What are the possibilities to achieve 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 switched Point-to-Point Links

- (1) THz WPANs/WLANs
- (2) Wireless data to home
- (3) Kiosk downloads
- (4) Backhaul/Fronthaul links
- (5) Wireless Links in Data Centers
- (6) Intra-Device Communication

Current Activities of Institut für Nachrichtentechnik at TU Braunschweig in the Area of THz Communications

Running Research Projects
- H2020-dBRoW
- H2020 - TERAPOD
- THz for Railway Communications
- THz for Nano Communications

Standardisation and Regulation
- IEEE 802.15
- Chair IEEE 802.15 IG THz (Thomas Kürner)
- CEPT-Coordination WRC 19 AI 1.5 (Sebastian Rey)

Recently procured Measurement Equipment
- Procurement of the globally first Channel Sounder @ 300 GHz

Structure of the remaining Talk
- Results from recent research activities at TU Braunschweig
- Propagation Characterisation
  - Measurements and Modeling of Indoor Propagation
  - Terahertz Intra-Device Propagation Channel
- Ultra-high data rate transmission with steerable antennas @300 GHz
- Overview on ongoing Activities in Standardisation and Regulation
- Outlook Potential for future Applications in Nano Communications
Outline

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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


Rough Surface Scattering in Specular Direction

Measured Surface Properties of Raufaser

Raufaser, 70 Grad, TE Polarization

Relative Oberflächenhöhe [mm]

f [GHz]

f [GHz]

f [GHz]
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 Polyethylene lens

<table>
<thead>
<tr>
<th>Measurement parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>275 - 325 GHz</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>2°</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>145 dB</td>
</tr>
<tr>
<td>Measurement duration for one position (360° x 360°)</td>
<td>90 h</td>
</tr>
</tbody>
</table>

MIMO Measurement Results

- High channel correlation (between 0.6 and 0.86 for CTFs)
- Ergodic capacity of 6.21 bit/s/Hz derived for 2x2 MIMO at an SNR of 10 dB compared to 3.46 bit/s/Hz at the SISO case

Comparison between measured and (ray launching) predicted AoA

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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Size of Scenario [in cm]</th>
<th>Simulation run time</th>
<th>Memory requirements [GByte]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario as presented in the following slides</td>
<td>13x1x0.5</td>
<td>3 h</td>
<td>3.6</td>
</tr>
<tr>
<td>Medium scenario for intra-device communication</td>
<td>20x20x20</td>
<td>108d</td>
<td>2900</td>
</tr>
</tbody>
</table>

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

- In this investigation three effects are considered:
  - Impact of the transmitting antenna on the pulse shape
  - Propagation along metallic and plastic surfaces (ABS: acrylonitrile butadiene styrene)
  - Reflections at the transmitting and receiving antenna
- A simple scenario with two horn antennas separated by the distance $d_h$ above a surface is considered
- Simulated with
  - CST® Microwave Studio®
  - the transient solver due to the high bandwidth

Measuring the THz Intra-Device Channel

Rohde & Schwarz ZVA50 with Frequency Extensions ZVA-Z325

Standard Gain Horns
Absorbers
Absorbing Foil

Mock-Up:

Ray Tracing vs. Measurements at a 300 GHz Intra-Device Environment

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

- 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.
IEEE 802.15 TG3d Channel Model

- Intensive Ray Tracing for intra-device scenarios have been used for the development of the IEEE 802.15 TG3d Channel Model:
  https://mentor.ieee.org/802.15/dcn/14/15-14-0310-19-003d-channel-modeling-document.docx

Method for the derivation of Channel Statistics for the TG3d intra-device Channel Model

Use of Channel Models for Evaluation of System Proposals

- Based on the generated CTFs, link-level simulations for different MCSs have been conducted
- Results served as a basis for decisions on available MCS as well as realistic link distances, EVM and sensitivity requirements
- E.g. robust OOK will increase its SNR requirement by only 2dB when changing from 6dBi to 18dBi antennas and not any further if simple AWGN channel is assumed
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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 transmission with QPSK (limited by measurement equipment and linearity)

Setup of the TERAPAN demonstrator

- **1st Demonstrator (March 2015)**
  - 1st generation of chip design
  - mechanical beam 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

http://www.terapan.de
Targets for the Antenna Design for 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


Proposed Antenna

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>3.0 mm (horn width)</td>
</tr>
<tr>
<td>C</td>
<td>1.0 mm (horn height)</td>
</tr>
<tr>
<td>D</td>
<td>0.8640 mm (WR3)</td>
</tr>
<tr>
<td>E</td>
<td>0.4320 mm (WR3)</td>
</tr>
<tr>
<td>F (flare)</td>
<td>3.577 mm</td>
</tr>
<tr>
<td>spacing</td>
<td>1.25 mm = C + 0.25 mm</td>
</tr>
</tbody>
</table>
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°
  - Slightly different dimensions

Beam Steering and Grating Lobes

- Phase increment for a trapped angle $\alpha$
  \[ \delta = \frac{2\pi}{\lambda} \times \sin \alpha \]
- Grating lobe due to spacing of 1.25 mm
- Can grating lobes be avoided?
  - Customized WG
  - $D=0.55$ mm; usually 2E, but cut-off frequency is 325 GHz
- H-plane sectoral horn:
  - $C=13$ 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

Measurement Results

- 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)

Beam Tracking of Moving Mobile Devices

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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
  - Wireless Links in Data Centers

- The standard is expected to be published in October 2018.
Standardisation – IEEE 802.15 Interest Group THz

- The Interest Group THz has been established already in 2008
- Chair: Thomas Kürner (TU Braunschweig)
- Vice-Chair: Iwao Hosako (NICT)

The focus of the Interest Group is primarily concerned with THz communications and related network applications operating in the THz frequency bands between 275 and 3000 GHz.

TG 3d is a spin-off from this Interest Group.

The Interest Group may yield the establishment of further Study Groups with applications different from the scope of TG3d.

Regulation:
Spectrum Issues (Outcome of WRC 2012)

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;

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

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

- ITU-R is invited to
  - identify technical and operational characteristics
  - study spectrum needs
  - develop propagation models
  - conduct sharing studies with the passive services
  - identify candidate frequency bands

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THz Communications for biomedical Nano Sensors

- Hundreds of physical, chemical and biological nano sensors & nano actuator are considered with different specific targets.
- The capabilities of nano machines are constrained by detection & actuation range.
- Integrating nano sensor with nano communication transceiver could enhance the range of applications and capabilities for these nano sensors.

- EM communication among nanosensors will be enabled by the development of nano-antennas and the corresponding electromagnetic transceiver.
- Graphene-based nano-path antenna show novel properties, different from metallic antenna.
- EM waves propagating in graphene have a lower propagation speed than in metallic antennas.
- Nano-sized graphene-based antenna radiates in THz band (0.1-10 THz).

A harsh Propagation Environment:
Molecular Path Loss & Molecular Noise in Human Tissue

- Nano-sized graphene-based antenna radiates in THz band (0.1-10 THz).
- Graphene-based nano-path antenna show novel properties, different from metallic antenna.
- EM waves propagating in graphene have a lower propagation speed than in metallic antennas.
- Nano-sized graphene-based antenna radiates in THz band (0.1-10 THz).
Some Challenges to be met in order to make Nano Communications happen

- Nano communication limitation (compared to current wireless network communication paradigm):
  - Very small size (µm)
  - Limited power (energy harvesting)
  - Limited computational resources
    - complex modulation, coding & protocol must be avoided
  - No synchronization time
  - High molecular absorption loss and molecular noise.

- Wireless Nano Sensor Network needed to overcome the limited transmission range of individual Nano nodes to convey the information.

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Conclusion and Outlook

- Frequency bands beyond 275 GHz offer 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 is almost completed
- Activities targeting allocation of spectrum beyond 275 GHz at WRC 2019 (AI 1.15)
- Potential to use THz also for nano communications

Vielen Dank für Ihre Aufmerksamkeit.

Thank you for paying attention!

Prof. Dr.-Ing. Thomas Kürner
t.kuerner@tu-bs.de