Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Performance of Antennas in THz Indoor Communication Channels

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Abstract: THz indoor channel modeling activites have revealed that symbol rates achievable by THz communication systems are severely limited by the temporal channel dispersion as long as no highly directive antennas are employed (cf. doc. 15-11-0180-01-0thz). Therefore, the impact of antenna types on broadband THz channel characteristics is investigated in order to provide a basis for the specification of antenna properties. Furthermore, the affection of communication links by non-perfect antenna alignment is considered, wherefrom requirements for the antenna alignment accuracy are derived.

Re: 15-11-0180-01-0thz-spatial-and-temporal-dispersion-in-thz-indoor-propagation-channels.pdf

Purpose: Contribution to advanced THz channel modeling and THz antenna requirement specification

Performance of Antennas in THz Indoor Communication Channels

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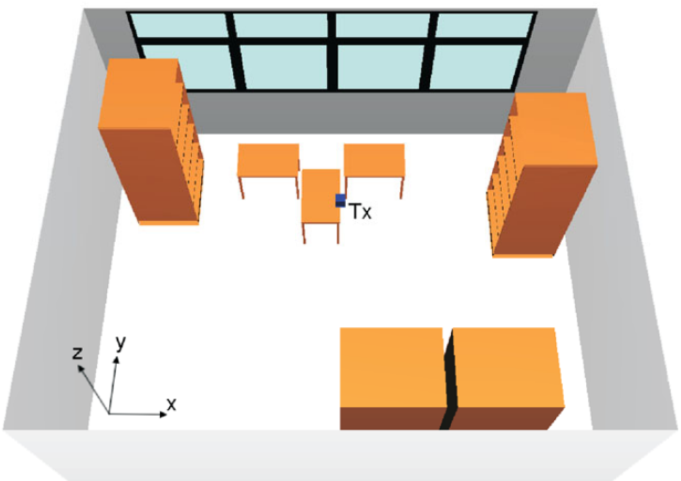
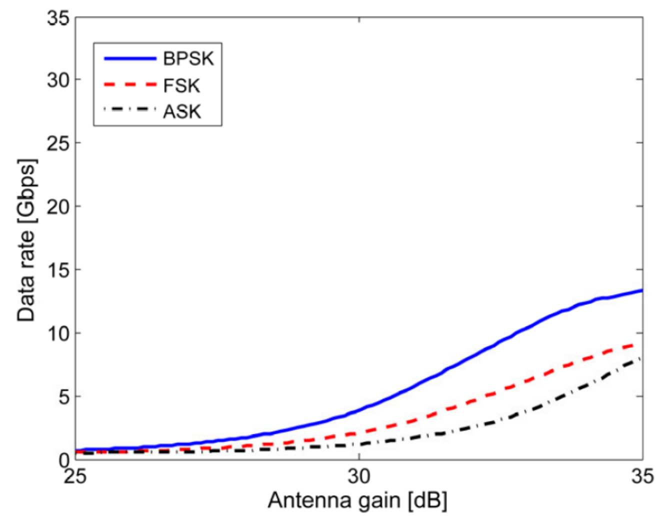
Outline

1. **Introduction**
2. Antenna Types
3. Impact on Channel Characteristics
4. Misalignment
5. Summary/Outlook

Introduction (1)

- *Previous work*: Investigation of achievable data rates dependent on the mere antenna gain
- *Limitations*: Based on path loss only, no broadband channel aspects (e.g. temporal dispersion)





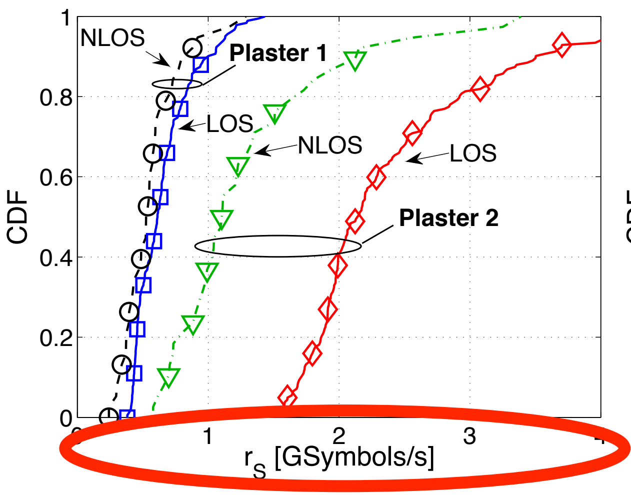
→ Very high antenna gains become necessary

→ How are broadband channel characteristics, i.e. the temporal or spatial dispersion, affected by the antenna?

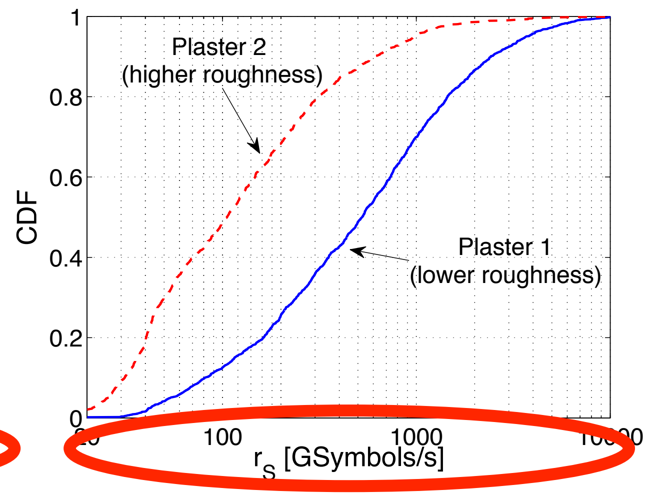
R. Piesiewicz, M. Jacob, J. Schoebel, T. Kürner: “Influence of hardware parameters on the performance of future indoor THz communication systems under realistic propagation conditions”, in Proc. 4th *European Radar Conference (EuRAD)*, Munich, pp. 327-330, October 2007

Introduction (2)

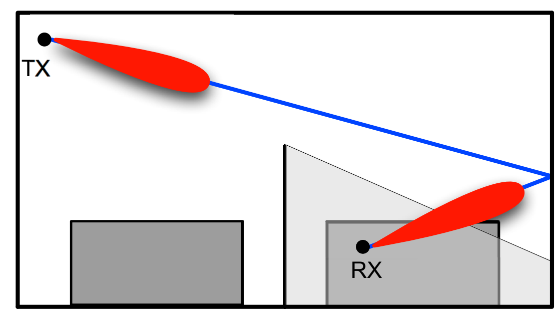
- *Previous work*: Affection of achievable symbol rates by temporal channel dispersion
- Maximum possible symbol rates in an indoor scenario:



Omnidirectional antenna



Highly directional link



- Symbol rates limited by high temporal dispersion

→ Effective spatial filtering required

IEEE doc. 802.15-15-11-0180-01-0thz

Introduction (3)

- Antennas will be critical to
  - overcome the high free space losses (e.g. FSL_{300GHz} higher by 42 dB than $FSL_{2.4GHz}$)
  - compensate for low output powers
  - suppress or utilize multipath propagation
  - dynamically react to ray shadowing

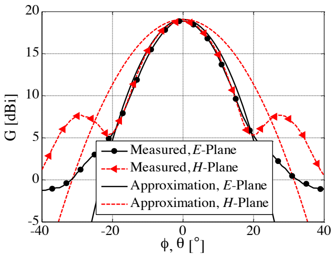
- *Open aspects:* How do the antennas affect
  1. the resulting path loss?
  2. the RMS delay spread?
  3. the Rician *k*-factor?
  4. the system sensitivity against non-perfect antenna alignment?
  5. the overall system performance?

  → Which antennas are optimal for THz communications?

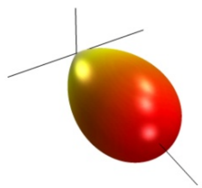
Introduction (4)

- *Methodology:*

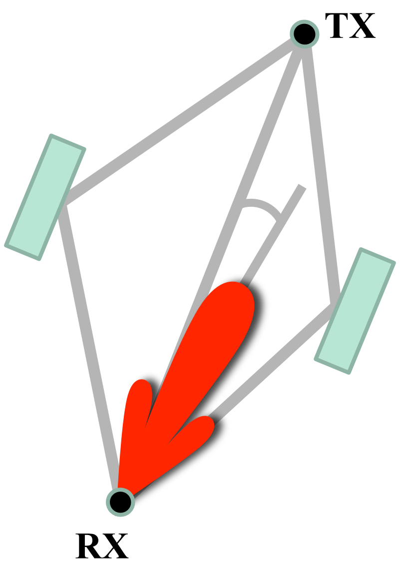
Antenna measurements



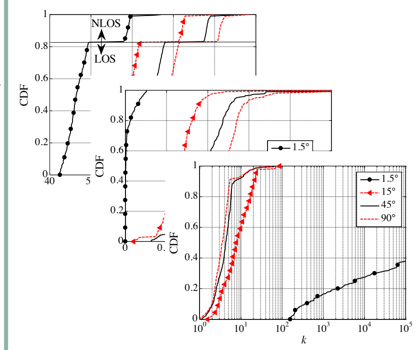
Antenna modeling



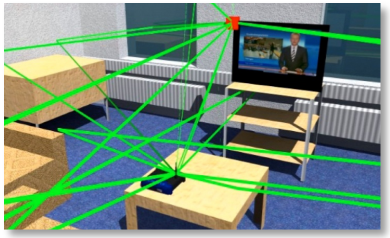
Weighting of multipaths with antenna diagrams

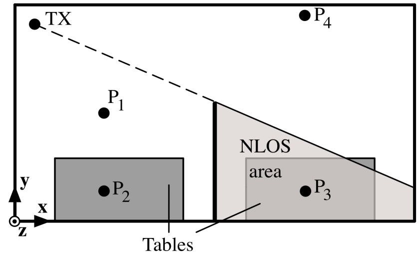


Evaluations:
- Path loss
- RMS delay spread
- ...



Ray tracing



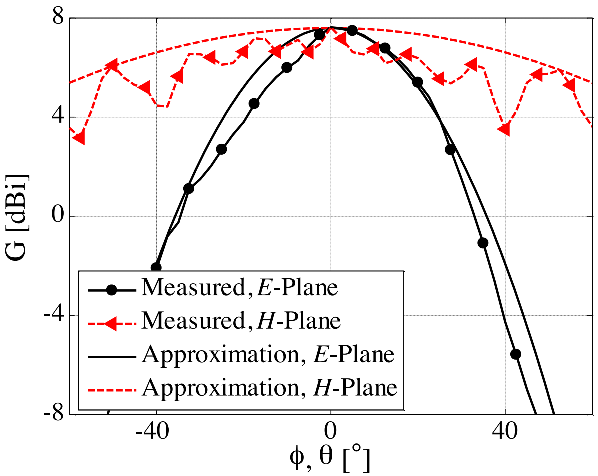


Outline

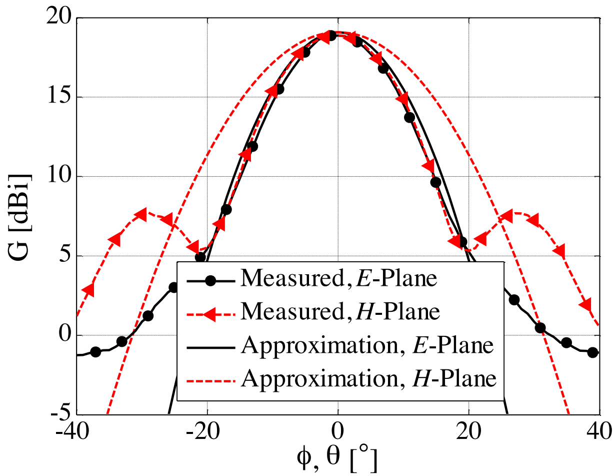
1. Introduction
2. **Antenna Types**
   - **Antenna Measurements**
   - **Gaussian Beam Model**
3. Impact on Channel Characteristics
4. Misalignment
5. Summary/Outlook

Antenna Measurements (1)

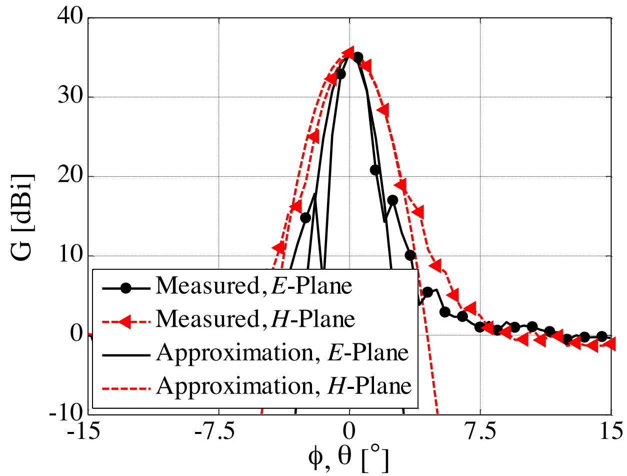
- Measured radiation patterns of actual THz antennas at 300 GHz:



Waveguide



Standard gain horn (SGH)



SGH + polyethylene lens

→ Good agreement between measured radiation behavior and approximation with Gaussian beam model

→ Neglegible drawback: Sidelobes not modeled

Gaussian Beam Model (1)

- *Motivation*: Continuous beamwidth variation necessary for theoretical studies
- *Idea*: Approximatian of antenna patterns with a Gaussian function:

$$G(\phi,\theta) = G_0 \cdot e^{-\left(\frac{\phi-\phi_0}{\sigma_{g,\phi}}\right)^2} \cdot e^{-\left(\frac{\theta-\theta_0}{\sigma_{g,\theta}}\right)^2}$$

- *Advantage*: Arbitrary half power beamwidths selectable:

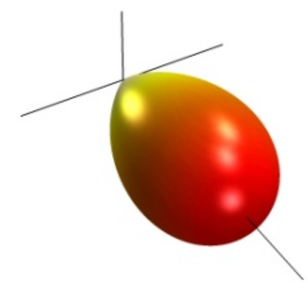
$$HPBW_{\phi,\theta} = \sigma_{g,\phi,\theta} \cdot \sqrt{4 \cdot \ln 2}$$

→ Gaussian beams are sufficient to approximate radiation patterns of realistic antenna types

→ Also, the main lobe of antenna arrays can be modeled

→ All following studies implicitly apply to smart antennas as well

Example:



HPBW = 15°
22.1 dBi

Gaussian Beam Model (2)

- Comparison of measured and approximated gains:

		Waveguide	SGH	SGH with lense
Meas.	Gain	7.7 dBi	18.6 dBi	35.6 dBi
	$HPBW_\phi$	130°	16.5°	2.6°
	$HPBW_\theta$	46.2°	17.1°	1.6°
Approx.	Gain	7.6 dBi	18.9 dBi	35.4 dBi
	$\sigma_{g,\phi}$	84°	15°	1.56°
	$\sigma_{g,\theta}$	27°	10°	0.96°

Derived Gaussian beam parameters serve as reference for theoretical investigations

Outline

1. Introduction
2. Antenna Types
3. **Impact on Channel Characteristics**
   - **Scenario Introduction**
   - **Path Loss**
   - ***k*-Factor**
   - **RMS Delay Spread**
4. Misalignment
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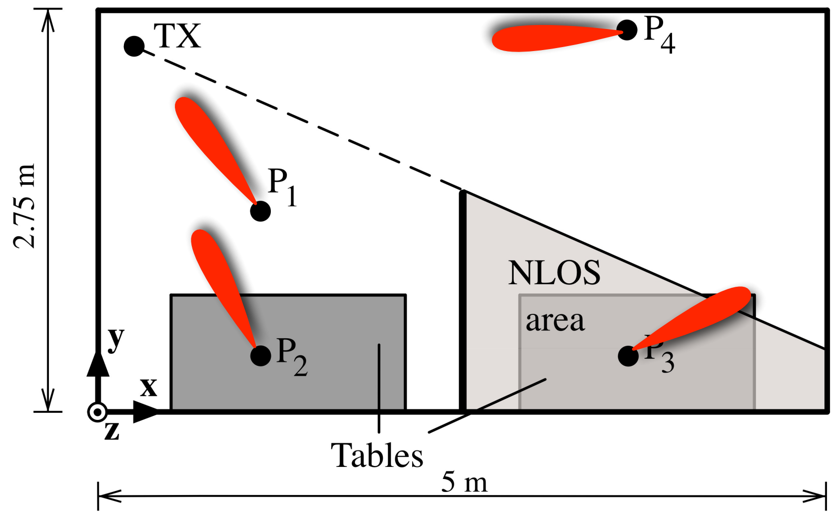
Scenario Introduction (1)

- Ray tracing simulations at f = 300 GHz in a realistic office scenario (top view, [1]):

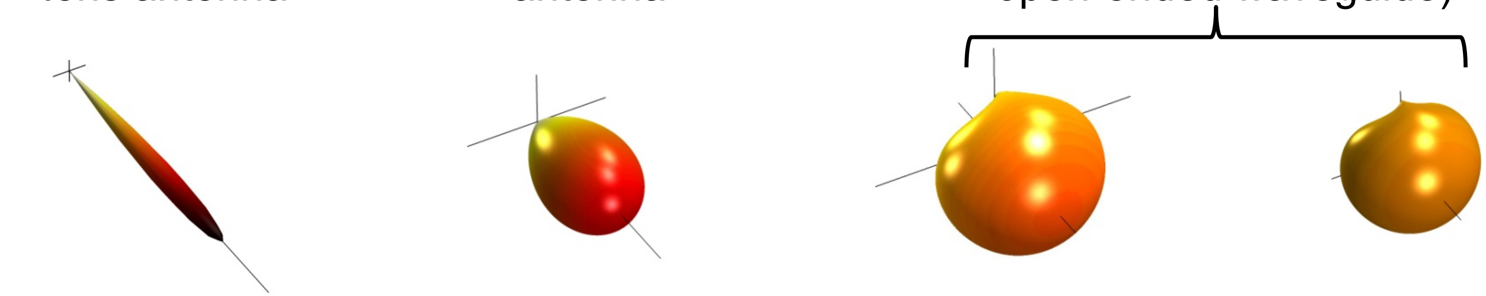


- Ideal omnidirectional antenna at TX, horizontally polarized
- Directional antenna with Gaussian beam at RX
  - Horizontal polarization
  - Symmetrical beam with $\sigma_{g,\Phi} = \sigma_{g,\Theta}$
  - Perfect beam alignment in the direction of the strongest ray
  - Consideration of four different HPBWs

Scenario Introduction (2)

- Gaussian beams with four representative HPBWs:

Highly directional lens antenna | Directional horn antenna | Less directional antennas (e.g. open-ended waveguide)



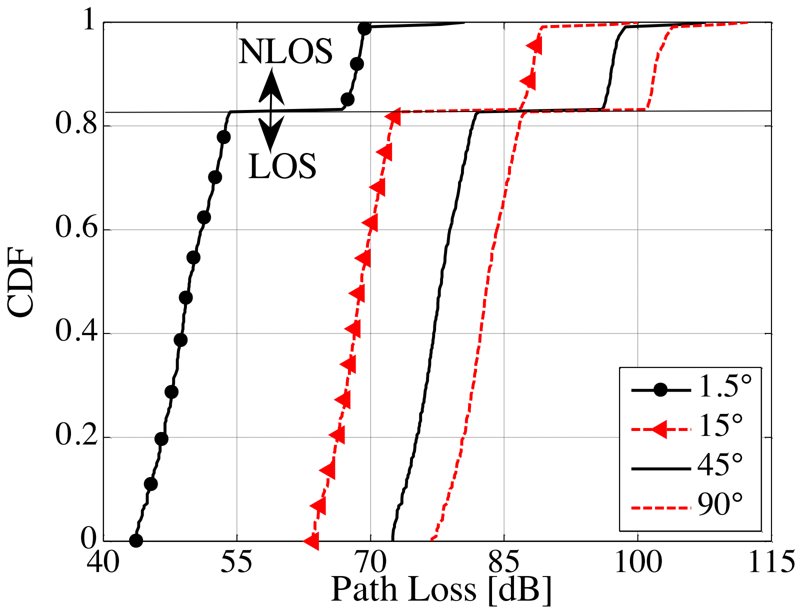
	Highly directional lens antenna	Directional horn antenna	Less directional antennas	
HPBW:	1.5°	15°	45°	90°
Gain:	43.1 dBi	22.1 dBi	12.8 dBi	7.5 dBi

→ Channel characteristics are evaluated for the different antennas

→ Similar lobe widths could also be created with antenna arrays

Path Loss

- Ray tracing at 220 RX positions throughout the room
- Cummulative distribution functions (CDFs) of the effective resulting path losses (PL):



- Similar curve shapes
→ No affection of the PL behavior by the beamwidth

- Differences between curves of 19.9 dB, 9.4 dB and 5.3 dB (left to right)
→ PL dominated by the mere antenna gain

HPBW	1.5°	15°	45°	90°
G_{max}	43.1 dBi ↔	22.1 dBi ↔	12.8 dBi ↔	7.5 dBi

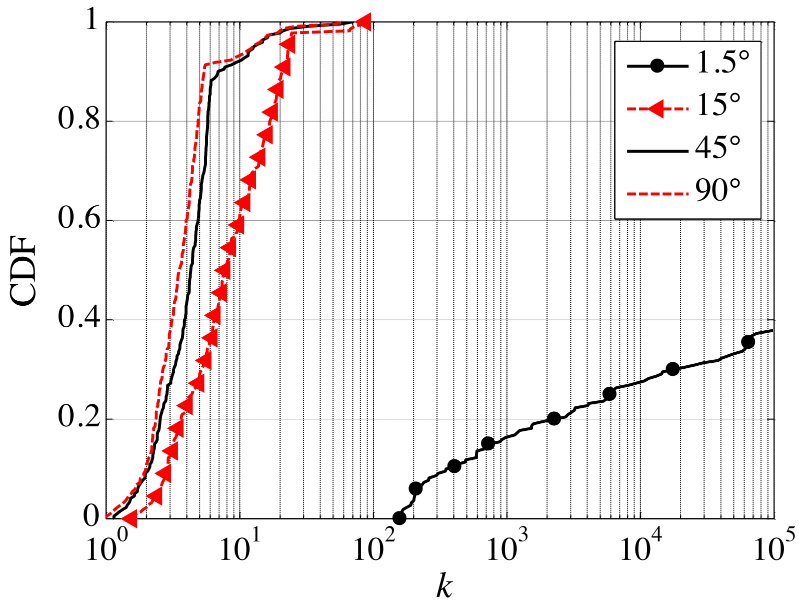
k-Factor (1)

- Rician *k*-factor as measure for the multipath-richness of a channel:

$$k = \frac{Power_{StrongestRay}}{\sum Power_{OtherRays}}$$

→ Higher *k* desirable for less fading and better channel conditions

- CDFs of *k* at the 220 RX positions:



- Increasing *k* with decreasing HPBW

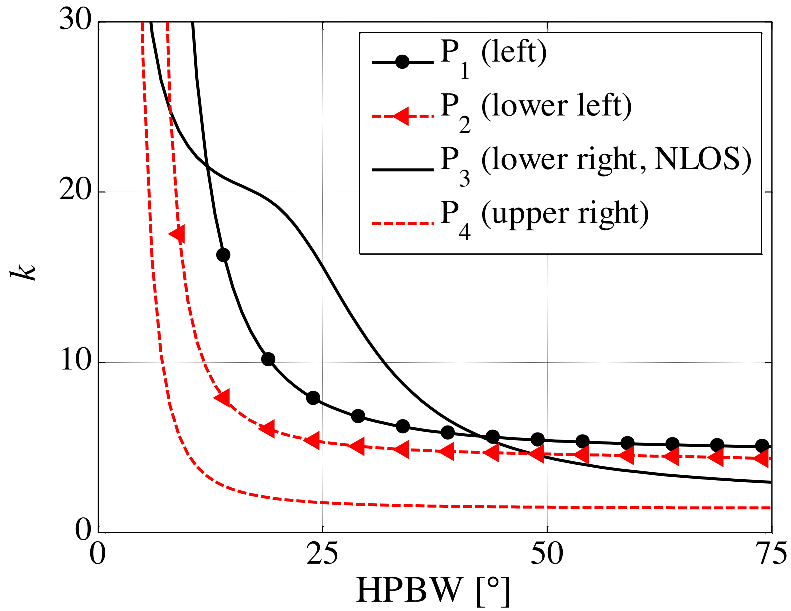
→ Multipath suppression due to spatial filtering

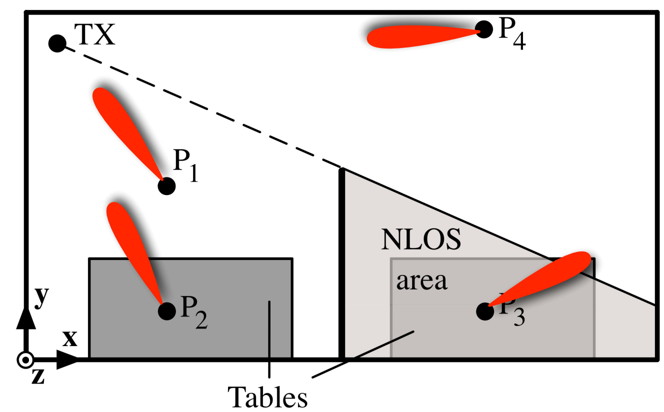
- No significant differences between HPBWs = 15°, 45°, 90°

→ Effective filtering only for very small HPBWs

k-Factor (2)

- Dependence of *k* on the HPBW:
  - Variation of the HPBW at four exemplary positions





- *k* almost constant for larger beamwidths

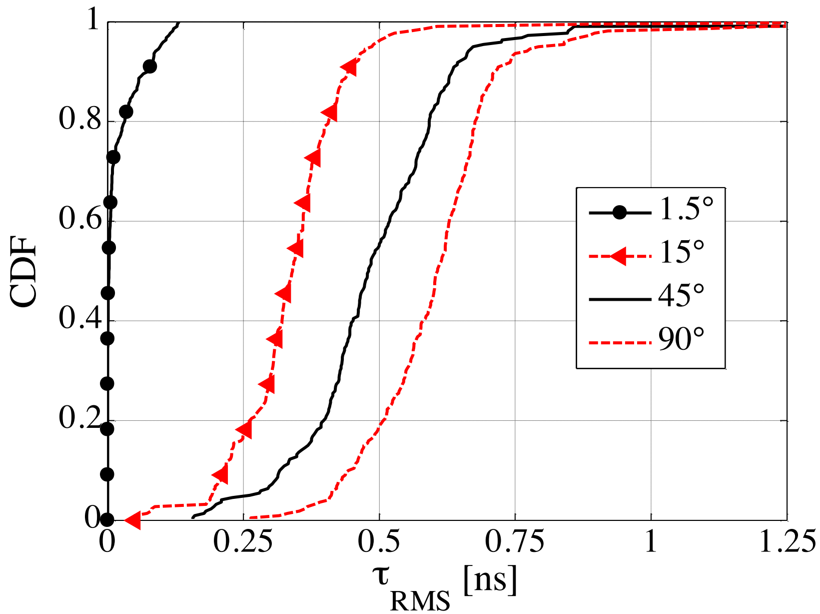
→ HPBWs below ≈10° required for effective spatial filtering (corresponding to gains beyond 25 dBi)

RMS Delay Spread (1)

- τ_{RMS} as measure for the temporal channel dispersion of a power delay profile:

$$\tau_{RMS} = \sqrt{\frac{\sum_i (\tau_i - \bar{\tau})^2 P_i}{\sum_i P_i}}$$

→ Very low τ_{RMS} << 1 ns desirable to avoid intersymbol interference (ISI)

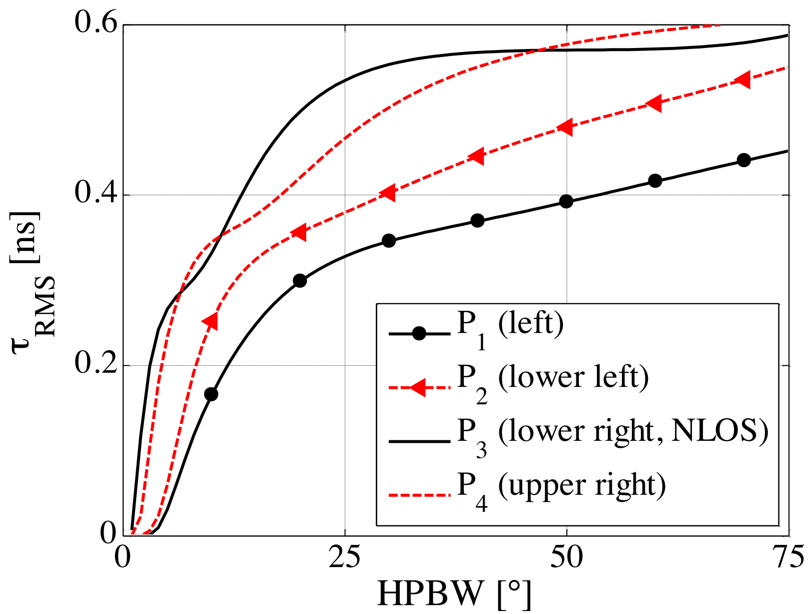


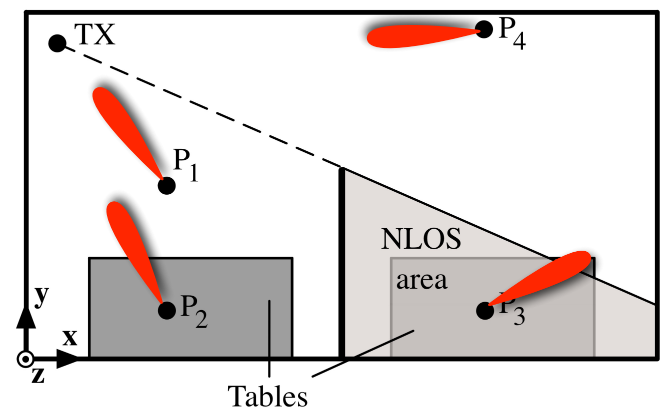
- Decreasing τ_{RMS} with decreasing HPBW
- Rather high delay spreads for HPBWs = 15°, 45°, 90°

→ Sufficiently small τ_{RMS} to support several 10 GSymbols/s without ISI only for HPBW = 1.5°

RMS Delay Spread (2)

- Dependence of τ_{RMS} on the HPBW:





→ Comparatively high temporal dispersion also for rather small HPBWs

→ HPBWs < ≈5° required to suppress ISI in case of up to 10 GSymbols/s and beyond

Path Loss/*k*-Factor/RMS Delay Spread (Summary)

- Averages of the path loss, the *k*-factor and the RMS delay spread at the 220 RX positions:

HPBW	1.5°	15°	45°	90°
G_{max}	43.1 dBi ↔	22.1 dBi	12.8 dBi	7.5 dBi
$\overline{PL}$	52.5 dB ↔	71.8 dB	80.7 dB	85.9 dB
k	$3.5 \cdot 10^{13}$	11.2	5.5	4.7
$\overline{\tau_{RMS}}$	17.9 ps	342 ps	593.7 ps	658.1 ps

→ Path loss is affected by the antenna gain only

→ Very high directivities (HPBWs < 10°) are required to effectively suppress multipath components

→ Intersymbol interference is preventable for HPBWs < ≈5°

→ Smart antennas can help to utilize the multipath propagation

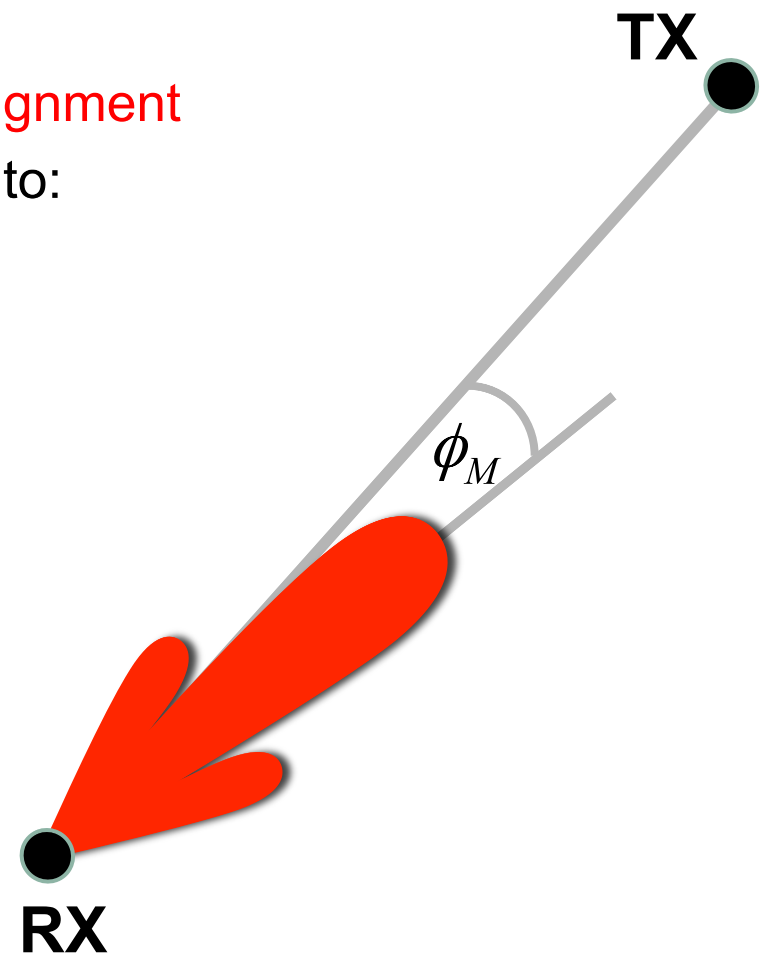
Outline

1. Introduction
2. Antenna Types
3. Impact on Channel Characteristics
4. **Misalignment**
   - **Theoretical Considerations**
   - **Path Loss Affection**
   - **Optimum Antenna Configurations**
   - **System Performance**
5. Summary/Outlook

Theoretical Considerations (1)

- The effective antenna gain is impaired significantly by non-perfect antenna alignment
- Antenna misalignment may occur due to:
  - *User*: device placement/antenna pointing
  - *Environmental influences* (fixed links): wind
  - *Hardware* (smart antennas): non-perfect phase shifters, manufacturing tolerances of delay lines
  - *Software* (smart antennas): incomplete channel state information, limited digital precision, imperfect estimation of angles of arrival/departure

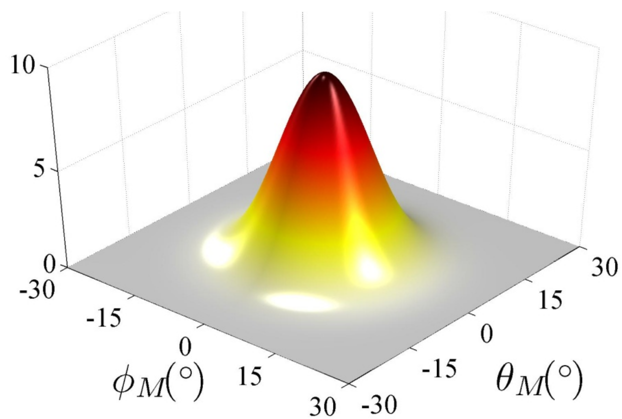
→ Misalignment investigations relevant not only for conventional, but also for smart antennas

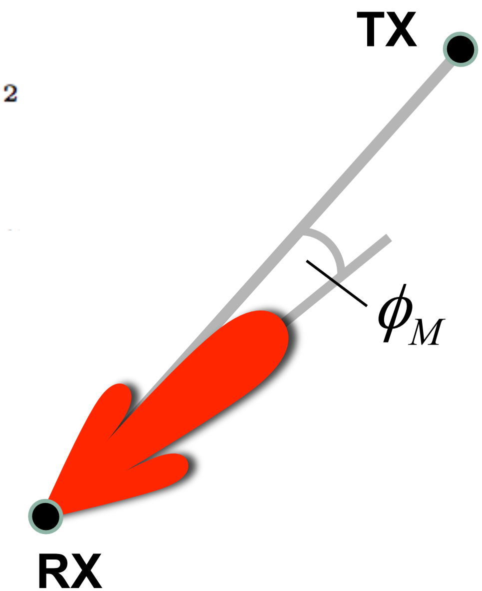


Theoretical Considerations (2)

- *Methodology*: 2D Gaussian probability density function (PDF) for the misalignment angles in azimuth and elevation:

$$f_{\phi_M,\theta_M}(\phi_M,\theta_M) = \frac{1}{2\pi\sigma_{M,\phi}\sigma_{M,\theta}} e^{-\frac{1}{2}\left(\frac{\phi_M}{\sigma_{M,\phi}}\right)^2 - \frac{1}{2}\left(\frac{\theta_M}{\sigma_{M,\theta}}\right)^2}$$



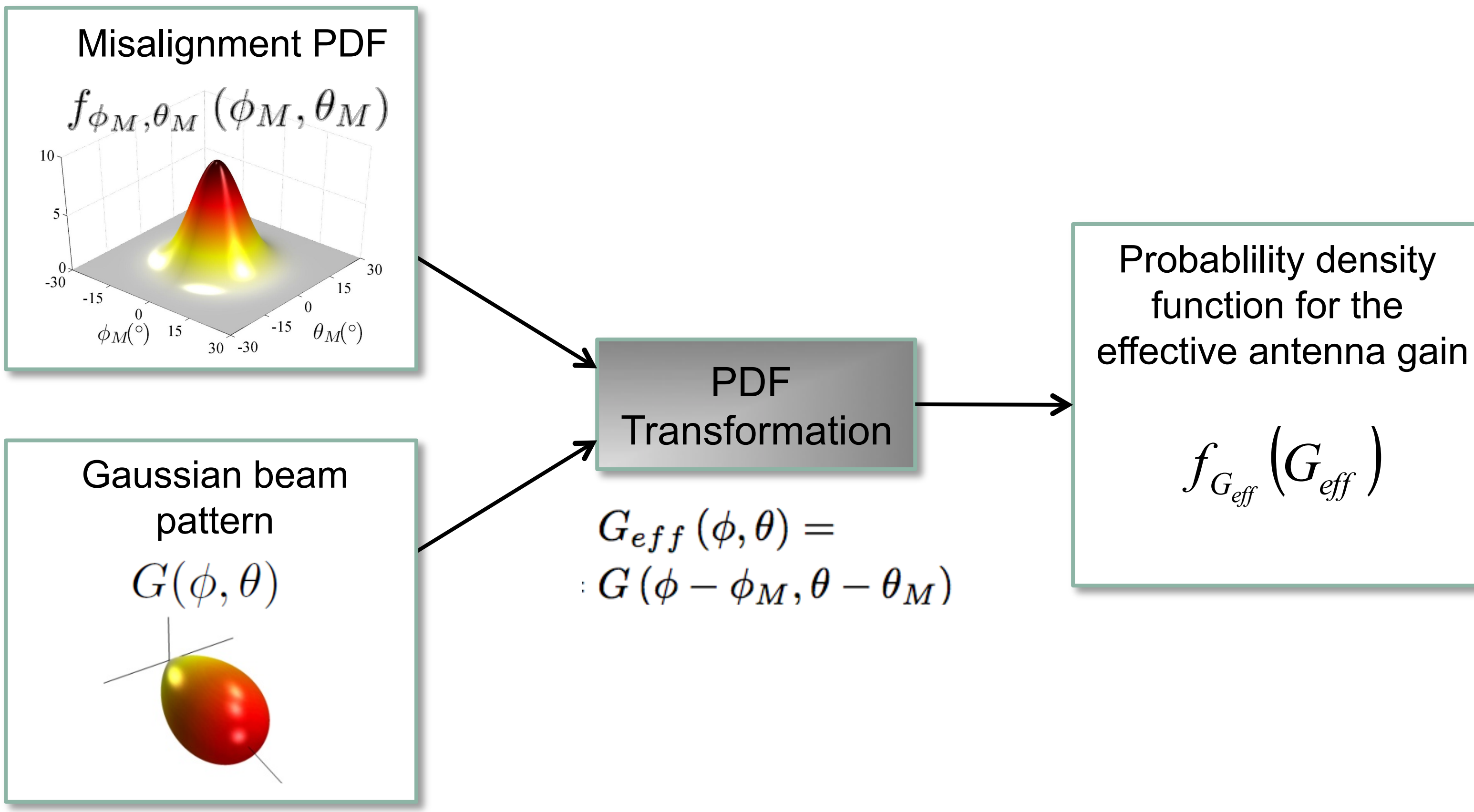


→ Radomization of the mispointing angles

→ Variation of the misalignment severeness with the misalignment standard deviations $\sigma_{M,\phi,\theta}$

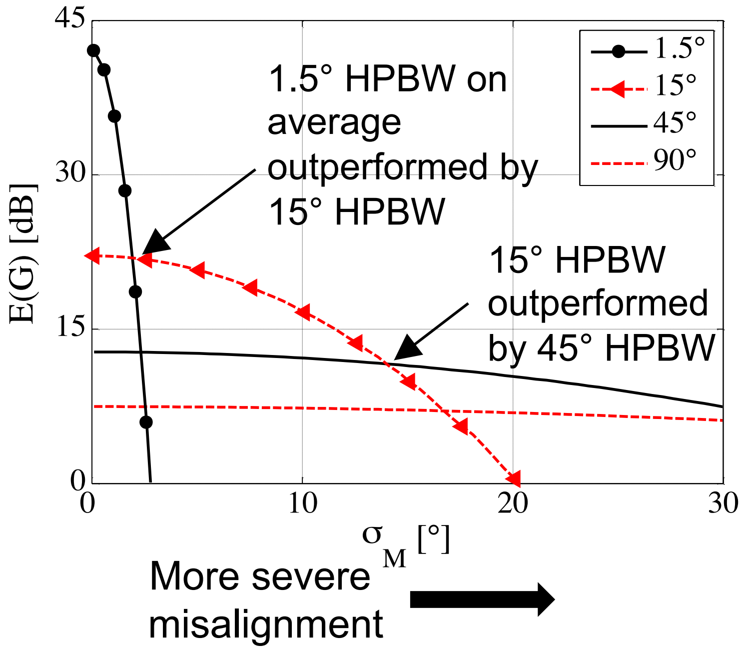
Theoretical Considerations (3)

- Effective antenna gain is no longer constant, but must be considered as a random variable



Theoretical Considerations (4)

- Expectation value of the effective antenna gain (different HPBWs):



→ The smaller the HPBW, the higher the sensitivity against misalignment

→ Less directive antennas provide higher average gains than highly directive antennas in case of stronger misalignment

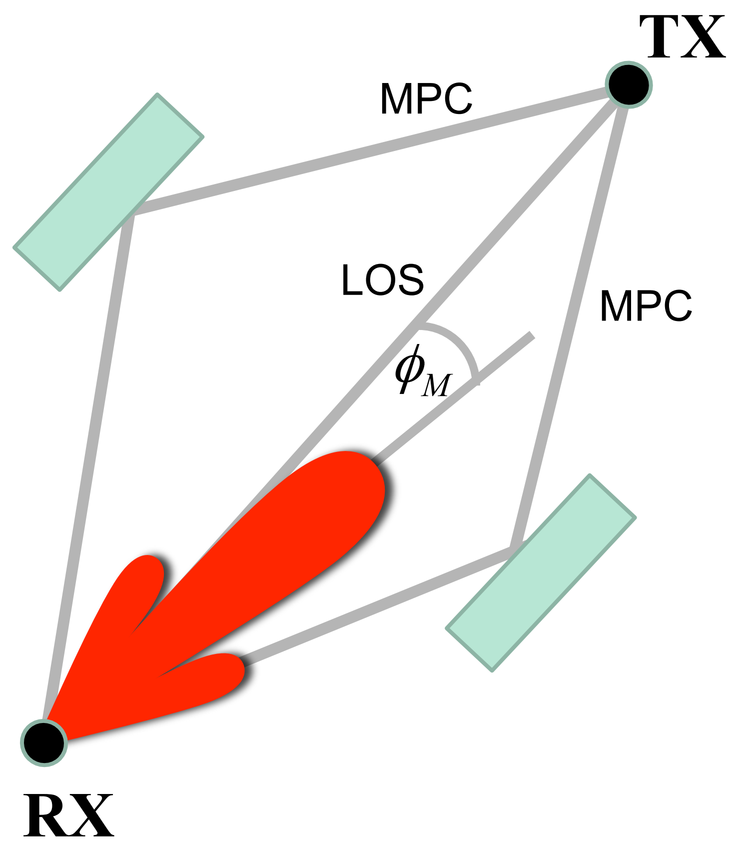
Path Loss Affection (1)

- So far, no path loss investigations available incorporating different antennas and non-perfect alignment
- *Aim*: path loss model in dependence on misalignment

→ PL model can be used for system simulations under consideration of misalignment and different HPBWs

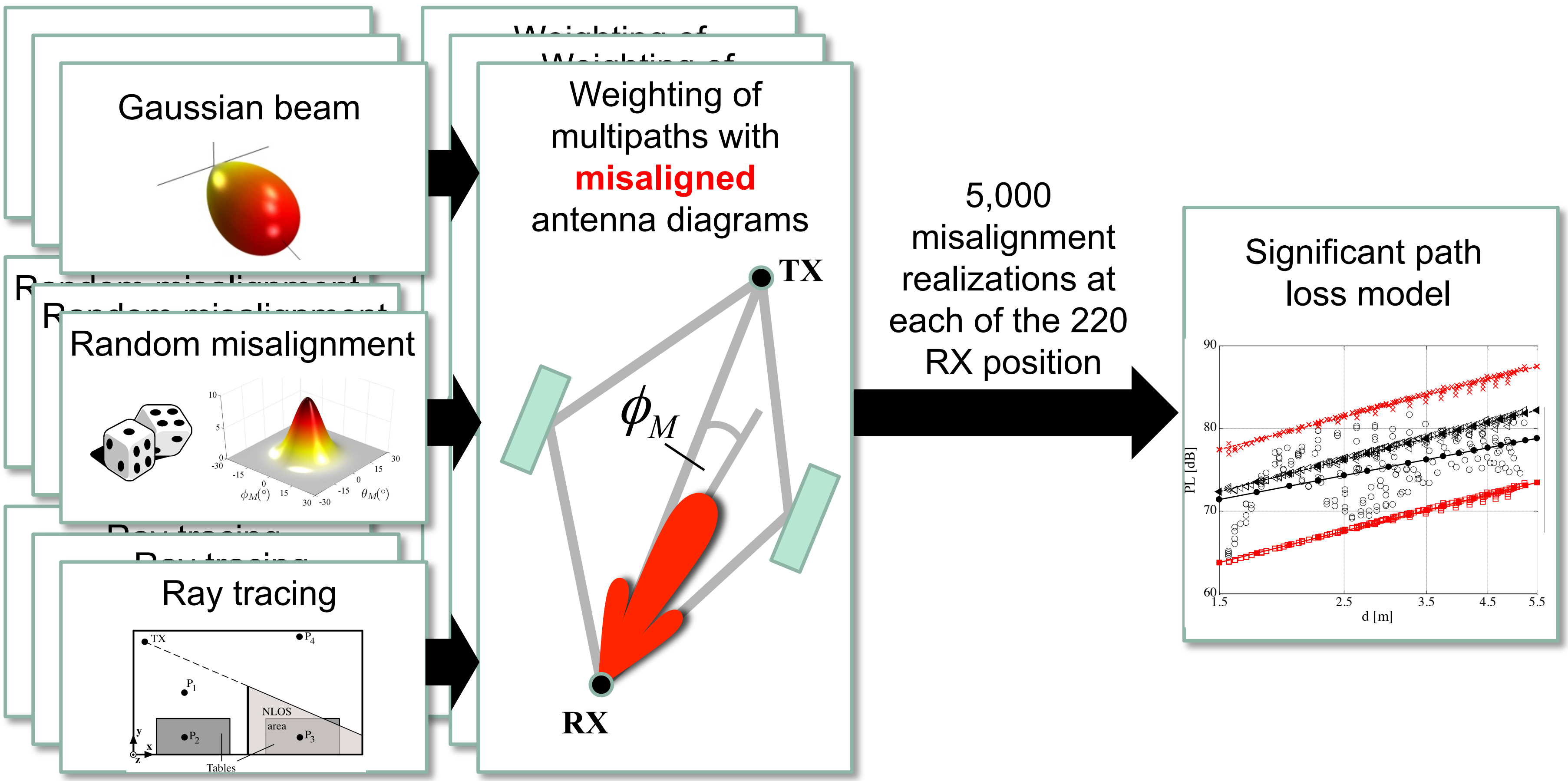
- *Problem*: not only main beam direction, but also all multipath components affected by random mispointing

→ No analytical PDF transformation possible because of different angles of arrival/departure



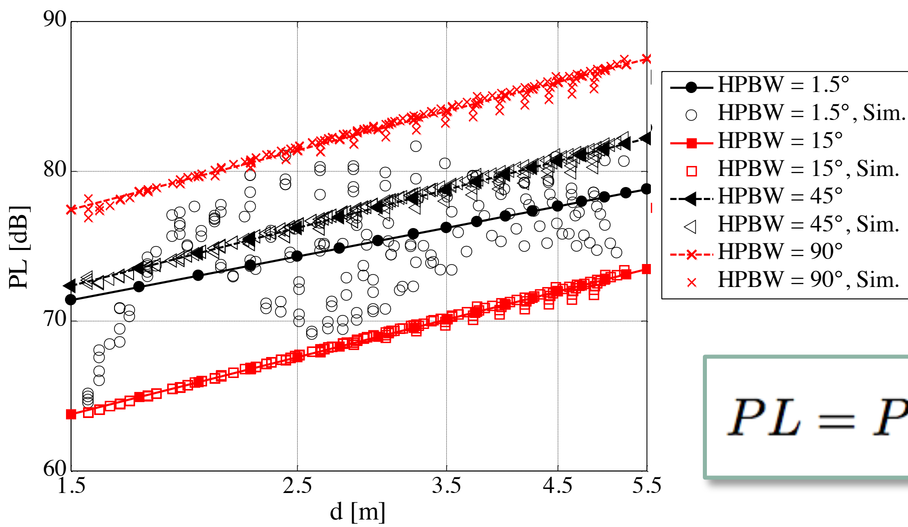
Path Loss Affection (2)

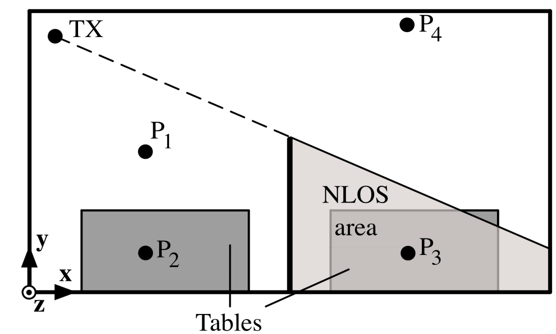
- *Solution*: Monte Carlo simulations



Path Loss Affection (3)

- Omni TX antenna, Gaussian RX pattern
- Misalignment standard deviation $\sigma_M = 2.5°$, LOS only
- Variation of the HPBW:





$$PL = PL_0 + 10n\log_{10}\left(d[\mathrm{m}]\right) + \chi\left(\sigma_{PL}\right)$$

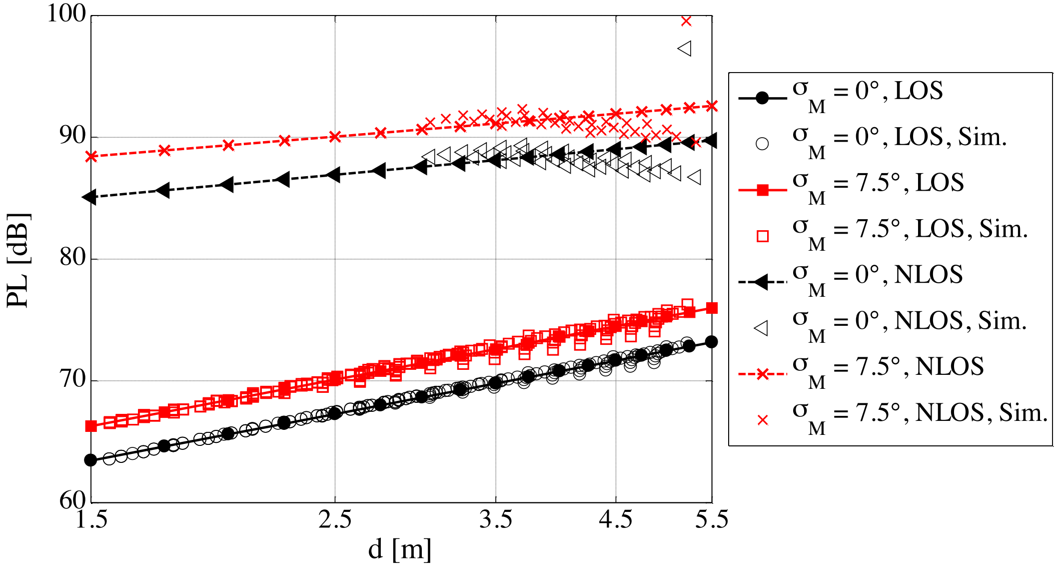
→ Best performance for HPBW = 15°

→ Good approximation with log-linear PL model as long as HPBW > σ_M

→ Model parameters can be found in [2]

Path Loss Affection (4)

- Comparison LOS vs. NLOS and σ_M = 0° vs. σ_M = 7.5°
- HPBW = 15°:

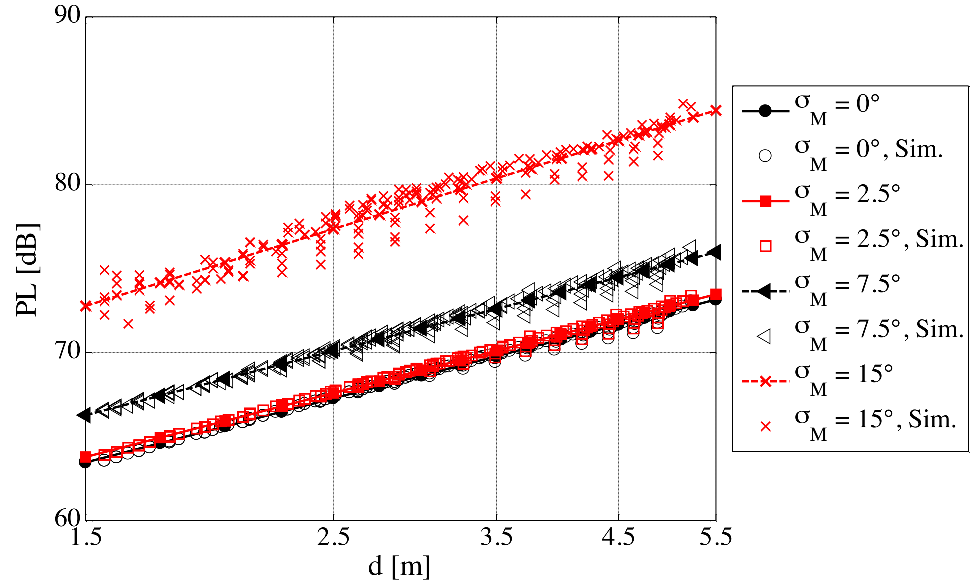


→ σ_M = 7.5° corresponds to an average increase of the PL by about 3 dB compared to perfect alignment

→ Model provides a similarly good approximation under both LOS and NLOS conditions

Path Loss Affection (5)

- Variation of σ_M
- HPBW = 15°:

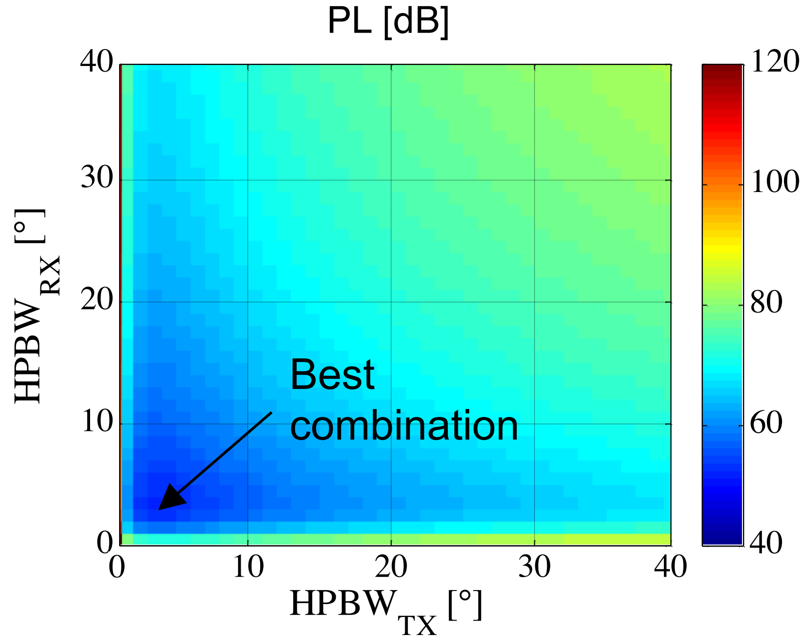


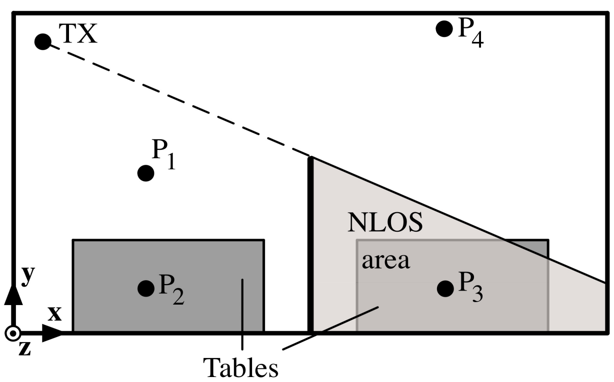
→ Significant impact of misalignment occurs only for $\sigma_M \geq \approx$HPBW

→ Antenna type and accuracy requirements for specific applications can be fixed dependent on the expected misalignment

Optimum Antenna Configurations (1)

- So far: one directive antenna only
- Now: directive, randomly misaligned antennas at both TX and RX
- Monte Carlo simulations for each HPBW combination at TX and RX (Position P_3), σ_M = 2.5°:

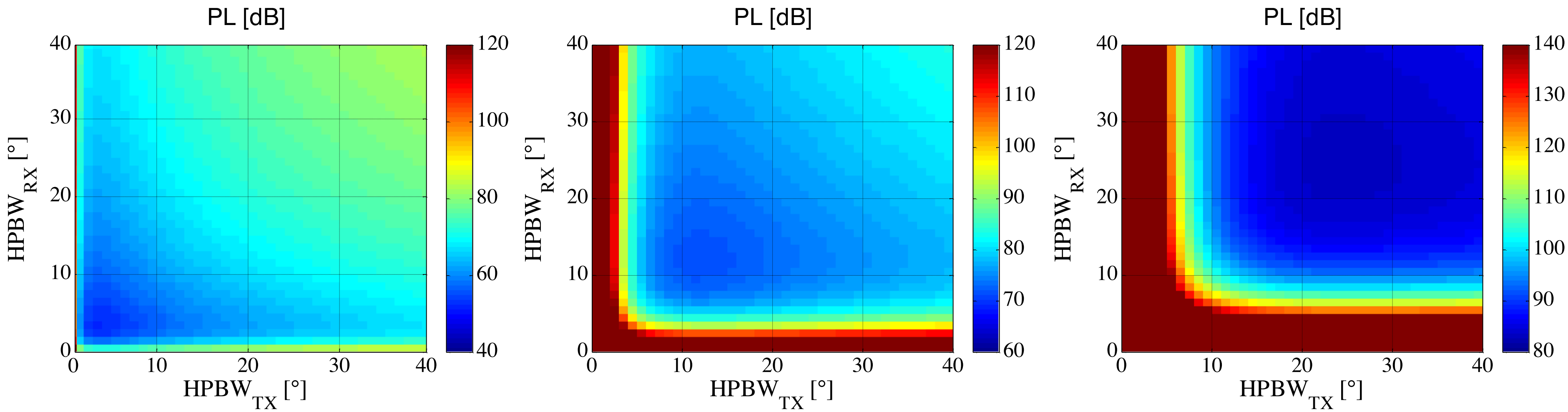




→ Best solution for a symmetric TX/RX configuration

Optimum Antenna Configurations (2)

- Dependence on the misalignment severeness:



$\sigma_M = 2.5°$ $\sigma_M = 7.5°$ $\sigma_M = 15°$

→ Less directive antennas preferable in case of higher misalignments

- Empiric relation between the misalignment standard deviation and the optimum HPBW:

$$HPBW_{opt} \approx 1.6 \cdot \sigma_M$$

→ Optimum antenna configuration defined by occuring misalignment

System Performance

- Assumption of a 40 Gbit/s link with a 16 QAM, f = 300 GHz
- Realistic radio components (TX output power -6 dBm, 8 dB RX conversion gain, 7.5 dB RX noise figure)
- Assumption of optimum HPBWs

Optimum HPBWs →

	P_1			P_2		
σ_M	2.5°	7.5°	15°	2.5°	7.5°	15°
$HPBW_{TX}$ [°]	4	12	25	4	12	25
$HPBW_{RX}$ [°]	4	12	25	4	12	25
PL [dB]	30.5	49.7	61.4	32.9	52.1	63.8
SNR [dB]	37.6	18.4	6.5	35.2	16	4.3
BER	≈0	$7.5 \cdot 10^{-5}$	0.13	≈0	$1.8 \cdot 10^{-3}$	0.18

- 40 Gbit/s data transmission still operational for σ_M = 7.5° (!)

→ Slight misalignments can be tolerated

- Link fails for σ_M = 15° despite the optimum HPBWs at TX and RX

→ High misalignments must be avoided at any rate

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3. Impact on Channel Characteristics
4. Misalignment
5. **Summary/Outlook**

Summary

- Realistic antennas have been measured and approximated accurately with a Gaussian beam model
- The influence of antennas on THz channel characteristics has been investigated based on ray tracing at 300 GHz in an indoor scenario:
    - *Path loss*: PL mainly depends on the mere antenna gain
    - *k-factor*: antenna beamwidths < 10° are required for effective spatial filtering
    - *RMS delay spread:* symbol rates may be serverely limited due to ISI for larger HPBWs > 5...10°
- Antenna misalignment has been studied
    - Misalignment can strongly impair THz channels and hinder data transmission
    - A path loss model has been derived which applicable to simulate systems under misalignment conditions for various HPBWs
    - The same antennas at the TX and RX with HPBWs slightly larger than the misalignment standard deviation provide the highest effective gain

Outlook

Next steps:

- Smart antennas including beamforming, beamswitching or beamsteering must be investigated regarding gain, radiation pattern and alignment accuracy
- Realistic system simulations will have to be performed with broadband channels to assess the overall THz system performance

References

[1] S. Priebe, M. Jacob, T. Kürner: „The Impact of Antenna Directivities on THz Indoor Channel Characteristics“, accepted for publication in Proc. *European Conference on Antennas and Propagation (EuCAP)*, Prague, 5 pages (electronic), March 2012

[2] S. Priebe, M. Jacob, T. Kürner: „Affection of THz Indoor Communication Links by Antenna Misalignment “, accepted for publication in Proc. *European Conference on Antennas and Propagation (EuCAP),* Prague, 5 pages (electronic), March 2012

Thank you for paying attention.

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