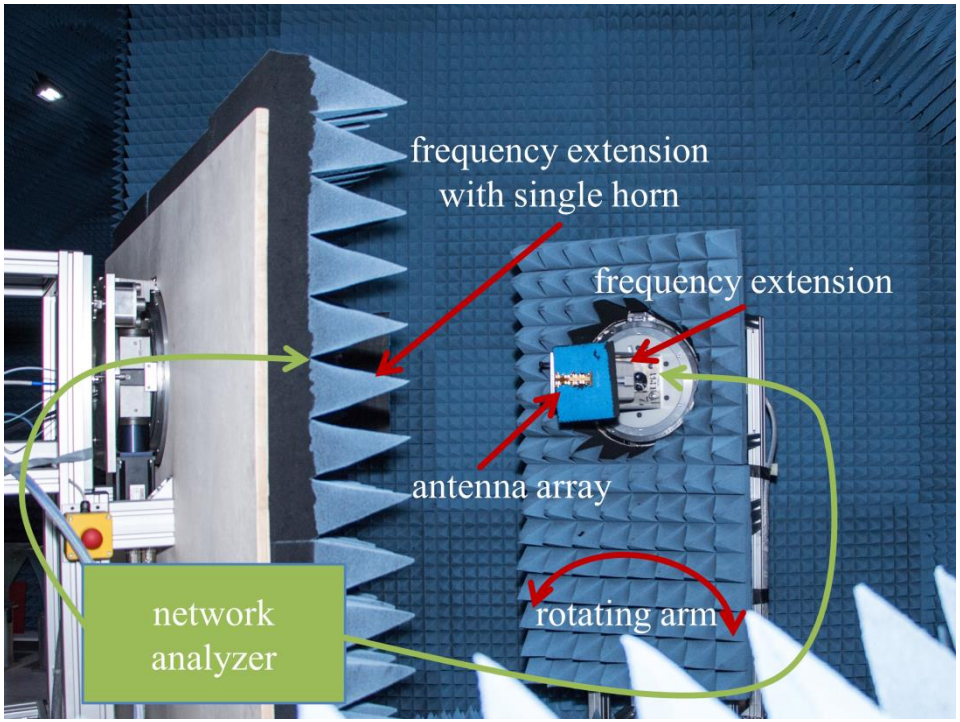
- Grating lobe due to spacing of 1.25 mm

- Can grating lobes be avoided?
  - Customized WG
    - E= 0.23 mm; half of the wave length
    - D= 0.55 mm; usually 2E, but cut-off frequency is 325 GHz
  - H-plane sectoral horn:
    - C=E; B= 13 mm; area constant for 14 dBi
  - Can not be manufactured; gain is only 9.5 dBi; S11 is worse.



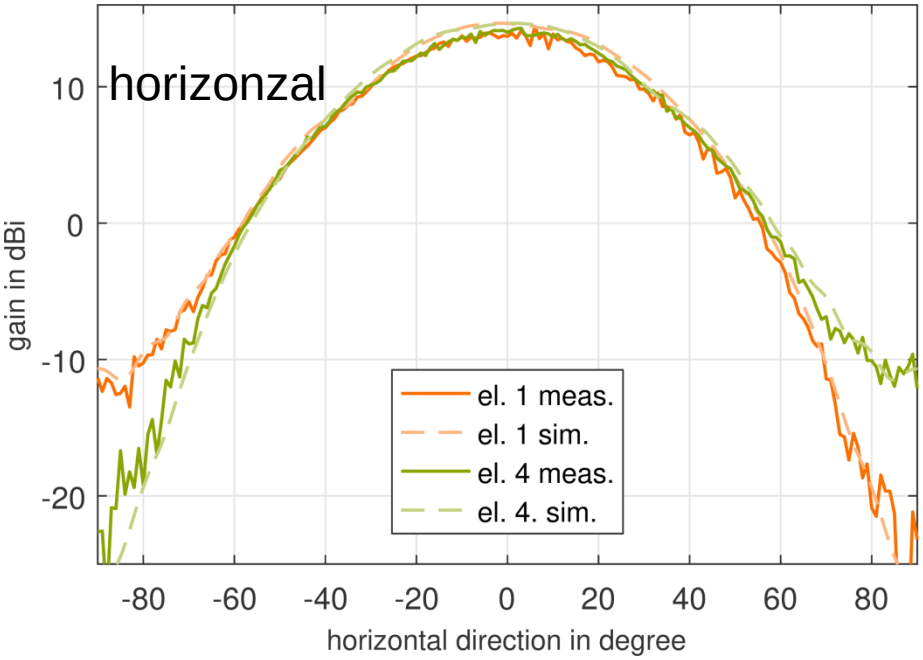
Measurement Setup

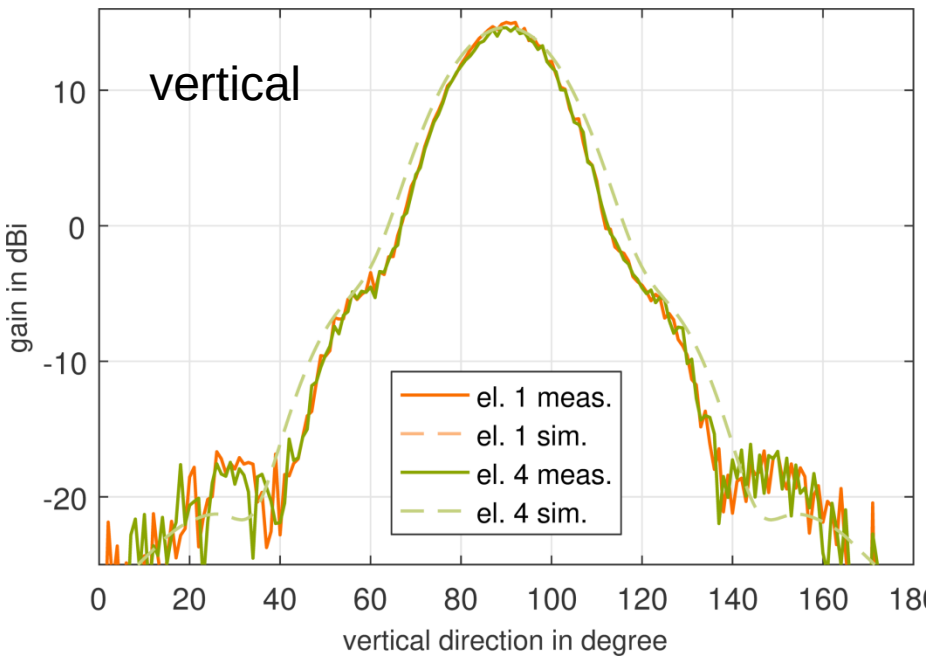
- Single antenna elements
  - inhouse made antenna scanner in a semi-anechoic chamber at PTB in Braunschweig
  - Vector network analyzer Rohde & Schwarz ZVA 50 with frequency extensions ZV-Z325
  - S12 is recorded and analyzed
  - Known reference horn on port 1, single element of the phased array at port 2
  - Measurement bandwidth 10 Hz, 220 – 325 GHz in 5 GHz steps, angular range +/- 90 degree



- Measurements of the array as a whole
  - No 5 port VNA at 300 GHz available
  - With TERAPAN 4 Channel Rx/Tx-Modules

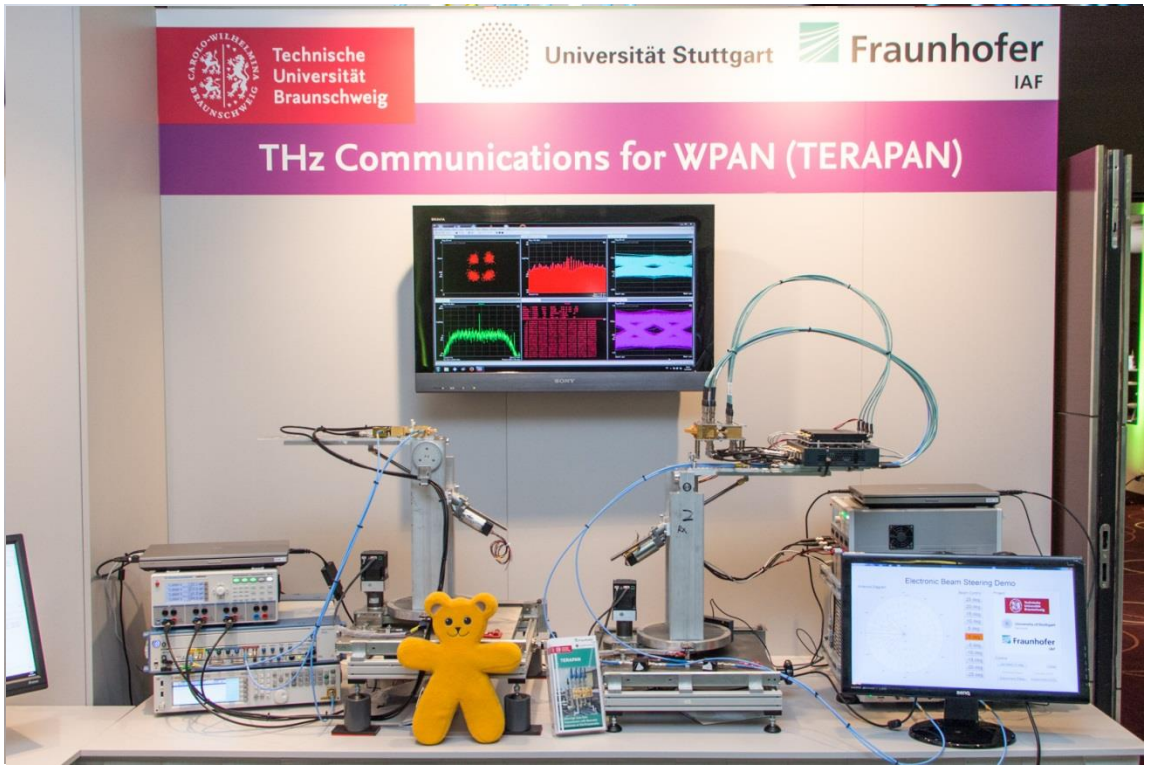
Preview: Measurement Results 300 GHz





- Measurements match the simulation very well (for the outer elements)
  - Less than 0.6 dB mean error for horizontal patterns, standard deviation <1.35 dB
  - Less than 1.2 dB mean error for vertical patterns, standard deviation < 3.3dB
  - Excellent match: Scattering parameters can not be traced back to SI units, yet.

Demonstration of Beam Steering at NGMN IC&E 2016



- Demo at NGMN IC&E 2016
  - 60 cm distance
  - single transmitter
  - 4 channel receiver with phased array antenna
  - electronic beam steering shown and verified by mechanical rotation
  - QPSK modulation
  - data rate of 12 Gbit/s (to see data transmission even within a side lobe)

Problem of Device Discovery at 300 GHz Communciation

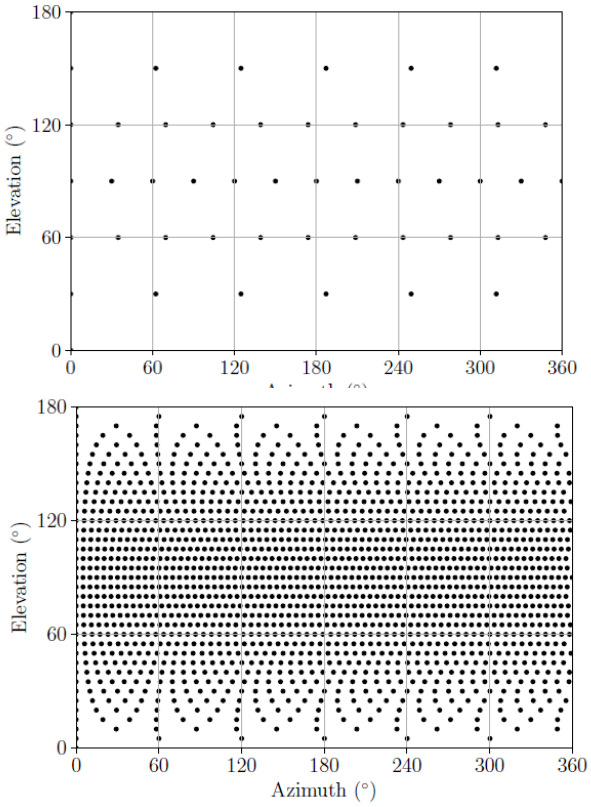
- Alignment of high gain antennas used for 300 GHz links is challenging especially in the device discovery phase during the set-up of the connection.
- Brute-force scanning of the angle-of-arrival at the receiver and of the angle-of-departure at the transmitter is too time-consuming.
- A two-step process can be applied, where rough estimations of the angles are derived at lower frequencies with antennas having lower gains in the first step [1], [2].

[1] B. Peng, S. Priebe, and T. Kürner, “Fast Beam Searching Concept for Indoor Terahertz Communications,” in Proc. 8th European Conference on Antennas and Propagation (EUCAP), pp. 483–487, IEEE, 2014.

[2] B. Peng, K. Guan, S. Rey, T. Kürner, Two-Step Angle-of-Arrival Estimation for Terahertz Communications Based on Correlation of Power-Angular Spectra in Frequency, Proc. European Conference on Antennas and Propagation EuCAP 2018, London, March 2018, electronic publication, 5 pages

Two-Step AoA estimation

- Pre-defined searching directions (different resolutions)



30°

98 scans

5°

1296 scans per AoA/AoD pair found in step 1

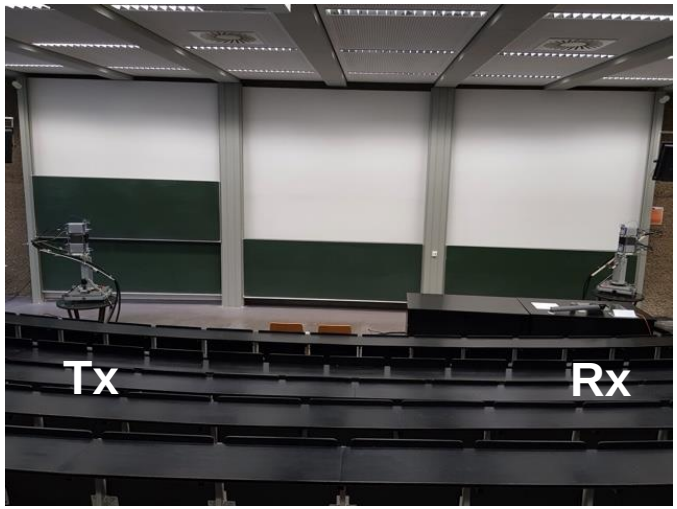
Algorithm 1 Two-step AoA estimation

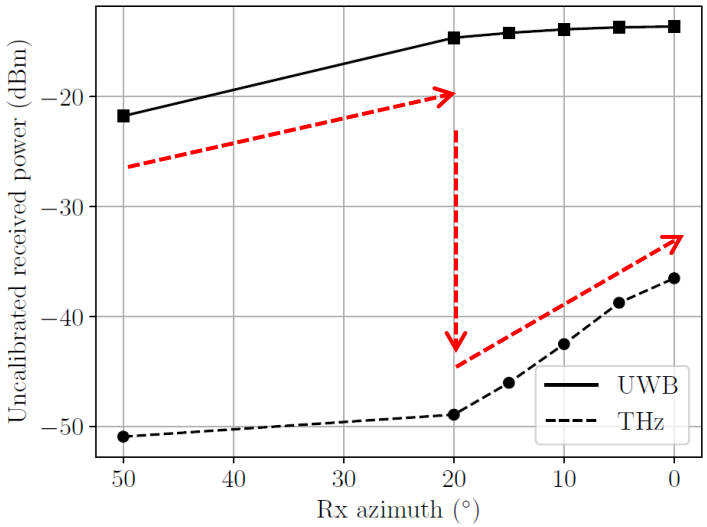
#1 transmits with an omni-directional antenna at low frequency
for every section main lobe direction of #2 **do**
  if #2 detects a signal higher than the noise level **then**
#2 transmits in the current main lobe direction at low frequency
    for every section main lobe direction of #1 **do**
      if #1 detects a signal higher than the noise level **then**
a pair of AoD and AoA is found
      end if
    end for
  end if
end for
for every pair of AoD and AoA **do**
  for every beam main lobe direction of #1 within range of the section **do** #1 transmit in the selected direction
    for every beam main lobe direction of #2 within range of the section **do**
      if #2 detects signal in the selected direction **then**
a pair of AoD and AoA is found
      end if
    end for
  end for
end for

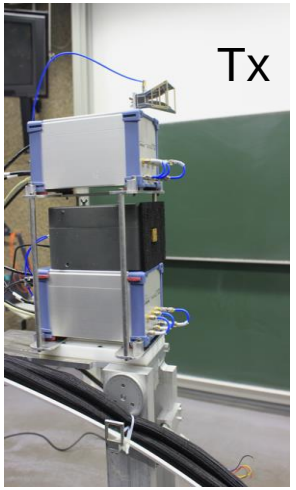
- **Full scan** with 5° resolution would require **3515625** scans
  => **Speed up** by a factor of up to **2521**

TUBS‘ Channel Sounder can be also used for a Demonstration of the Beam Searching Concept

- Demonstration in a large lecture hall
- Mechanical steerable Rx
- Rx is following received power
  - Step 1: 30° increment at lower frequency
  - Step 2: 5° increment at 300 GHz







Outline

1. Introduction to THz Communications
2. Propagation Characterisation
   - Measurements and Modeling of Indoor Propagation
   - Terahertz Intra-Device Propagation Channel
3. Ultra-high Data Rate transmission with steerable antennas @300 GHz
4. **Standardisation, Regulation and THz Communications @H2020**
5. Conclusion

Standardisation Activities @ IEEE 802

- The first project within IEEE 802 towards 100 Gbps has been approved in March 2014: Task Group IEEE 802.15.3d

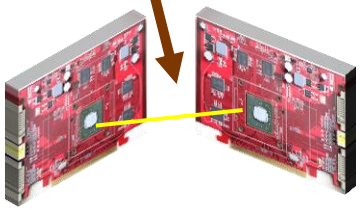
- Scope of the project: *„This amendment defines a wireless switched point-to-point physical layer to IEEE Std. 802.15.3 operating at a nominal PHY data rate of 100 Gbps with fallbacks to lower data rates as needed. Operation is considered in bands from 252 GHz to 325 GHz at ranges as short as a few centimeters and up to several 100m. Additionally, modifications to the Medium Access Control (MAC) layer, needed to support this new physical layer, are defined..”*

- Targeted applications:
  - Kiosk Downloading
  - Intra-Device Communication
  - Wireless Backhauling/Fronthauling
  - Additional Wireless Links in Data Centers

- The standard IEEE 802.15.3d-2017 has been approved on 28th September 2017 and published on 12th October 2018 as the worldwide first wireless communications standard operating at the 300 GHz frequency range

Applications targeted by IEEE 802.15.3d-2017

10...100 Gbit/s

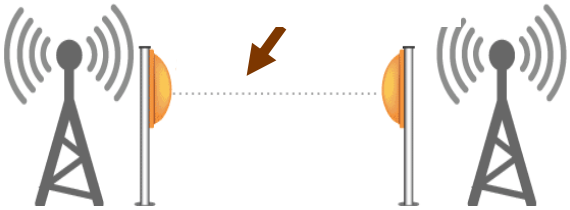


Intra-Device Communication

10...20 Gbit/s

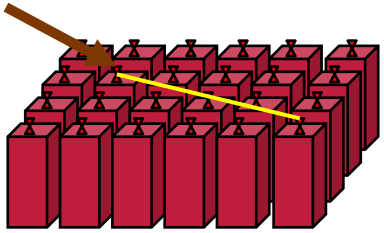
Kiosk downloads

10..100 Gbit/s



Backhaul/Fronthaul links

10...100 Gbit/s

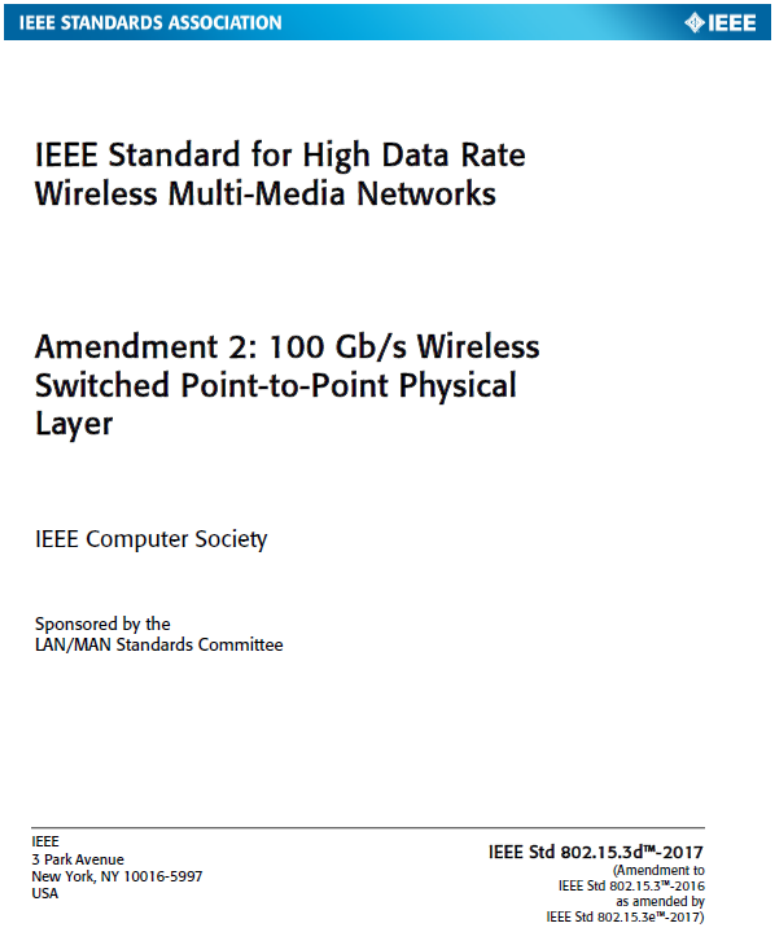


Additional Wireless Links in Data Centers

See also: “Applications Requirement Document (ARD)”, DCN: 15-14-0304-16-003d, IEEE 802.15 TG3d, May 2015, https://mentor.ieee.org/802.15/documents

Key facts of IEEE 802.15.3d

- New PHY for Std. IEEE 802.15.3-2016
- MAC is mainly based on IEEE 802.15.3e-2017, which introduced the concept of „Pairnet“
  - Point-to-point nature with highly-directive antennas reduces the problem of interference and „fighting for access“
  - Positions of Tx and Rx antennas are known
- 8 different channel bandwidths (as multiples of 2.16 GHz)
- 2 PHY-modes (THz-SC PHY, THz-OOK-PHY) with 7 modulation schemes:
  - BPSK, QPSK, 8-PSK, 8-APSK, 16-QAM, 64 QAM, OOK
- 3 channel coding schemes:
  - 14/15-rate LDPC (1440,1344), 11/14-rate LDPC (1440,1056), 11/14-rate RS(240,224)-code.


IEEE STANDARDS ASSOCIATION IEEE

IEEE Standard for High Data Rate Wireless Multi-Media Networks

Amendment 2: 100 Gb/s Wireless Switched Point-to-Point Physical Layer

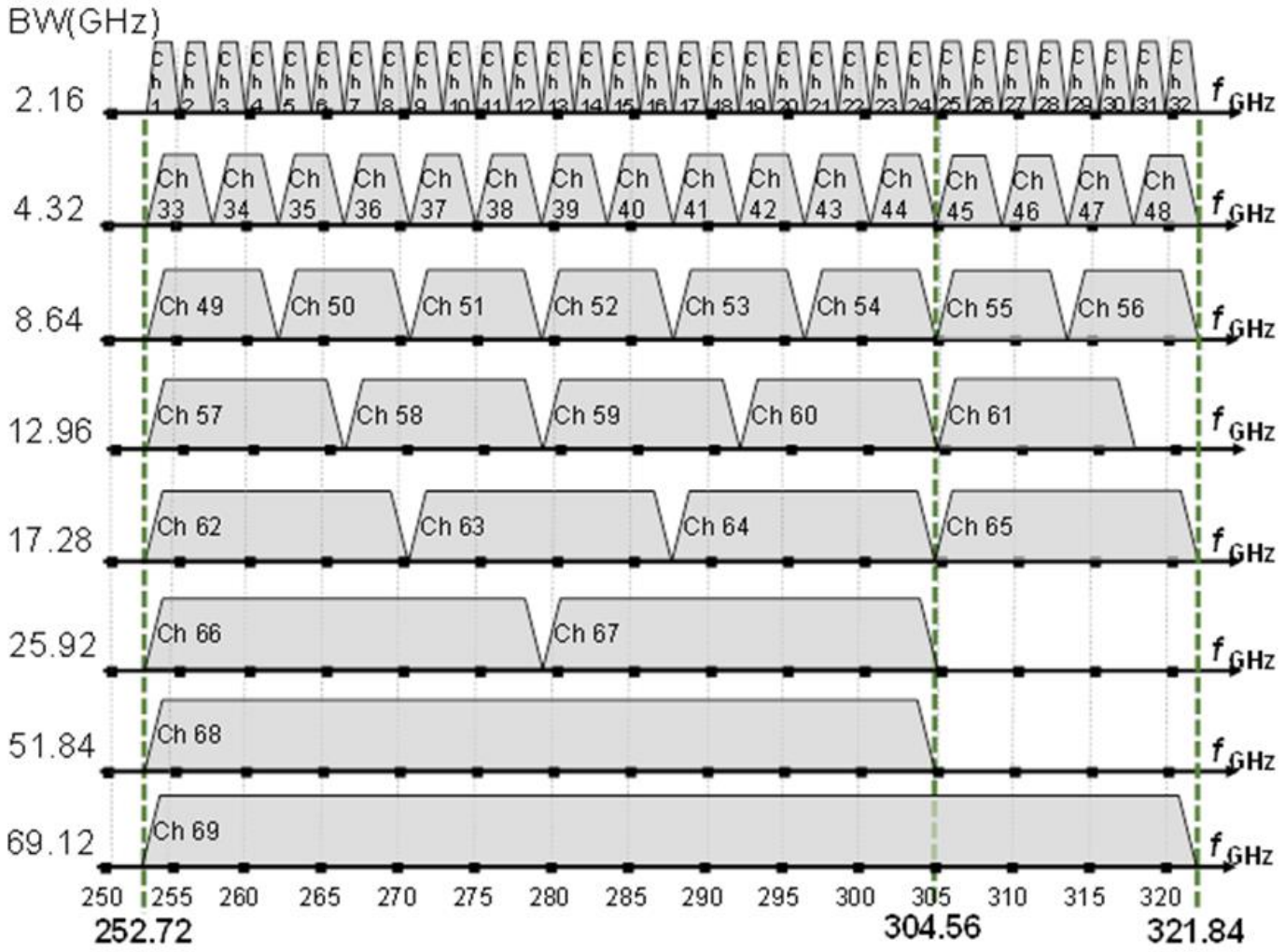
IEEE Computer Society

Sponsored by the LAN/MAN Standards Committee

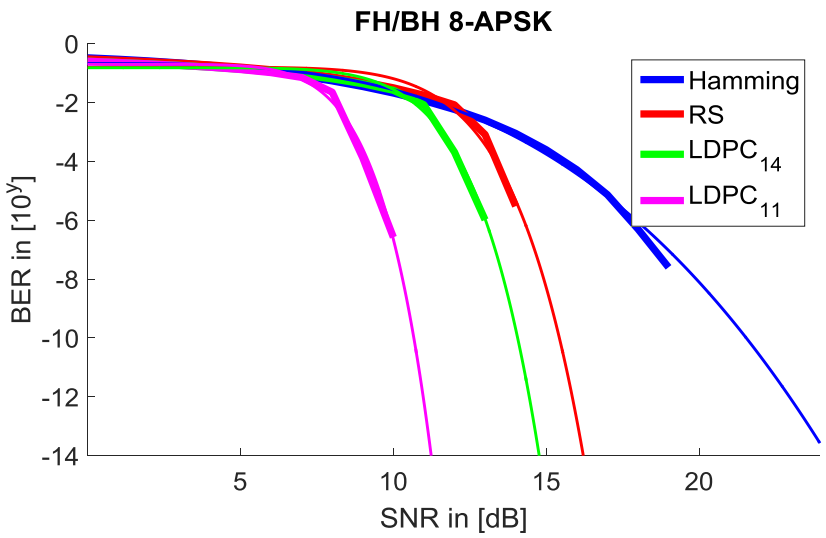
IEEE
3 Park Avenue
New York, NY 10016-5997
USA

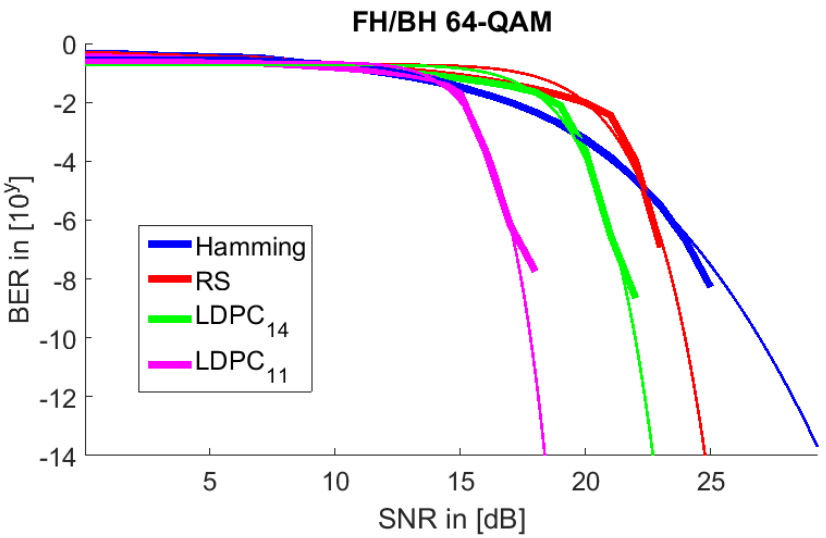
IEEE Std 802.15.3d™-2017
(Amendment to IEEE Std 802.15.3™-2016 as amended by IEEE Std 802.15.3e™-2017)

IEEE 802.15.3d Channel Plan



System Evaluation
Exemplary Results for the Backhaul/Fronthaul Application





- Link Level Simulations have been perfomed for all modulation and coding schemes
  => target Signal to Noise Ratio (SNR) for a required Bit Error Ratio (BER) of 10^{-12}
- Link budget analysis for all bandwidths
- Assumptions:
  - Transmitter output power of 1 W
  - Antenna gain of 40 dBi at both ends of the link

Achievable Link Distances and Data Rates for the Backhaul/Fronthaul Application

Assumption of a margin of 20 dB for atmospheric attenuation

MCS Identifier	Modulation	FEC Rate	Maximum Link Distance in m							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	5343	3778	2671	2181	1889	1542	1091	944
1	BPSK	14/15	3646	2578	1823	1488	1289	1052	744	644
2	QPSK	11/15	3796	2684	1898	1550	1342	1096	775	671
3	QPSK	14/15	2563	1812	1282	1046	906	740	523	453
4	8-PSK	11/15	2157	1525	1078	880	762	623	440	381
5	8-PSK	14/15	1725	1220	862	704	610	498	352	305
6	8-APSK	11/15	2157	1525	1078	880	762	623	440	381
7	8-APSK	14/15	1729	1223	864	706	611	499	353	306
8	16-QAM	11/15	1709	1209	855	698	604	493	349	302
9	16-QAM	14/15	1152	814	576	470	407	332	235	204
10	64-QAM	11/15	949	671	475	387	336	274	194	168
11	64-QAM	14/15	581	411	291	237	205	168	119	103

Data rate > 50 Gbit/s

Data rate > 100 Gbit/s

Starting point for Radio Regulations: Outcome of WRC 2012

5.565 A number of bands in the frequency range 275-1 000 GHz are identified for use by administrations for passive service applications. The following specific frequency bands are identified for measurements by passive services:

– radio astronomy service: 275-323 GHz, 327-371 GHz, 388-424 GHz, 426-442 GHz, 453-510 GHz, 623-711 GHz, 795-909 GHz and 926-945 GHz;

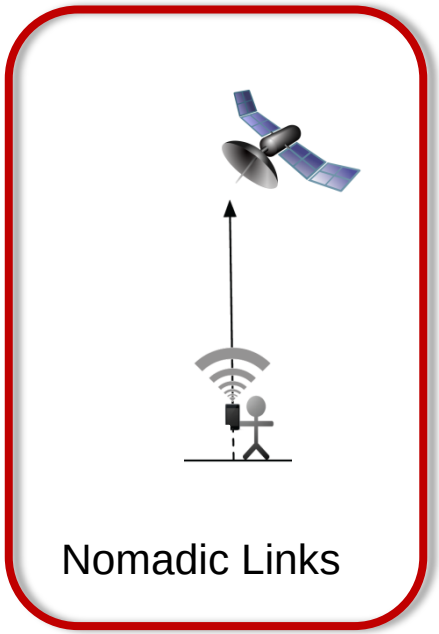
– Earth exploration-satellite service (passive) and space research service (passive): 275-286 GHz, 296-306 GHz, 313-356 GHz, 361-365 GHz, 369-392 GHz, 397-399 GHz, 409-411 GHz, 416-434 GHz, 439-467 GHz, 477-502 GHz, 523-527 GHz, 538-581 GHz, 611-630 GHz, 634-654 GHz,657-692 GHz, 713-718 GHz,729-733 GHz, 750-754 GHz, 771-776 GHz, 823-846 GHz, 850-854 GHz, 857-862 GHz, 866-882 GHz, 905-928 GHz, 951-956 GHz, 968-973 GHz and 985-990 GHz.

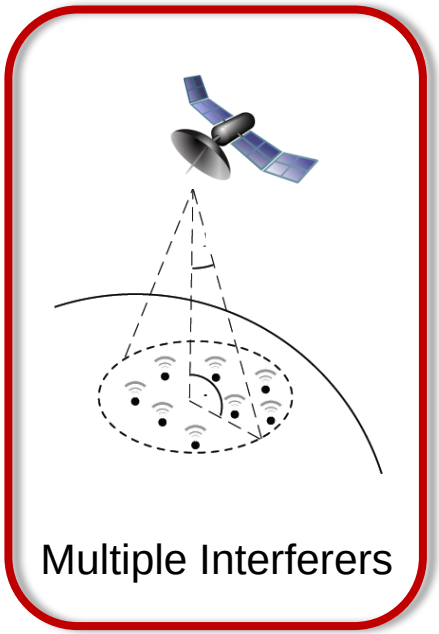
The use of the range 275-1 000 GHz by the passive services does not preclude use of this range by active services.

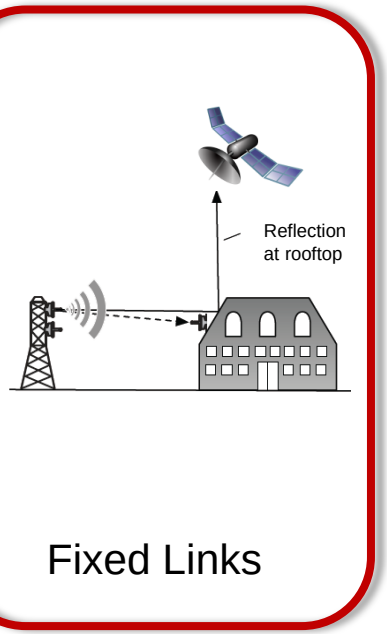
Administrations wishing to make frequencies in the 275-1 000 GHz range available for active service applications are urged to take all practicable steps to protect these passive services from harmful interference until the date when the Table of Frequency Allocations is established in the above-mentioned 275-1 000 GHz frequency range.

All frequencies in the range 1 000-3 000 GHz may be used by both active and passive services. (WRC-12)

Possible Interference Scenarios to be studied


Nomadic Links


Multiple Interferers



Fixed Links

Airborne Systems

- Interference Mitigation has to be considered right from the beginning, when developing THz Communications Systems

S. Priebe et al. „Interference Investigations of Active Communications and Passive Earth Exploration Services in the THz Frequency Range“, IEEE Transactions on THz Science and Technology, vol. 2, no. 5, pp. 525-537, 2012

The use of the frequency band 275 to 450 GHz for mobile and fixed services is subject to WRC 2019 AI 1.15

WRC 2015 agreed in resolution 767:

- to have an agenda item for WRC 2019 to consider identification of spectrum for land-mobile and fixed active services in the range of 275 GHz to 450 GHz while maintaining protection of the passive services identified in the existing footnote 5.565.

- ITU-R is invited to
  - identify technical and operational characteristics (WP 5A and 5C for the new active services, WP 7C and 7D for existing passive services)
  - study spectrum needs (WP 5A and 5C)
  - develop propagation models (SG 3)
  - conduct sharing studies with the passive services (WP 1A)
  - identify candidate frequency bands (WP 1A)

- ITU-R WP1A is leading the preparation of AI 1.15 and conducting the sharing studies.

Current status of the preparatory work of AI 1.15 WRC 2019

- The supporting Working Parties (WPs 5A, 5C, 7C, 7D and SG3) have finished their tasks.
- Regarding the new active services the reports ITU-R F.2416 and ITU-R M.2417 have been published. The applications are Close Proximity/Kiosk Downloading, Intra-Device Communications and additional wireless links in data centers (land mobile) and wireless front-/backhaul links (fixed services).
- The frequency bands of interest are
  - between 275 to 450 GHz for land mobile applications.
  - especially, 275-325 GHz and 380-445 GHz for fixed service applications (maybe another band is possible in between).

- WP 1A is conducting sharing studies and preliminary study results are available.
  - For instances in the band 275 to 296 GHz coexistence with the passive services seems to be possible. This provides a continues bandwidth of 44 GHz with the existing bands from 252-275 GHz.
  - Other bands are under consideration.

H2020-ICT-09-2017-Cluster on Networks Beyond 5G

- Six projects from the H2020 call ICT-09-2017 have been funded:

  - DREAM: D-band Radio solution Enabling up to 100Gb/s reconfigurable Approach for Meshed beyond 5G network
  - EPIC: Enabling Practical Wireless Tb/s Communications with Next Generation Channel Coding
  - TERAPOD: Terahertz based Ultra High Bandwidth Wireless Access Networks
  - TERRANOVA: Terabit/s Wireless Connectivity by Terahertz Innovative Technologies to deliver Optical Network Quality of Experience in Systems Beyond 5G
  - ULTRAWAVE: Ultra capacity wireless layer beyond 100 GHz based on millimeter wave Traveling Wave Tubes
  - WORTECS: Wireless Optical/Radio Terabit Communications

dream EPIC terapod TERRANOVA ULTRAWAVE

- These six projects have agreed to form an unofficial cluster in order to try to coordinate some dissemination activities to maximise the impact of the projects.

Outline

1. Introduction to THz Communications
2. Propagation Characterisation
   - Measurements and Modeling of Indoor Propagation
   - Terahertz Intra-Device Propagation Channel
3. Ultra-high Data Rate transmission with steerable antennas @300 GHz
4. Standardisation, Regulation and THz Communications @H2020
5. **Conclusion**

Conclusion

- Frequency bands beyond 275 GHz offer a huge potential to implement wireless communication systems with data rates targeting 100 Gbit/s

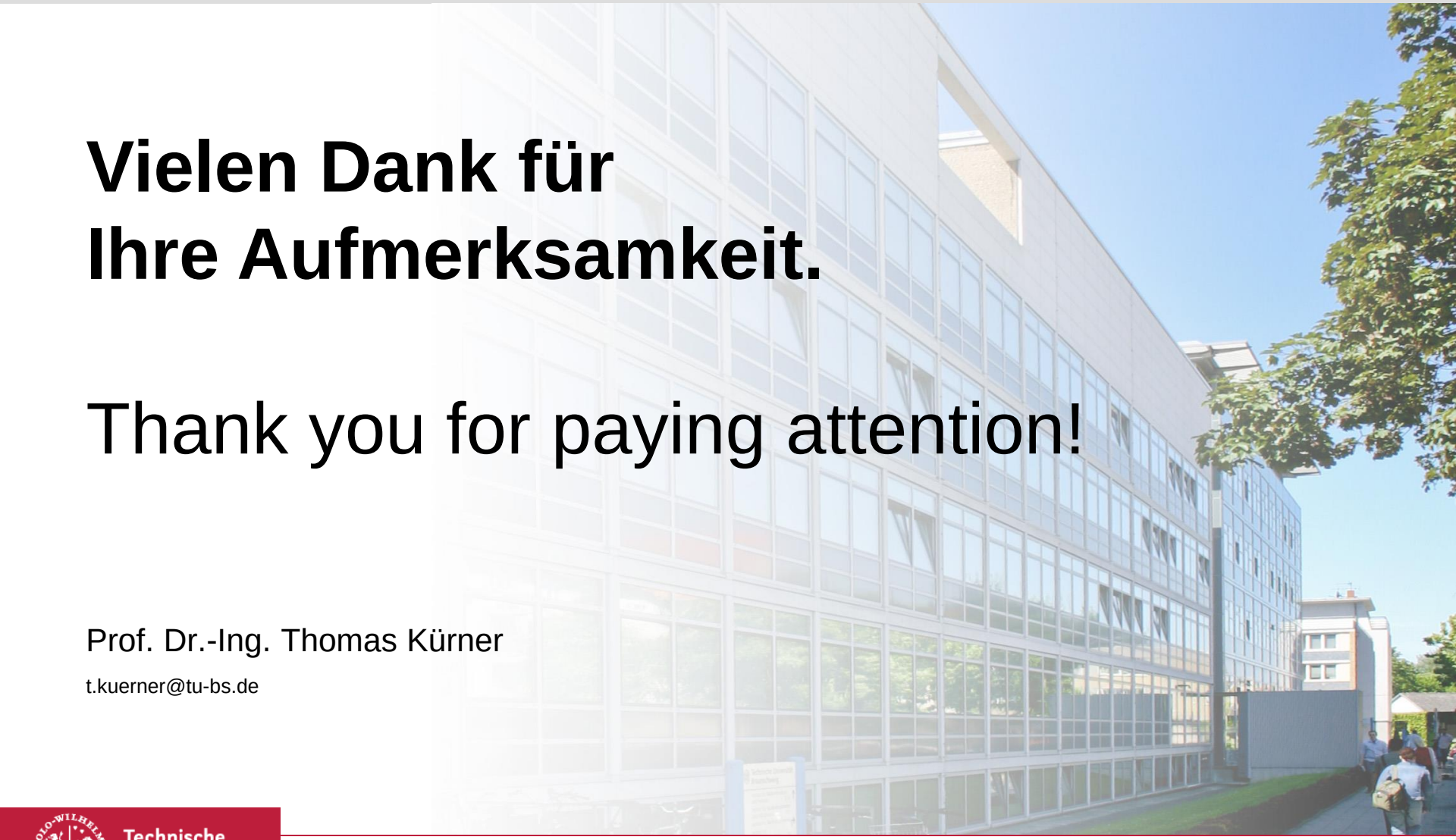
- Examples for ongoing research have been presented:
  - Channel modeling for indoor and intra-device communication
  - MMIC-based demonstrator with steerable antennas

- A first standard @ IEEE 802 has been completed

- Activities targeting allocation of spectrum beyond 275 GHz at WRC 2019 (AI 1.15)

- A couple of H2020 projects are working towards THz Communications

THz Communications is a real option for wireless networks beyond 5G!



Vielen Dank für Ihre Aufmerksamkeit.

Thank you for paying attention!

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