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Submission Title: Diffuse Rough Surface Scattering Analysis for THz Communication Systems
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Re: doc.: IEEE 802.15-15-10-0436-01-0thz-towards-a-300-ghz-channel-model

Abstract: Rough surface scattering from common indoor materials like plaster or ingrain wallpaper is expected to exert a high impact on the propagation of THz waves in indoor scenarios. A suitable scattering model is obligatory for correct propagation simulations. In this presentation, the implementation of the Kirchhoff scattering theory as well as of a perturbation approach into a ray tracing algorithm is demonstrated. Ray tracing simulations are validated against measurements. The polarization-dependent impact of scattering on 300 GHz propagation channels is investigated in an indoor scenario.

Purpose: Investigation of rough surface scattering at THz frequencies as input for THz channel modeling

Diffuse Rough Surface Scattering Analysis for THz Communication Systems

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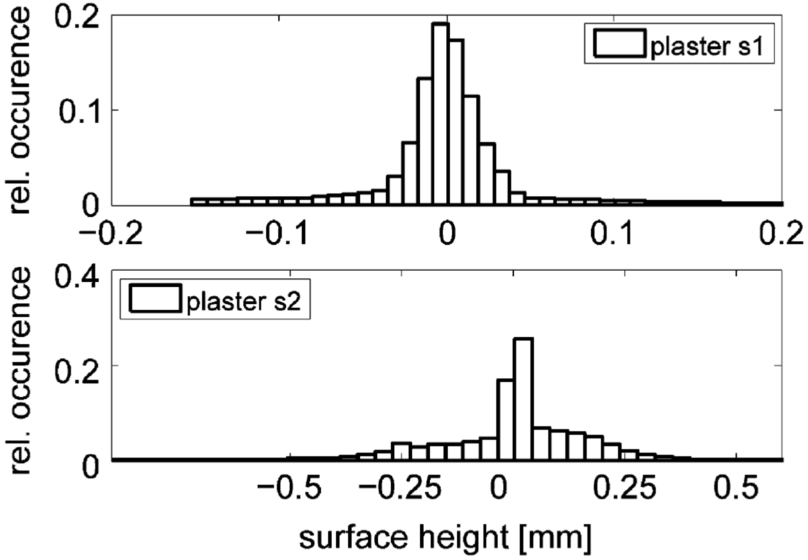
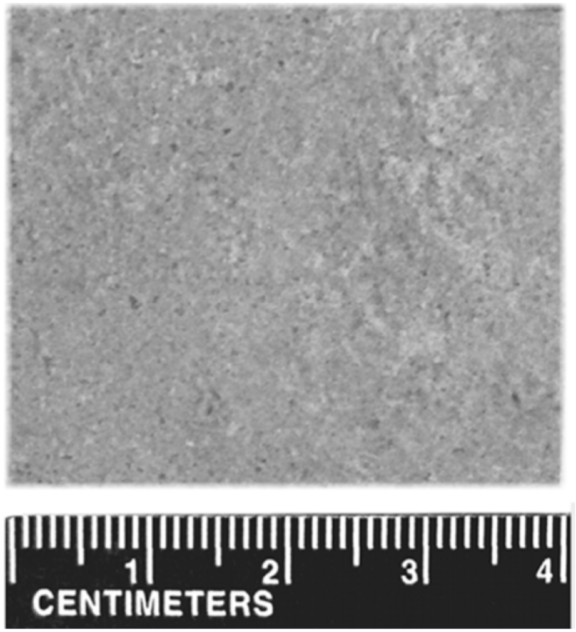
Outline

1. **Introduction**
2. Scattering Models
3. Implementation Aspects
4. Scattering Impact on THz Propagation Channels
5. Summary/Outlook

Introduction (1)

- Previous work by the Terahertz Communications Lab (TCL): Characterization of statistical rough surface parameters



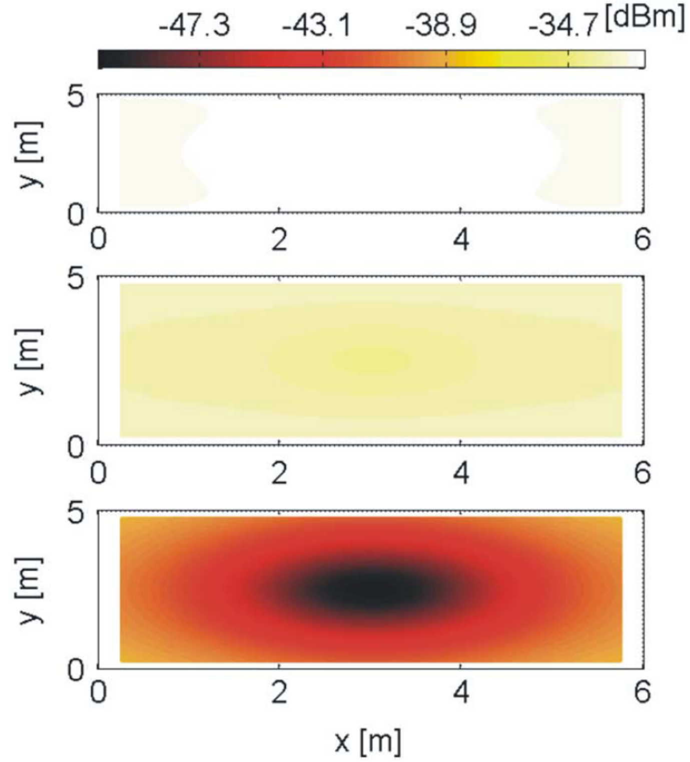


R. Piesiewicz, C. Jansen, D. Mittleman, T. Kleine-Ostmann, M. Koch, and T. Kürner, “Scattering Analysis for the Modeling of THz Communication Systems,” *IEEE Trans. on Ant. and Prop.*, *vol. 55, no. 11 Part* 1, pp. 3002–3009, 2007.

→ Necessary input for rough surface scattering models

Introduction (2)

- Influence of rough surfaces on the specular reflections at 350 GHz



Smooth walls

Plaster 1
(low roughness)

Plaster 2
(higher roughness)

R. Piesiewicz, C. Jansen, D. Mittleman, T. Kleine-Ostmann, M. Koch, and T. Kürner, "Scattering Analysis for the Modeling of THz Communication Systems," *IEEE Trans. on Ant. and Prop.*, *vol. 55, no. 11 Part* 1, pp. 3002–3009, 2007.

→ Diffuse scattering?

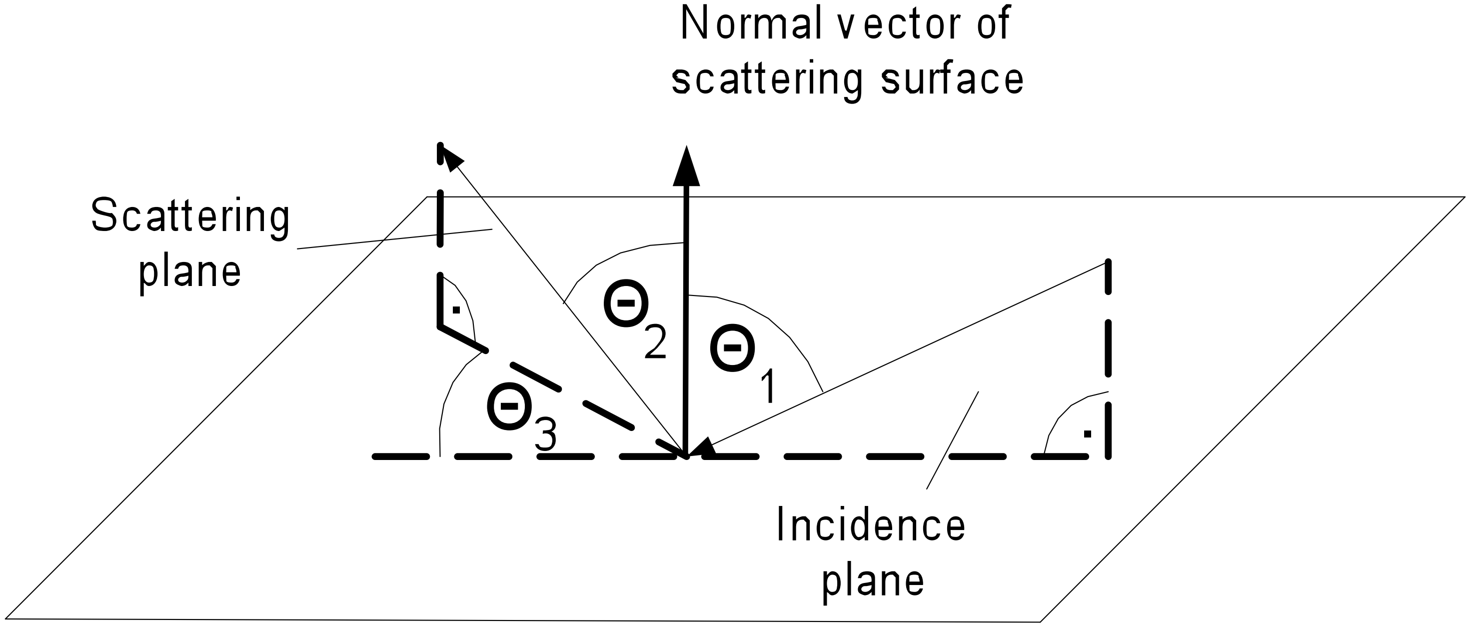
→ Impact of scattering on broadband channel characteristics?

Outline

1. Introduction
2. **Scattering Models**
   - **Kirchhoff Scattering Theory**
   - **Perturbation Method**
   - **Geometrical Depolarization**
3. Implementation Aspects
4. Scattering Impact on THz Propagation Channels
5. Summary/Outlook

Kirchhoff Scattering Theory (1)

- analytically describes rough surface scattering
- relies on a Gaussian height deviation distribution
- is applicable for scattering from typical building materials at THz frequencies like plaster, wallpaper etc.



Kirchhoff Scattering Theory (2)

- Power reflection factor:

$$\langle R_{power}\rangle = \left(\frac{kA\cdot\cos(\theta_1)}{\pi r_0}\right)^2 \cdot \langle\rho\rho^*\rangle$$

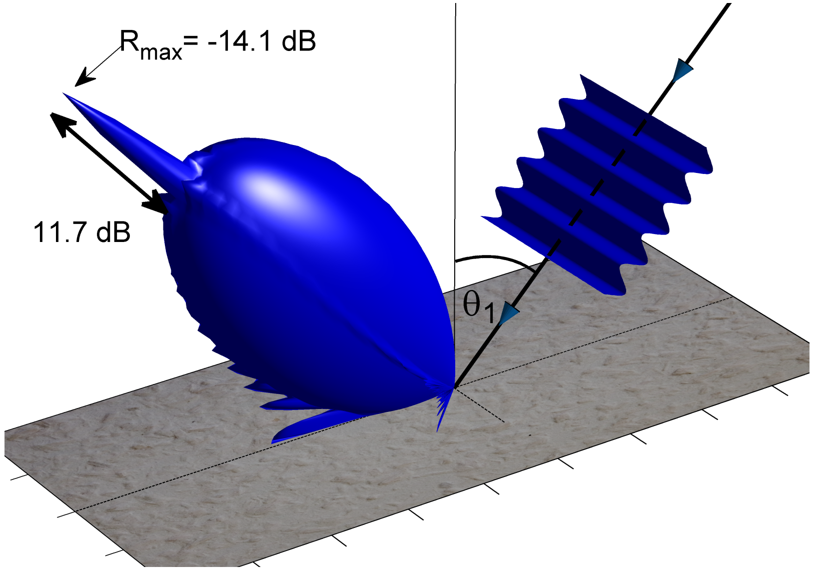
- Scattering coefficient (ideal conductivity):

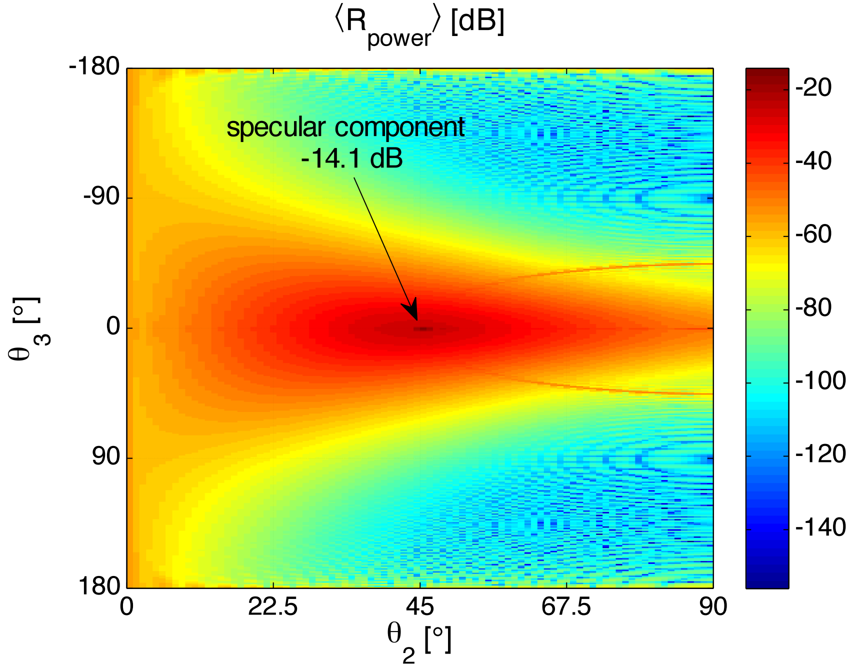
$$\langle\rho\rho^*\rangle_\infty = e^{-g}\cdot\left(\underbrace{\rho_0^2}_{\text{Specular}} + \underbrace{\frac{\pi l_{corr}^2 F^2}{A}\sum_{m=1}^{\infty}\frac{g^m}{m!m}e^{-\frac{v_{xy}^2 l_{corr}^2}{4m}}}_{\text{Non-specular}}\right)$$

k	Wave number	g	Roughness factor
r_0	Distance from scattering point to RX	σ_h	Surface height standard deviation
A	Illuminated area	v_{xy}	Geometry- and wavelength-dependent term
F	Geometrical factor	l_{corr}	Surface correlation length

Kirchhoff Scattering Theory (3)

- The power reflection factor for $A = 100 \cdot l_{corr}^2$, f = 300 GHz, $\theta_1 = 45°$, $|r_{TE}| = 1$, $r_0 = 2$ m and realistic material parameters $l_{corr} = 2.3$ mm, $\sigma_h = 0.13$ mm of ingrain wallpaper:





→ Drawback of Kirchhoff theory: no depolarization

Perturbation Theory (1)

- Power reflection factor:

$$R_{Power,mn} = \frac{k^4 \cdot A \cdot \sigma^2}{(2\pi r_0)^2} \Phi_{mn}(\theta_1, \theta_2, \theta_3) \, S(k'_{sc})$$

- Polarization-dependent factor:

$$\Phi_{mn} = 4 \cos^2 \theta_1 \cos^2 \theta_2 Q_{mn}^2$$

- Spatial surface spectrum (Gaussian height distribution):

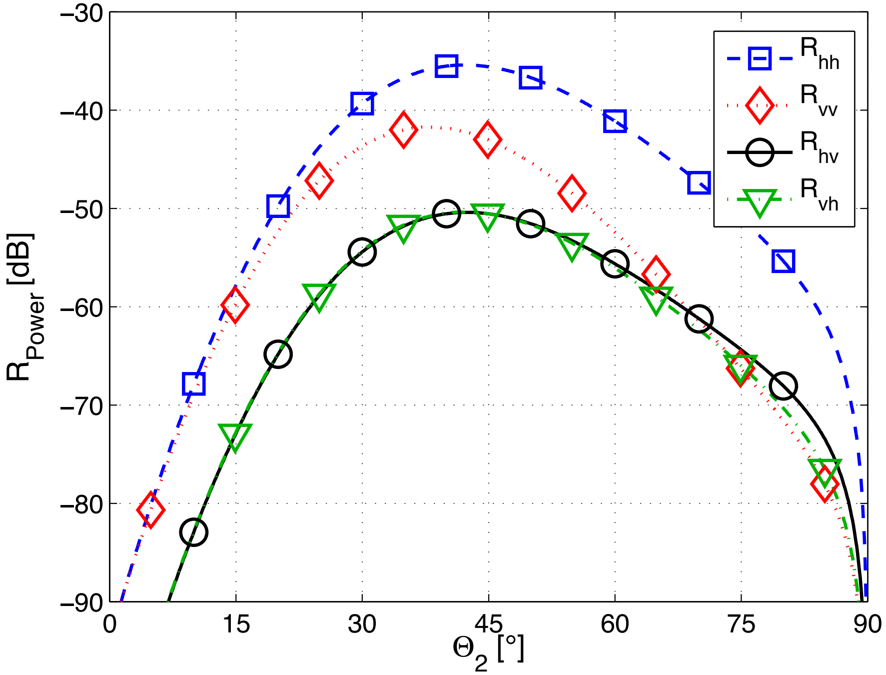
$$S(k'_{sc}) = l_{corr}^2 \pi e^{-\frac{(k'_{sc} \cdot l_{corr})^2}{4}}$$

→ Similar dependences like the Kirchhoff theory, but fully polarimetric

Q_{mn}	Geometry-, polarization- and material parameter dependent factor [1]	k'_{sc}	Scattered wave number projected onto surface
m,n	Polarization indices (h: horizontal, v: vertical)		

Perturbation Theory (2)

- The power reflection factor for $A = 100 \cdot l_{corr}^2$, f = 300 GHz, $\theta_1 = 45°$, $\theta_3 = 10°$, $r_0 = 1$ m and realistic material parameters $\varepsilon' = 3.691$, $\varepsilon'' = 0.217$, $l_{corr} = 1.7$ mm and $\sigma_h = 0.15$ mm of plaster:



→ High cross-polarization

→ Drawback: no specular component

Geometrical Depolarization (Jones Calculus)

- Received electric field:

$$E_{RX} = \mathbf{g}_{RX}^{H} \cdot \mathbf{P} \cdot \mathbf{g}_{TX} \cdot L \cdot E_{TX}$$

- Polarization-dependent scattering matrix:

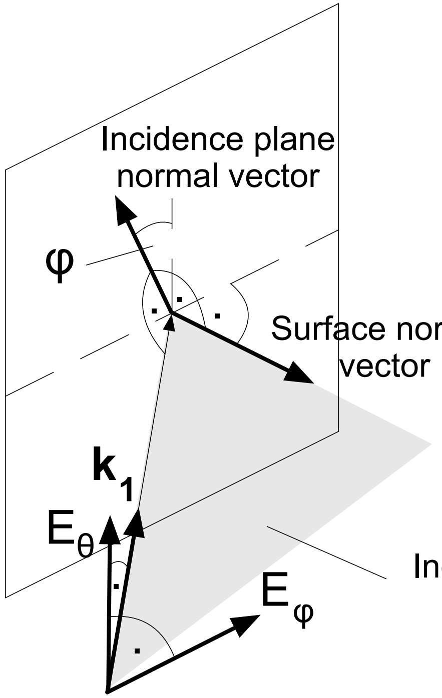
$$\mathbf{P} = \mathbf{R}(\varphi_{\mathbf{RX}}) \cdot \mathbf{R_n} \cdot \mathbf{R}(\varphi_{\mathbf{p_n}}) \ldots \cdot \mathbf{R_2} \cdot \mathbf{R}(\varphi_{\mathbf{p_2}}) \cdot \mathbf{R_1} \cdot \mathbf{R}(\varphi_{\mathbf{TX}})$$

- Rotation Matrix:

$$\mathbf{R}(\varphi) = \begin{pmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{pmatrix}$$

- Reflection/scattering matrix:

$$\mathbf{R_n} = \begin{pmatrix} r_{\perp,n} & \zeta_{1,n} \\ \zeta_{2,n} & r_{\parallel,n} \end{pmatrix}$$



g	Antenna Jones vector
L	Propagation loss
E_{TX}	Electric field

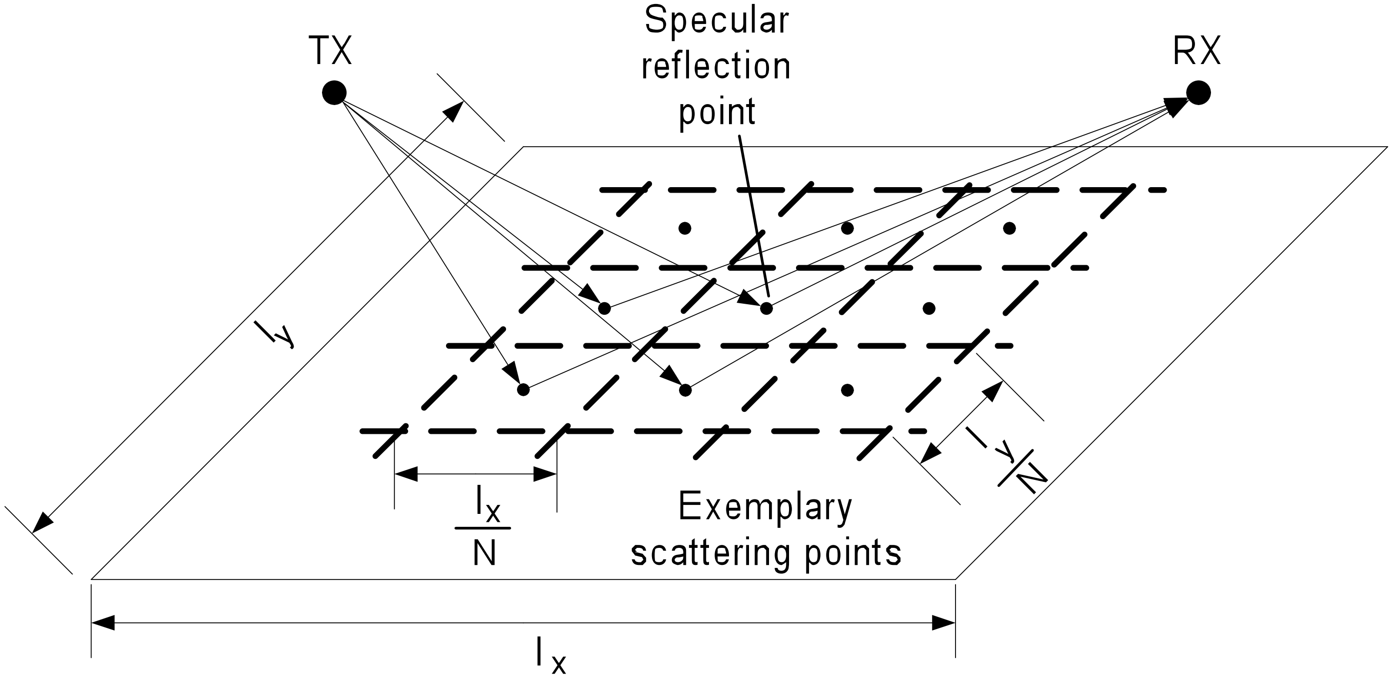
→ Co-polarization in scattering matrix according to Kirchhoff, cross-polarization according to perturbation approach

Outline

1. Introduction
2. Scattering Models
3. **Implementation Aspects**
    - **Implementation Into Ray Tracing**
    - **Validation**
4. Scattering Impact on THz Propagation Channels
5. Summary/Outlook

Implementation Into Ray Tracing

- Division of surface into square tiles around specular reflection point:



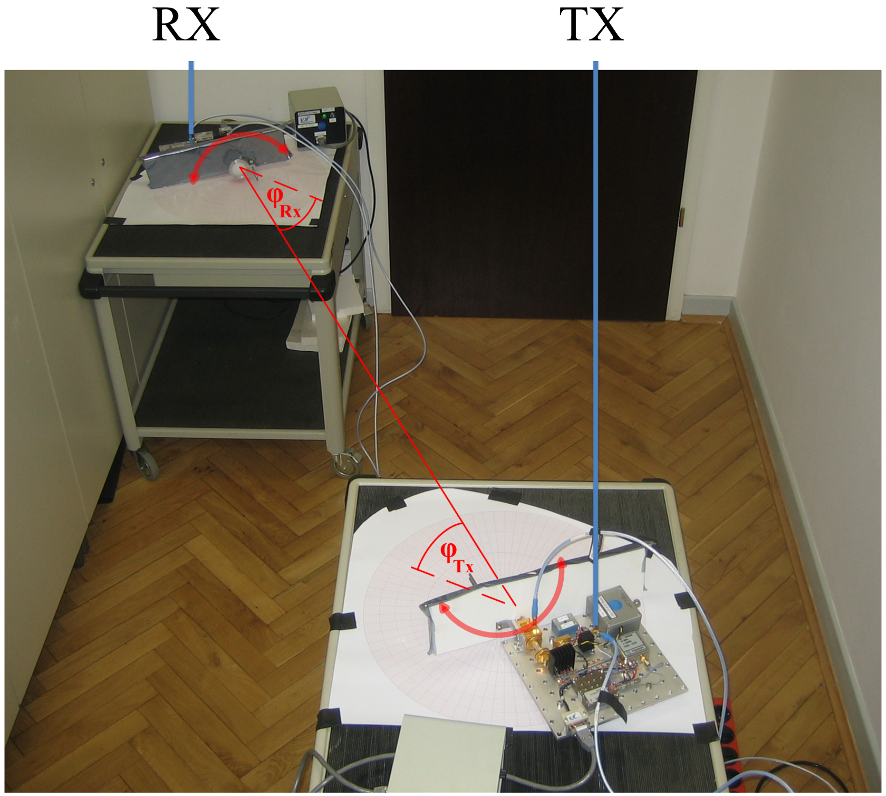
→ N^2 scattered rays with a power proportional to $\frac{A}{N^2}$

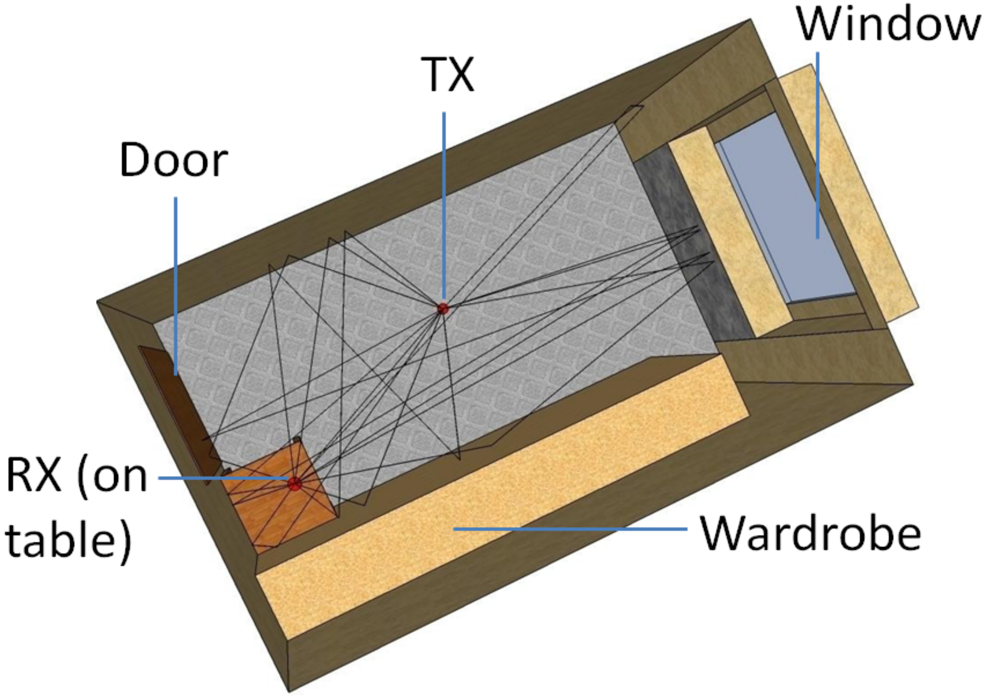
→ Totally scattered power constant regardless of tile size

→ Tradeoff between accuracy and computational time

Validation (1)

- Channel measurements and ray tracing in a small office room with plaster walls at 300 GHz:

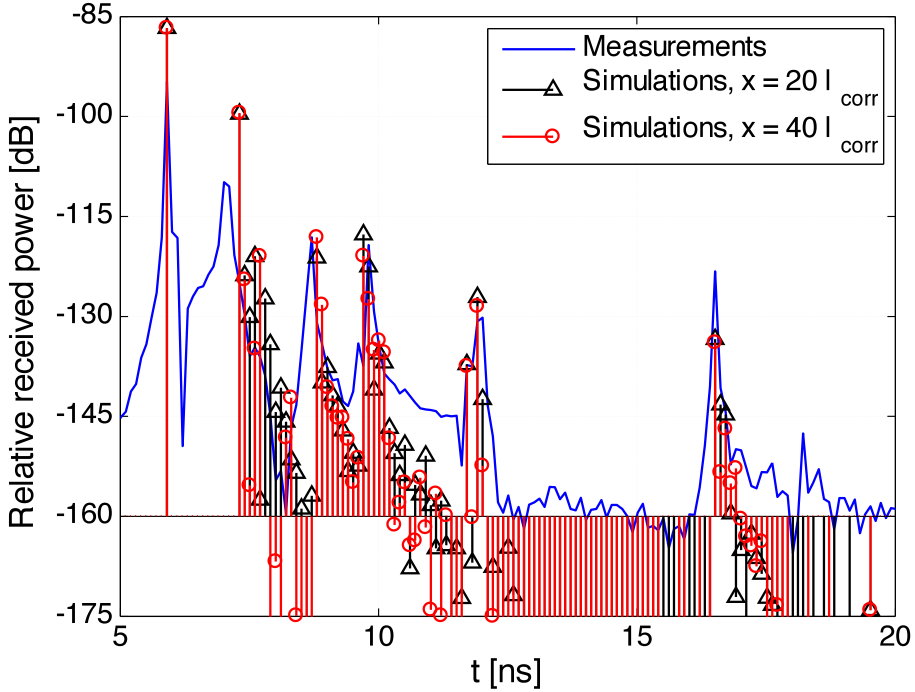




cf. doc.: IEEE 802.15-15-10-0436-01-0thz

Validation (2)

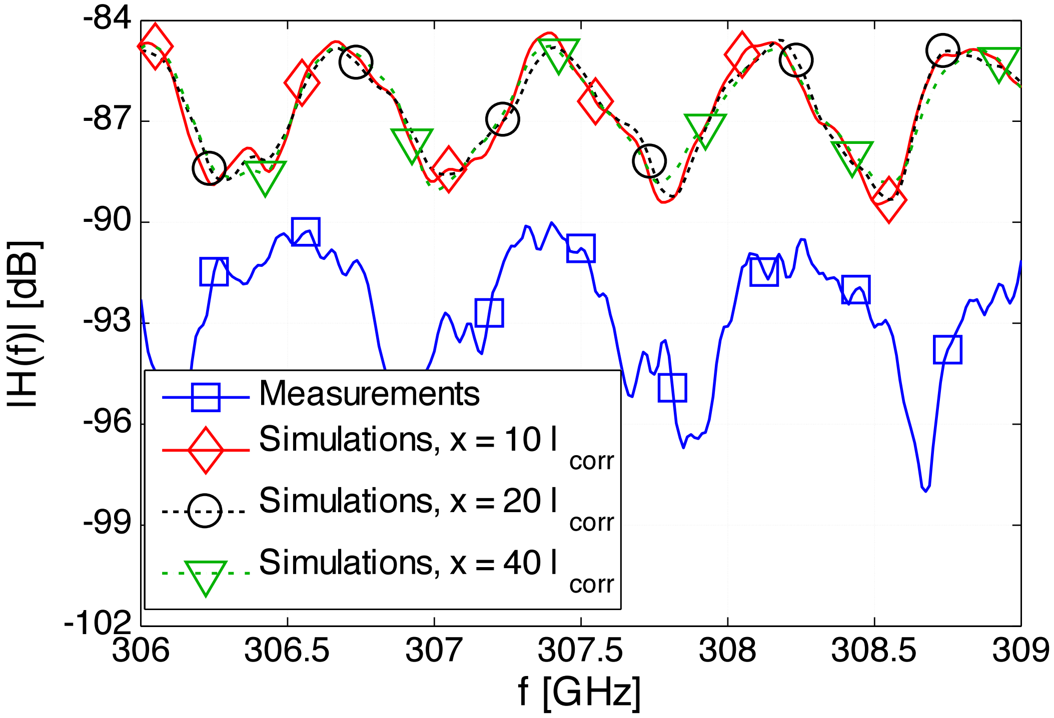
- Measured/simulated channel impulse responses for different tile sizes $A_{tile} = x \cdot x$:



→ Good agreement between simulations and measurements regardless of tile size

Validation (3)

- Measured/simulated channel transfer functions for different tile sizes:



→ Good agreement of the general behavior also over frequency

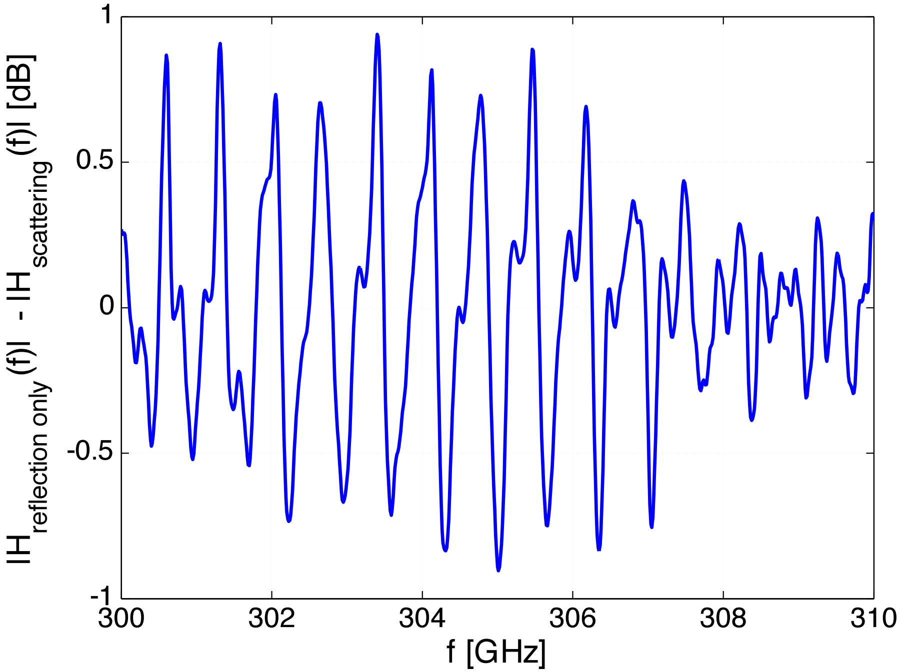
→ Difference between the mean attenuations mainly due to deviations between measured and simulated LOS power

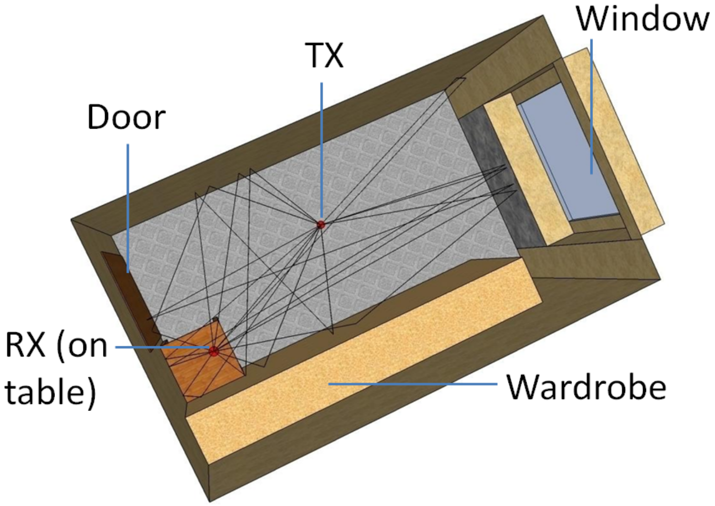
Outline

1. Introduction
2. Scattering Models
3. Implementation Aspects
4. **Scattering Impact on THz Propagation Channels**
    - **Fading**
    - **Relevant Scattering Area**
    - **Polarization**
5. Summary/Outlook

Fading

- Difference between simulated transfer functions in the office setup with and without scattering (omnidirectional antenna):



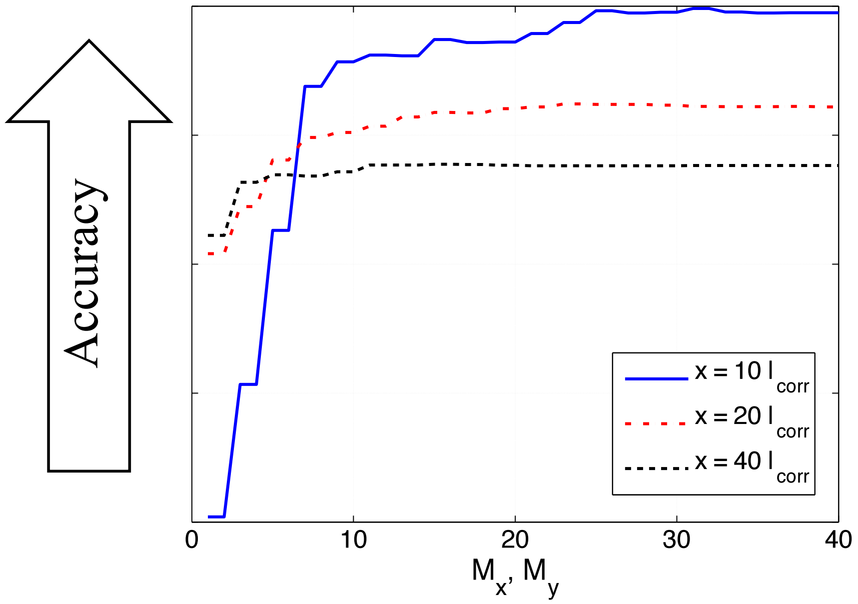


→ Deviations of up to 1.8 dB peak-to-peak over a bandwidth of 10 GHz

→ Consideration of scattering obligatory for propagation modeling

Active Scattering Area

- Variation of the numbers $M_{x,y}$ of respected tiles in x- and y-direction around specular reflection point
- Difference between the channel transfer functions with and w/o scattering summed up over 10 GHz bandwidth:



→Main scattering contribution around specular reflection point

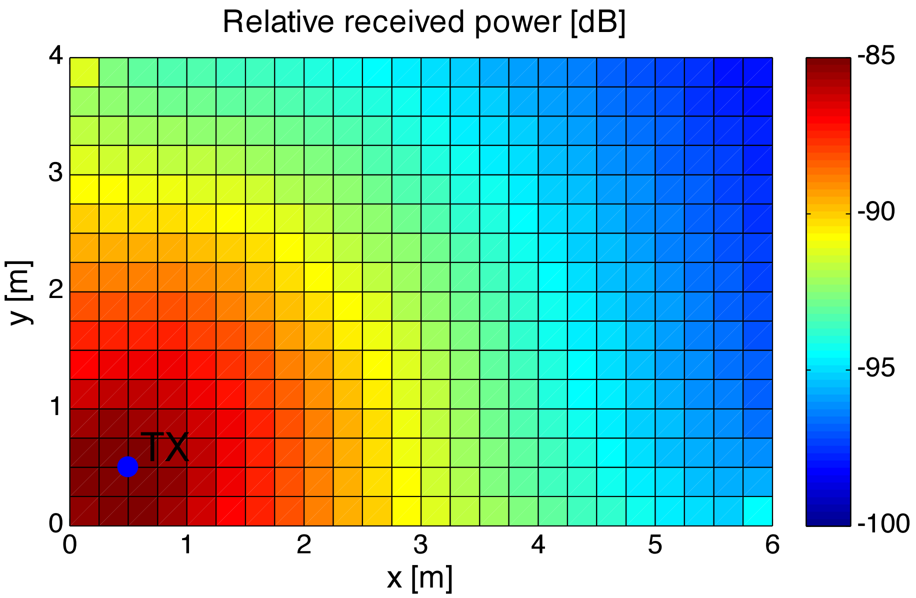
→Limited number of tiles sufficient (accuracy ↔ computational time)

→Higher accuracy for smaller tiles

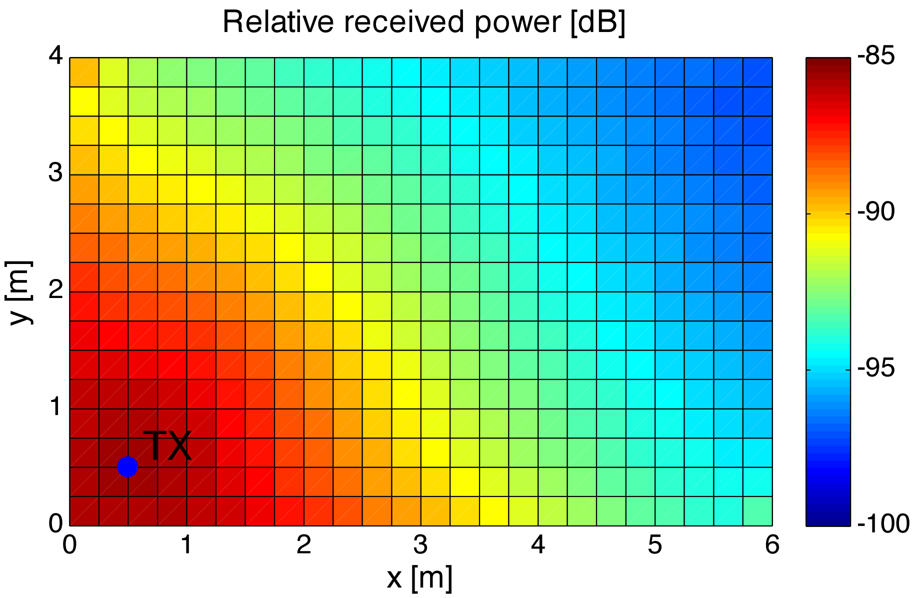
Polarization (1)

- Coverage simulations in an unfurnished office room (6 m × 4 m × 2.5 m) with rough plaster walls and ceiling
- TX placed at x = 0.5 m, y = 0.5 m, z = 2.3 m; RX at z = 0.8 m
- Omnidirectional antennas with different polarizations

→ Connection of nomadic device to an access point



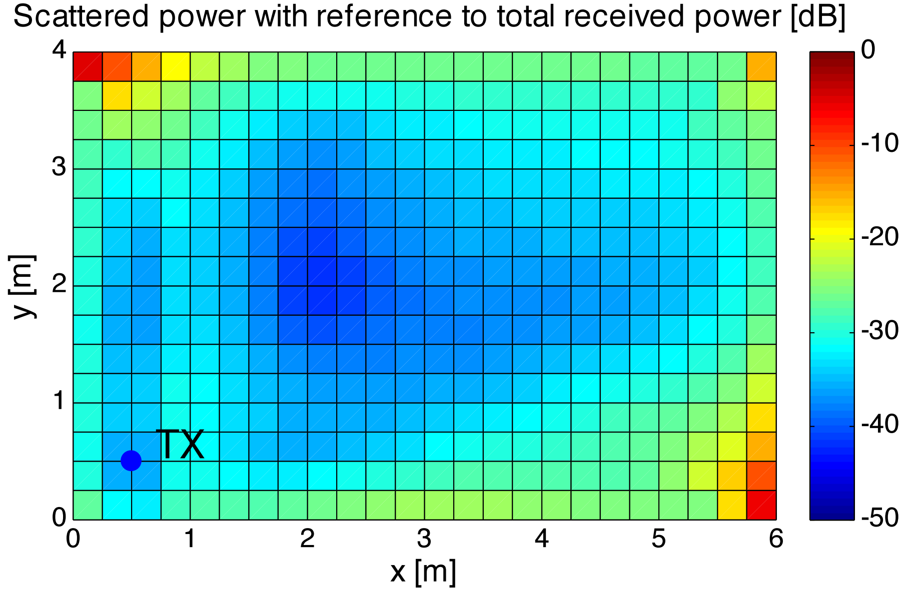
Horizontal polarization



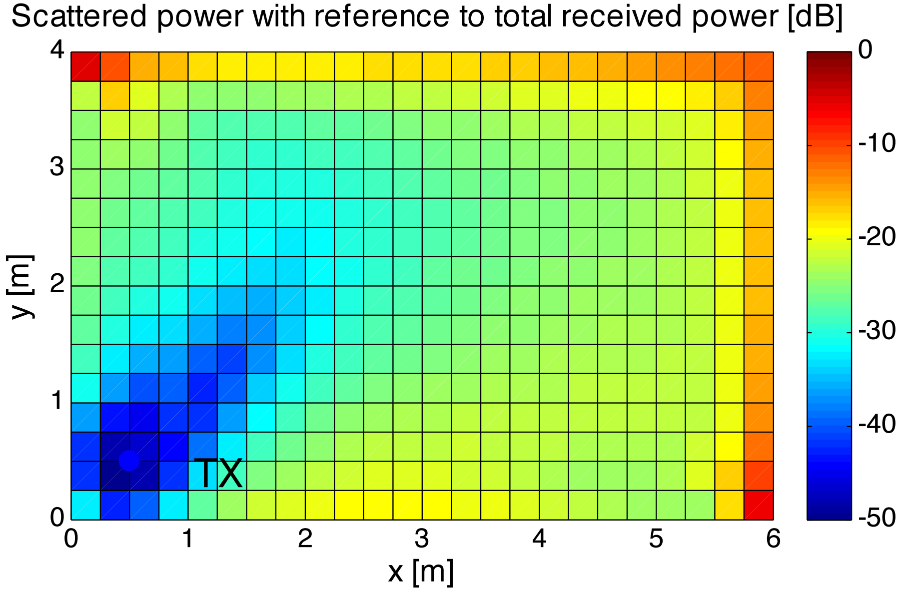
Vertical polarization

Polarization (2)

- Relative contribution of the scattered power to the total received power:



Horizontal polarization



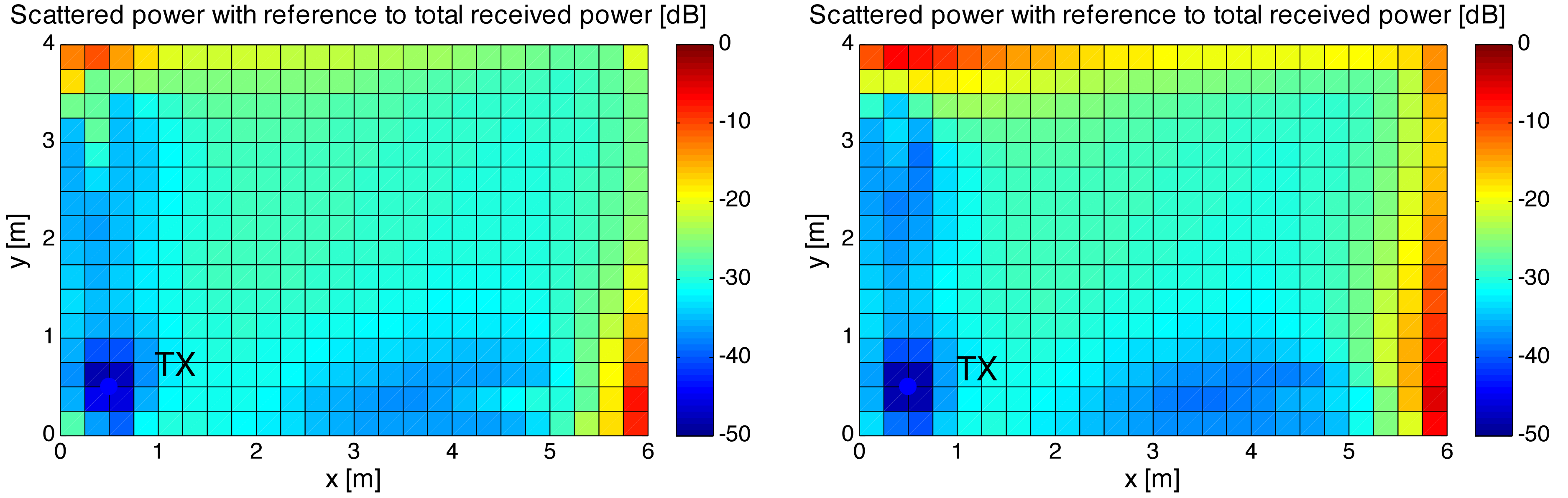
Vertical polarization

→ Higher scattering impact for vertical polarization

→ Scattering most relevant in corners of the room and close to walls

Polarization (3)

- Influence of cross-polarization:



Vertical to horizontal polarization

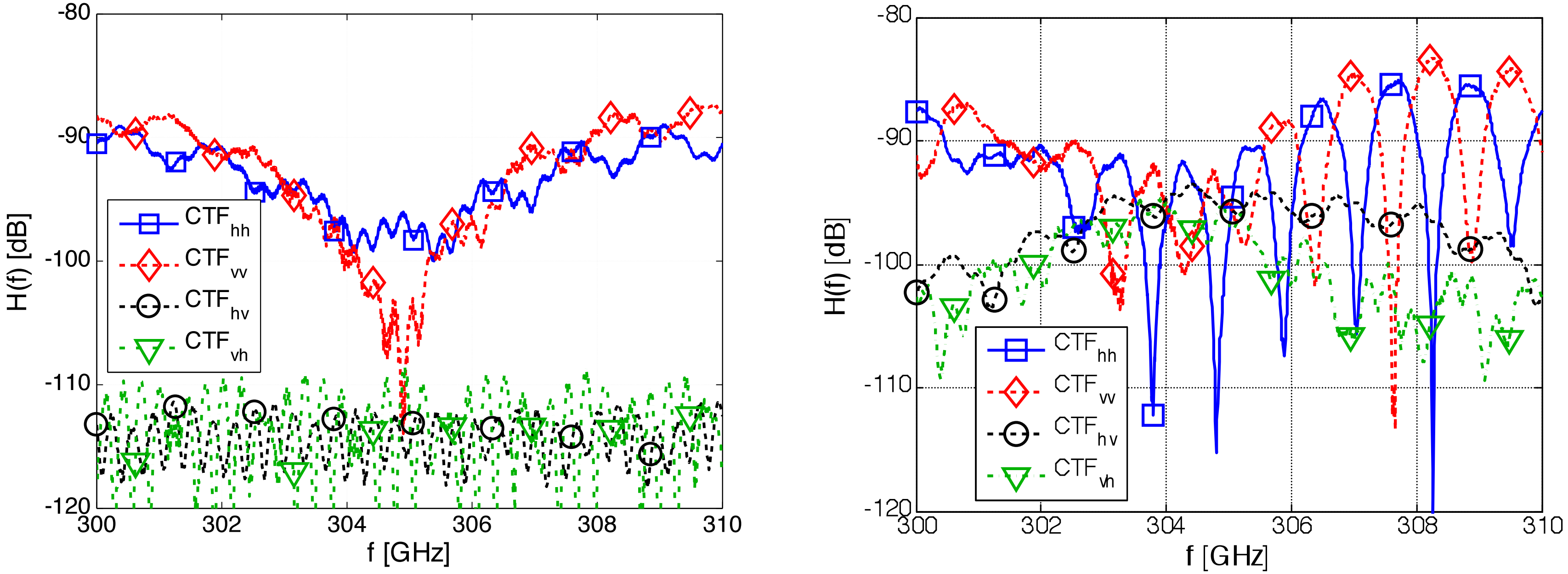
Horizontal to vertical polarization

→ High depolarization close to walls

→ Cross-polarization not negligible

Polarization (4)

- Impact of scattering in the unfurnished room on the channel transfer functions at a critical position (x = 0.125 m, y = 3.875 m):



Reflections only

Reflections and scattering

→ Increased frequency selectivity induced by scattering

→ High cross-polarization over a broad frequency range

→ Scattering relevant regardless of the polarization

Outline

1. Introduction
2. Scattering Models
3. Implementation Aspects
4. Scattering Impact on THz Propagation Channels
5. **Summary/Outlook**

Summary

- The Kirchhoff scattering solution has been implemented into a ray tracing algorithm in order to model rough surface scattering
- A perturbation approach additionally accounts for depolarization due to scattering
- The Jones calculus is used to describe the geometrical depolarization
- Ray tracing simulations have been validated against measurements
- Ray tracing has been performed in small indoor scenarios in order to investigate the relevance of scattering at 300 GHz
  - High frequency selectivity may be caused by scattering regardless of the polarization
  - A strong scattering impact occurs especially near walls and in the corners of the room
  - Depolarization induced by scattering is non-negligible

Outlook

- The impact of the surface roughness on THz propagation channels will be investigated
- Angular and temporal dispersion due to scattering will be considered
- An abstract stochastic scattering model will be developed for the fast generation of channel realizations

→ First system simulations will be performed to gain performance estimations of THz communication channels under realistic propagation conditions

References

More information on the topic can be found in:

[1] Priebe, S.; Jacob, M.; Jansen, C.; Kürner, T.: *Non-Specular Scattering Modeling for THz Propagation Simulations*. Accepted for the 5th European Conference on Antennas and Propagation (EuCAP), 5 pages, Rome, April 2011.

[2] Priebe, S.; Jacob, M.; Kürner, T.: *Polarization Investigation of Rough Surface Scattering for THz Propagation Modeling*. Accepted for the 5th European Conference on Antennas and Propagation (EuCAP), 5 pages, Rome, April 2011.

Thank you for paying attention.

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