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Submission Title: Channel Model for Intra-Device Communications

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Source: Alexander Fricke, Thomas Kürner, TU Braunschweig
Mounir Achir, Philippe LeBars, CANON

E-Mail: fricke@ifn.ing.tu-bs.de/t.kuerner@tu-bs.de
mounir.achir@crf.canon.fr / philippe.lebars@crf.canon.fr

Re: n/a

Abstract: In this contribution, the modeling methodology and results for the propagation channel encountered in the application intra-device communications are presented.

Purpose: Contribution towards developing an intra-device channel model for use in TG 3d

Channel Model for Intra-Device Communications

Alexander Fricke, Thomas Kürner
TU Braunschweig

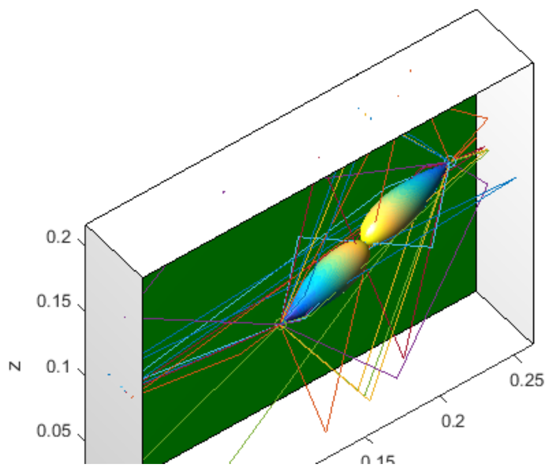
Mounir Achir, Philippe LeBars
CANON

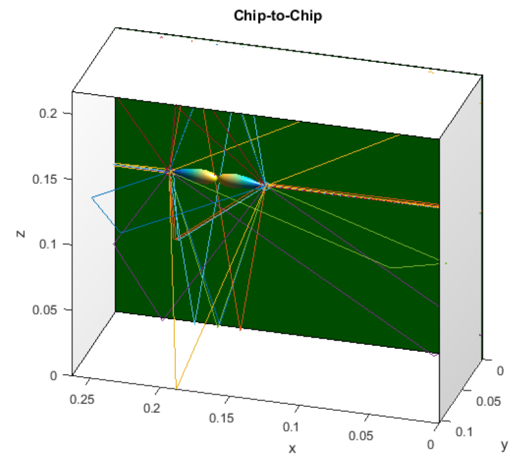
Outline

- **General Modeling Approach**
- Intra-Device Scenarios
- Intra-Device Results
- Conclusion

General Modeling Approach

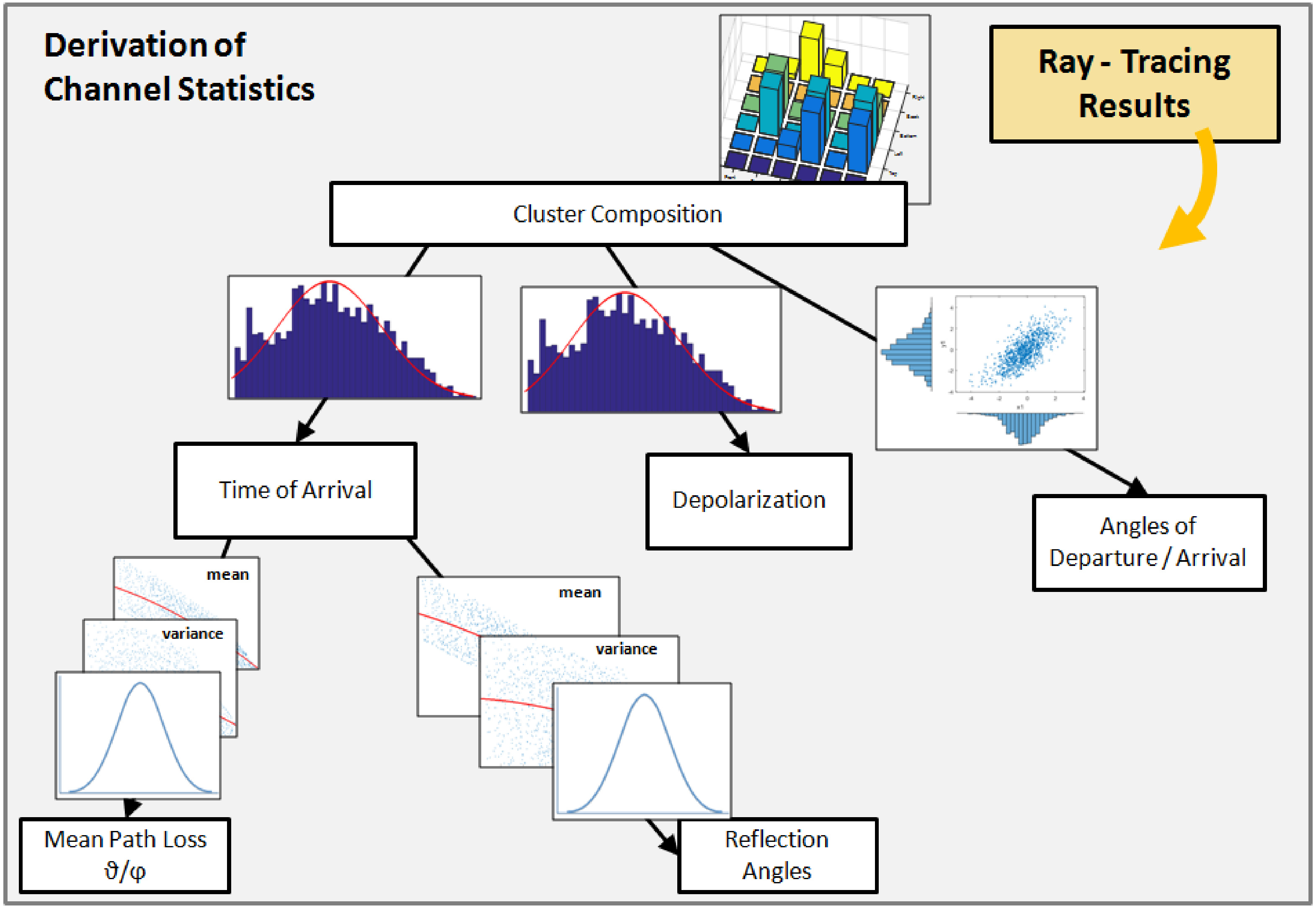
- The channel model is **derived from a ray-tracing** approach that has been developed to account for the peculiarities of intra-device communications in the THz - range
- It includes the electromagnetic influence of **plastic layers**, **metals** and **printed circuit boards**
- Moreover, the characteristics of **gaussian antenna profiles** are included





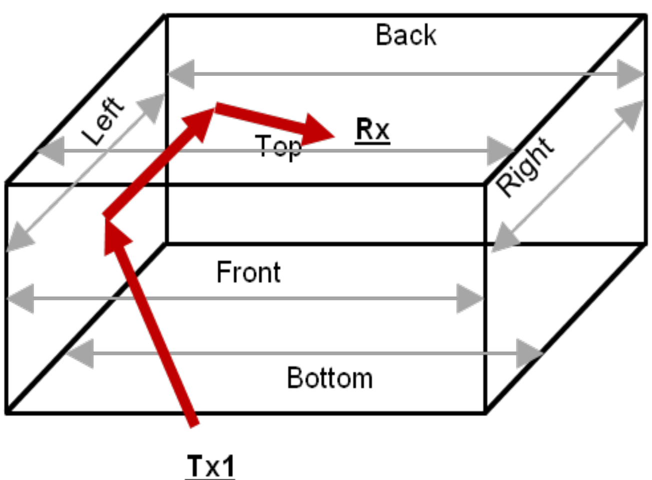
- From the ray-tracing results, the characteristics of the channel regarding **cluster composition**, **path loss** and **polarization properties** as well **as angular and temporal profiles** are extracted
- These characteristics are used to configure a so-called channel generator which is utilized to generate a **large number of realistic channel realizations** (i.e. frequency responses) for the corresponding use cases

Structure of the Channel Description



Cluster Composition (1)

- The most important component of every channel realization is the cluster composition of each channel
- By holding the actual number and types of propagation paths, it contains most of the **implicit information** regarding the **underlying channel geometry**
- **This kind of information assures** that the channel realizations produce **realistic channel transfer functions** that may actually occur inside a real channel

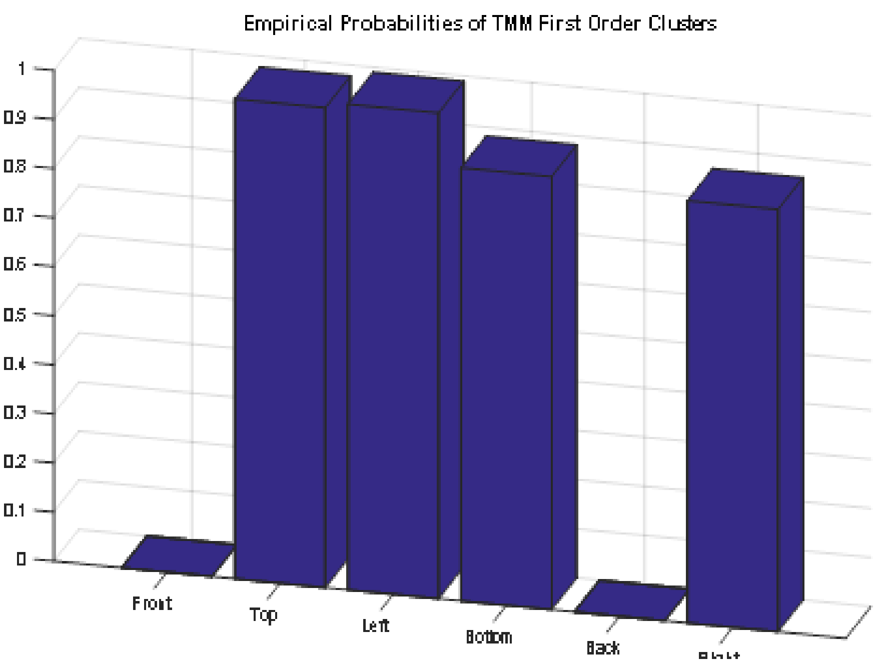


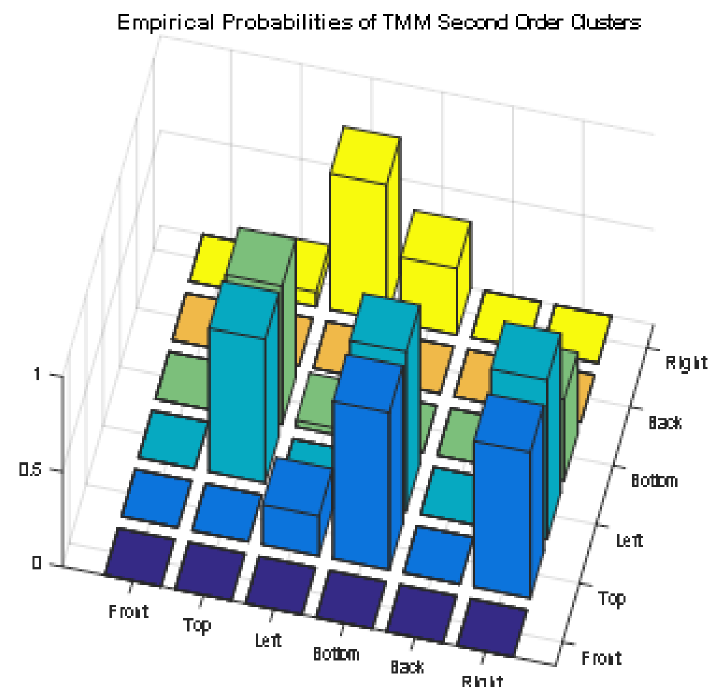
Wall	Index
Top	1
Bottom	2
Left	3
Right	4
Front	5
Back	6

[0 0 0 0 0 0]
[0 0 0 0 0 0]
[0 1 0 0 0 1]
[0 0 0 0 0 0]
[0 0 1 0 0 0]
[0 0 0 0 0 0]

Cluster Composition (2)

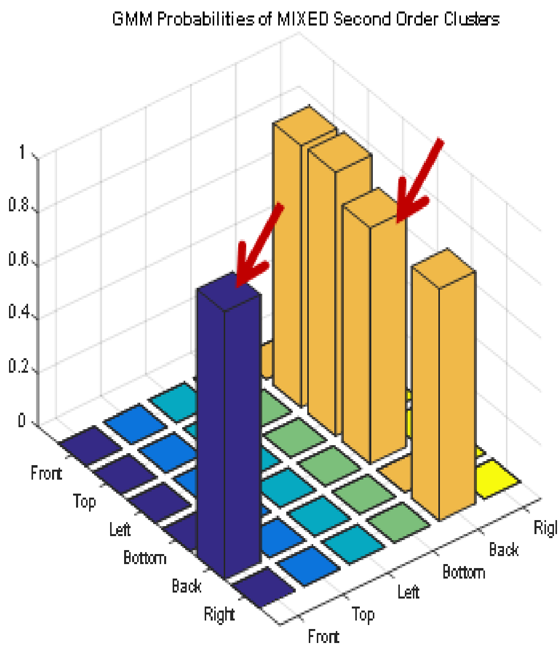
- **For every kind of propagation cluster** such as ‘reflection from a PCB’ or ‘double reflection from plastic surfaces’, a Gaussian Mixture Model (GMM) is generated
- From the GMM, the actual cluster composition of a channel realization is drawn

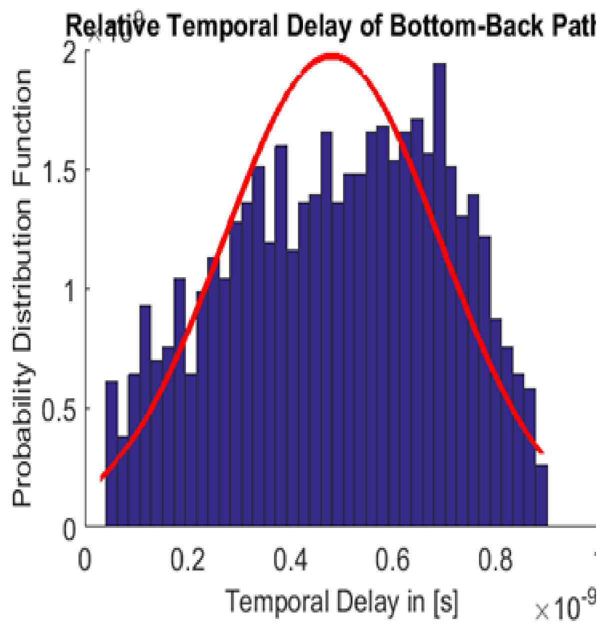


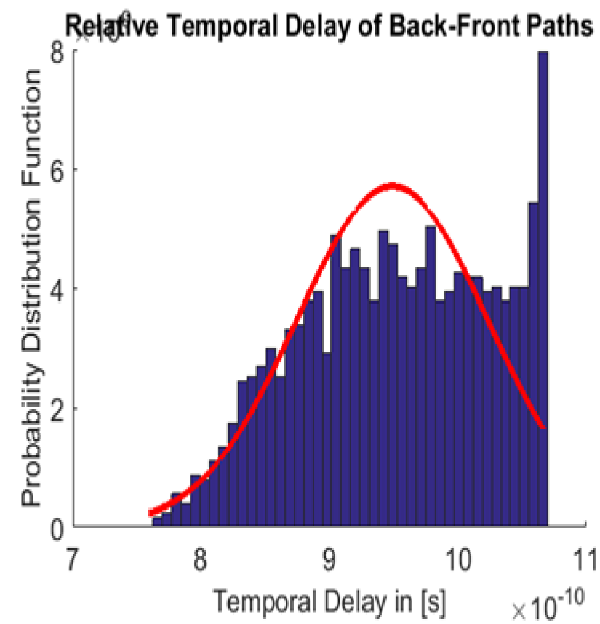


Time of Arrival (1)

- After generating the cluster composition, the propagation time of each path (Time of Arrival, ToA), is generated.
- It is assumed, that the **propagation delays of the various cluster types follow normal distributions**.
- For the **direct path**, the propagation delay is modeled as **absolute delay**. For all **reflected clusters**, the delay is modeled **with respect to the line-of sight component** to ensure physical correctness

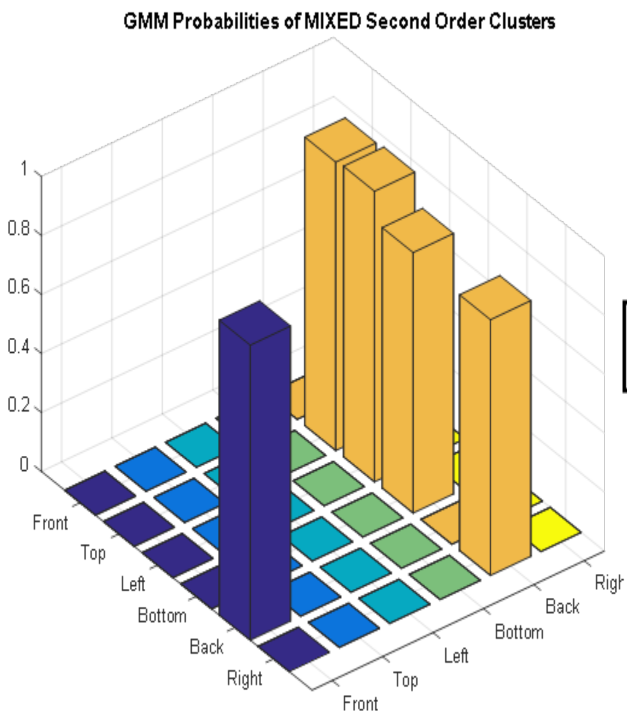






Time of Arrival (2)

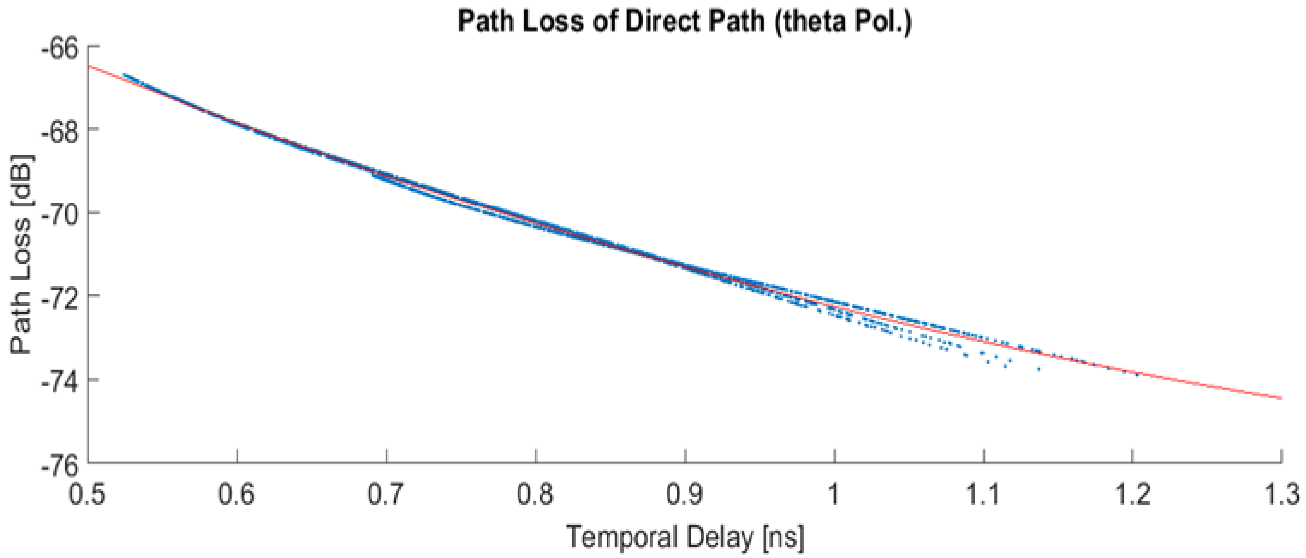
- For the ToA and all following modeling steps, the parameters of the corresponding **distribution functions** are stored **for every possible cluster type**
- This way, a large number of parameters has to be stored; however, the channel model again takes a **large amount of implicit geometrical information**, ensuring the generation of channel impulse response that **correspond to realistic propagation channels**



	Front	Top	Left	Botto m	Back	Right
Front						
Top					Distrib {2,5}	
Left					Distrib {3,5}	
Botto m					Distrib {4,5}	
Back	Distrib {5,1}					
Right					Distrib {6,5}	

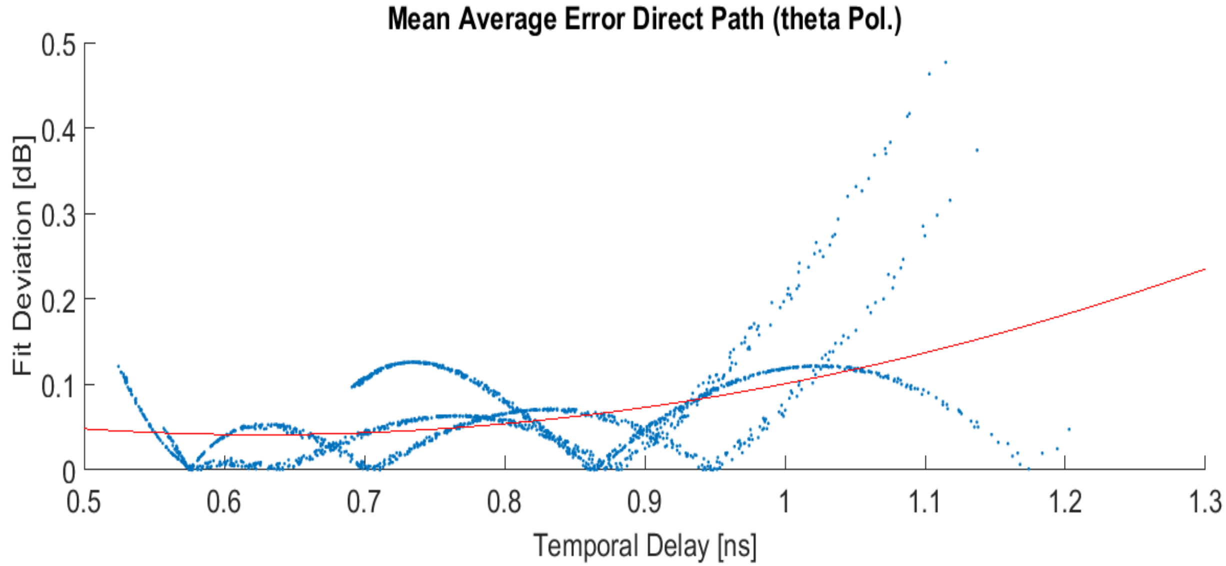
Mean Path Loss (1)

- It is considered **physically meaningful** that the path loss is modeled as a **function of path delay**
- The **mean path loss** is evaluated for **both canonical polarizations**
- For the path loss and all other characteristics that are modeled as functional relationships, the underlying form of the functions are **second order polynomials** (sufficient for small value ranges)

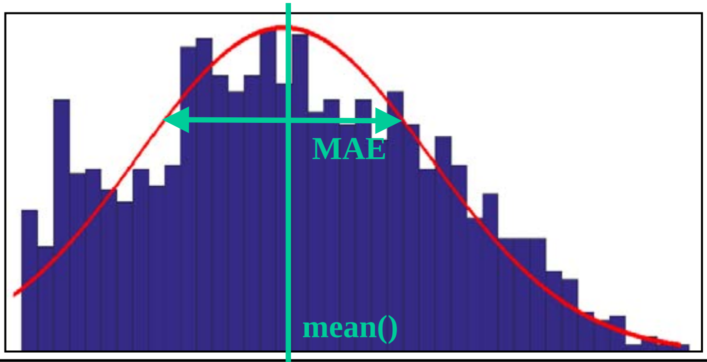


- Along with this functional relationship, the **mean average error** of the fit is again modeled as second order function

Mean Path Loss (2)

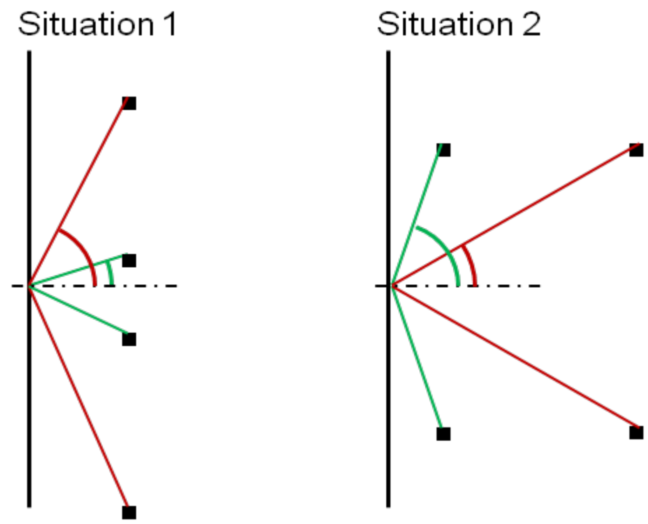


- The **mean path loss** and the **mean average error** are then **fed to a Gaussian Distribution (GD)** to generate the actual mean path loss values for a concrete channel realization



Reflection Angles

- In the same manner as the path delays, the first reflection angles of all reflected paths are modeled as **functions of the path delay**.
- Different geometries may lead to **varying types of relationships**



- In the case of **n^{th}-order reflections**, the reflection angle is modeled as a **function of the corresponding $(n-1)^{th}$ order** reflection angle.

Depolarization

- To this point, the mean path loss properties have been evaluated for the phi and theta components of the electromagnetic field
- However, the **channel matrix** of a polarimetric radio channel consists of **four elements** to account for the phenomenon of **depolarization**

$$\begin{pmatrix} E_{Rx,\upsilon,\phi} \\ E_{Rx,\upsilon,\phi} \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} \cdot \begin{pmatrix} E_{Tx,\upsilon,\phi} \\ E_{Tx,\upsilon,\phi} \end{pmatrix}$$

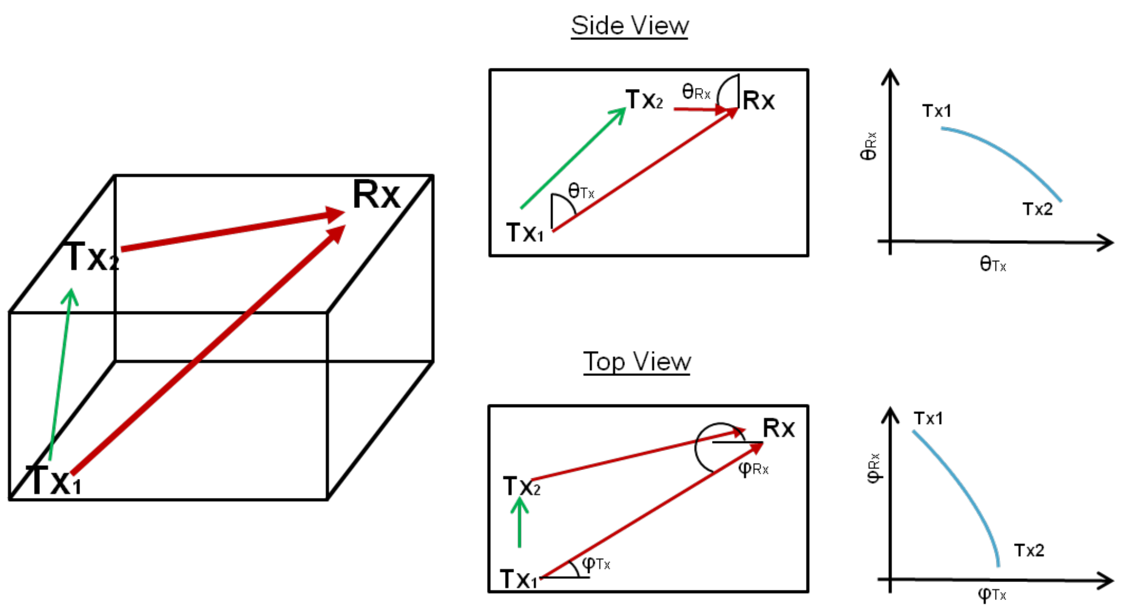
- In the above expressions, the elements H_{11} and H_{22} lead to a **talk-over between the two canonic polarizations**
- Thus, after the generation of the mean path losses for theta- and phi-polarization, the **depolarization angle** of each cluster is derived by

$$\gamma_{depol} = \operatorname{atan}\left(\frac{H_{12}}{H_{11}}\right) = \operatorname{atan}\left(\frac{H_{21}}{H_{22}}\right)$$

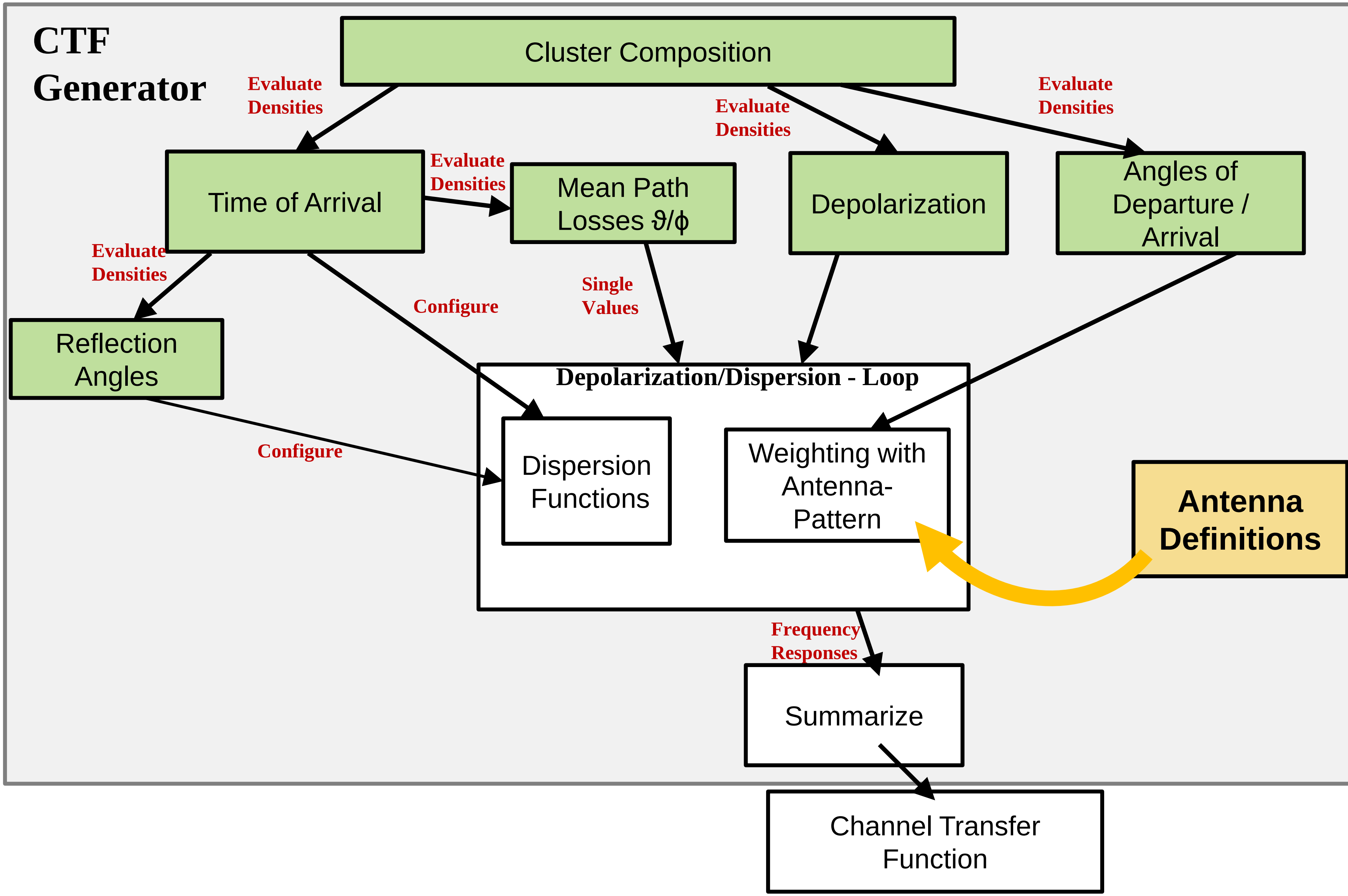
- As no functional dependency (e.g. to the time of arrival) could be observed, all depolarization angles for all reflection processes are modeled as Gaussian Distributions.

Angles of Departure / Arrival

- The final component necessary to fully characterize the Terahertz communication channel is the **angular profile** at the **transmitter** and the **receiver** site.
- As it is considered geometrically meaningful, the angle of departure at the Tx and the angle of arrival at the Rx are modeled **jointly for elongation theta and azimuth phi**

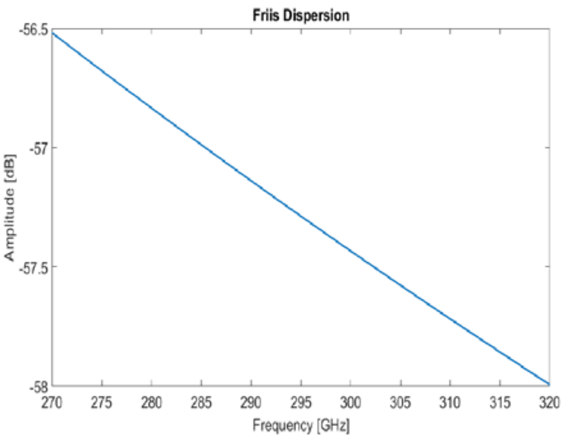


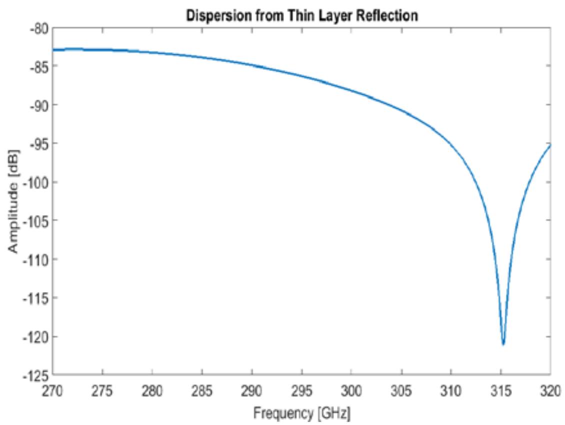
- As a consequence of the above observations, the AoA and AoD profiles in theta and phi are modeled as two-dimensional correlated probability densities (**Copula Distributions**)

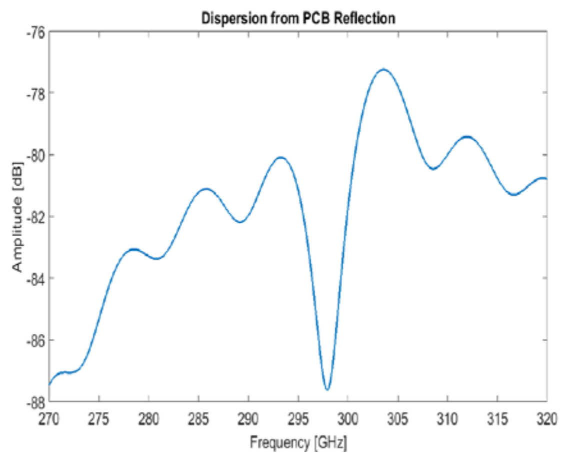

CTF Generator
Cluster Composition
Evaluate Densities
Evaluate Densities
Evaluate Densities
Time of Arrival
Evaluate Densities
Mean Path Losses ϑ/ϕ
Depolarization
Angles of Departure / Arrival
Evaluate Densities
Reflection Angles
Configure
Single Values
Depolarization/Dispersion - Loop
Dispersion Functions
Weighting with Antenna-Pattern
Configure
Antenna Definitions
Frequency Responses
Summarize
Channel Transfer Function

Dispersion Functions

- Due to the **broadband nature** of the investigated propagation channels, a single **mean path-loss** value is **not enough** information to characterize the propagation paths.
- Instead, the path loss is always a **function of frequency** due to **dispersion** stemming from Friis Transmission Equation as well as from the reflection processes at thin layers and printed circuit boards.







Channel Transfer Function

- The CTF provides a **complete description** of the propagation channel in the **frequency range under consideration**:

$$H(f,\vartheta_{Tx},\varphi_{Tx},\vartheta_{Rx},\varphi_{Rx},P_{Tx},P_{Rx}) = \sum_i A_{Rx}(\vartheta_{Rx}-\vartheta_{AoA,i},\varphi_{Rx}-\varphi_{AoA,i},P_{Rx})\cdot CTF_i(f,H_i) \cdot A_{Tx}(\vartheta_{Tx}-\vartheta_{AoD,i},\varphi_{Tx}-\varphi_{AoD,i},P_{Tx})$$

- The structure of the **CTFi** of the several clusters is:

$$CTF_i(f,H_i) = \begin{pmatrix} H_{i,11}(f) & H_{i,12}(f) \\ H_{i,21}(f) & H_{i,22}(f) \end{pmatrix}$$

- The terms of the **transmitting and receiving antennas** are:

$$A_{Tx/Rx} = g_{\frac{Tx}{Rx}}(\vartheta_{Tx/Rx}-\vartheta_i,\varphi_{Tx/Rx}-\varphi_i)\cdot\begin{pmatrix} J_{\vartheta,Tx/Rx} \\ J_{\varphi,Tx/Rx} \end{pmatrix}$$

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- **Intra-Device Scenarios**
- **Intra-Device Results**
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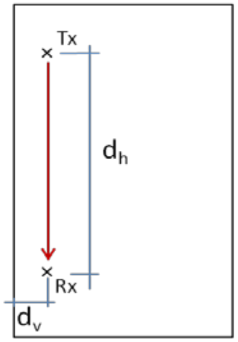
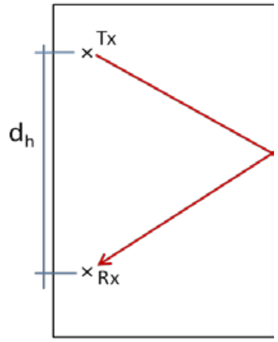
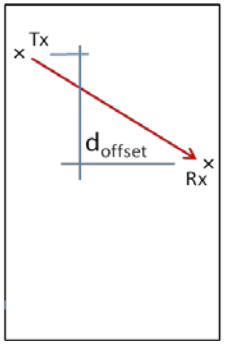
Intra-Device Communication Scenarios

Chip to Chip

Board to Board

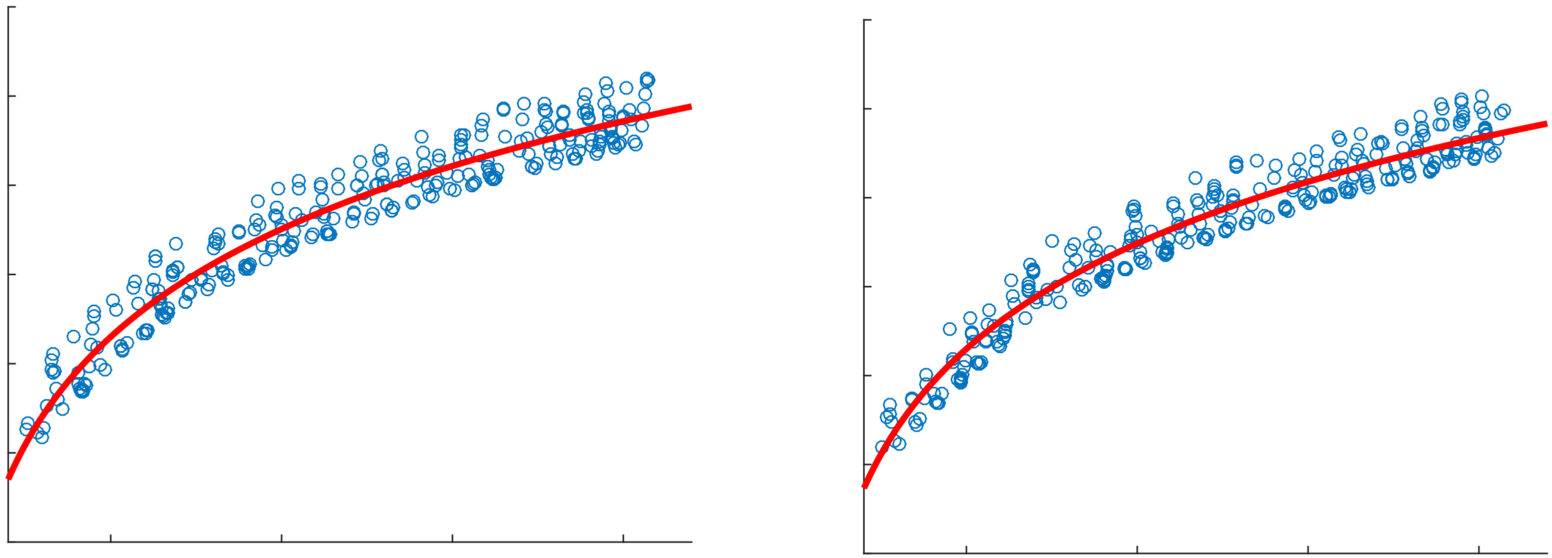






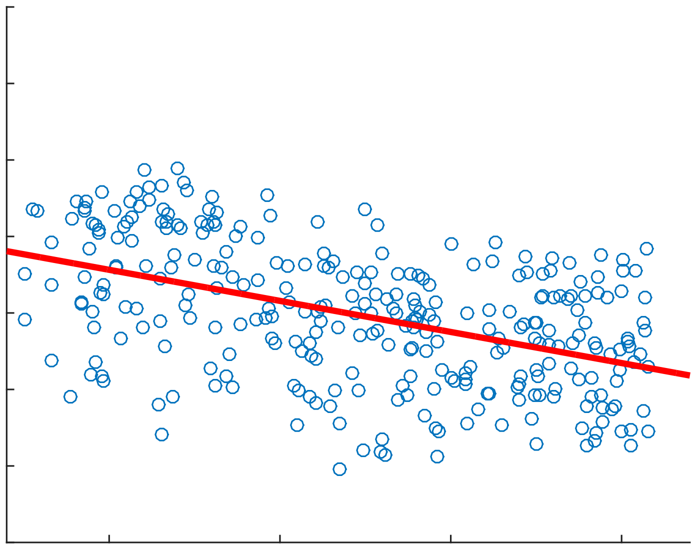
	C2C LOS Condition	**C2C NLOS Condition**	**Board to Board**
Short Description	Tx and Rx mounted on the same surface under LOS conditions; both antennas with perfectly aligned pencil-beams	Tx and Rx mounted on the same surface under NLOS con-ditions; both antennas with pencil-beams aligned towards a reflection path	Tx and Rx mounted on opposing surfaces, perfectly aligned with pencil beams towards each other
HPBW Tx (Θ, ϕ)	16.2°, 17.2°; 20.35dBi	16.2°, 17.2°; 20.35dBi	16.2°, 17.2°; 20.35dBi
HPBW Rx (Θ, ϕ)	16.2°, 17.2°; 20.35dBi	16.2°, 17.2°; 20.35dBi	16.2°, 17.2°; 20.35dBi

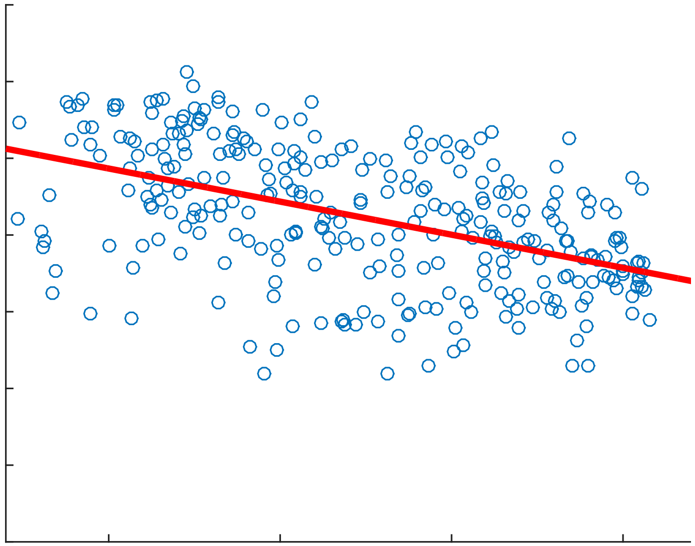
Intra-Device Results: Chip to Chip LOS



- As already observed for the air-dielectric communication types, the path-loss of the main signal follows a **log-distance dependent behavior** under **LOS** conditions.

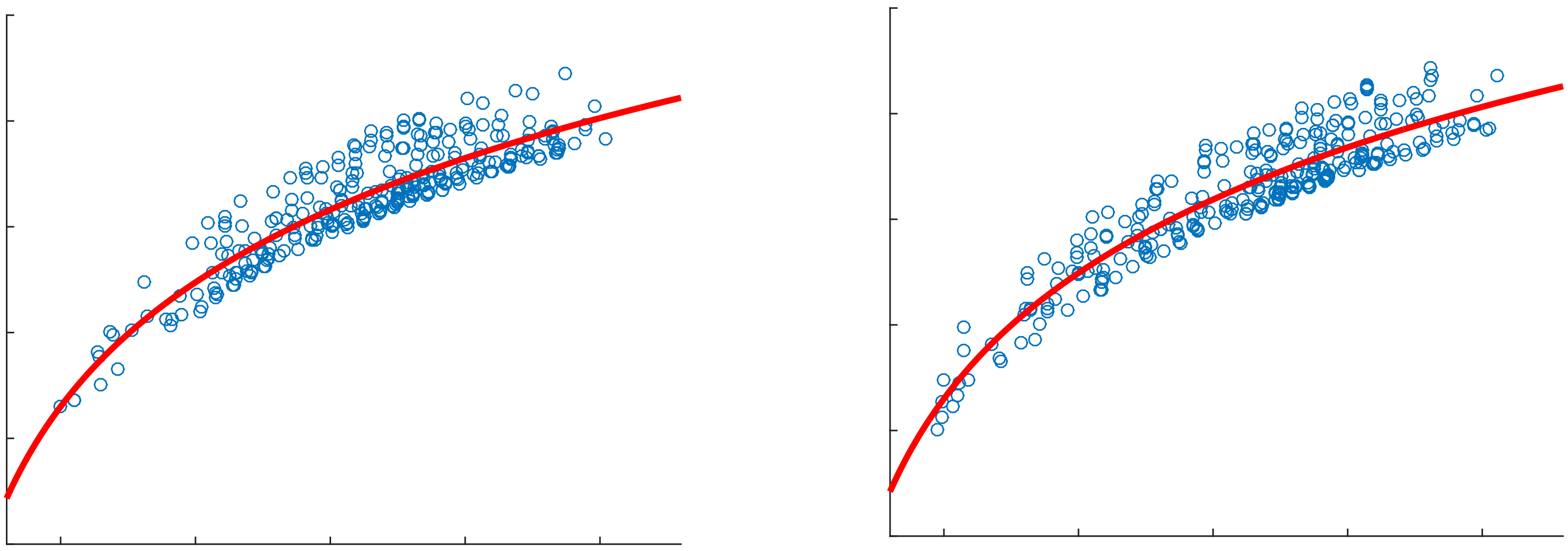
Intra-Device Results: Chip to Chip NLOS





- For the **directed NLOS** operational mode, the log-distance dependency of the path loss is not valid anymore. The simulated path losses are **rather equally distributed** over a certain amplitude range.
- This comprehensible since the length of the directed NLOS propagation path is **only indirectly coupled** to the **separation between Tx and Rx**.

Intra-Device Results: Board to Board



- The path-loss characteristics for board to board communications again show the same **log-distance dependent behavio**r as for the already investigated LOS communication types

Intra-Device Results: Path Loss Model

- For the **LOS** application cases, the path loss of the main signal follows the classical **log-distance dependency** already introduced

$$PL(d[m])_{total}[dB] = PL_{d_0}[dB] + 10 \cdot \gamma \cdot log_{10}\left(\frac{d[m]}{d_0[m]}\right) + \chi_g$$

- The parameters for the LOS operational modes are the following

Scenario	PL_{d_0}	d_0	γ	RMSE(χ_g)
Chip to Chip LOS, vertical	16.5	0.05	2.007	1.1934
Chip to Chip LOS, circular	16.5	0.05	1.969	1.1020
Board to Board, vertical	16.5	0.05	1.977	1.1502
Board to Board, circular	16.5	0.05	1.951	1.1437

- For Chip to Chip Communications in **NLOS** configuration, the observed path loss can be modeled by a **linear relationship** between Tx/Rx separation and path loss

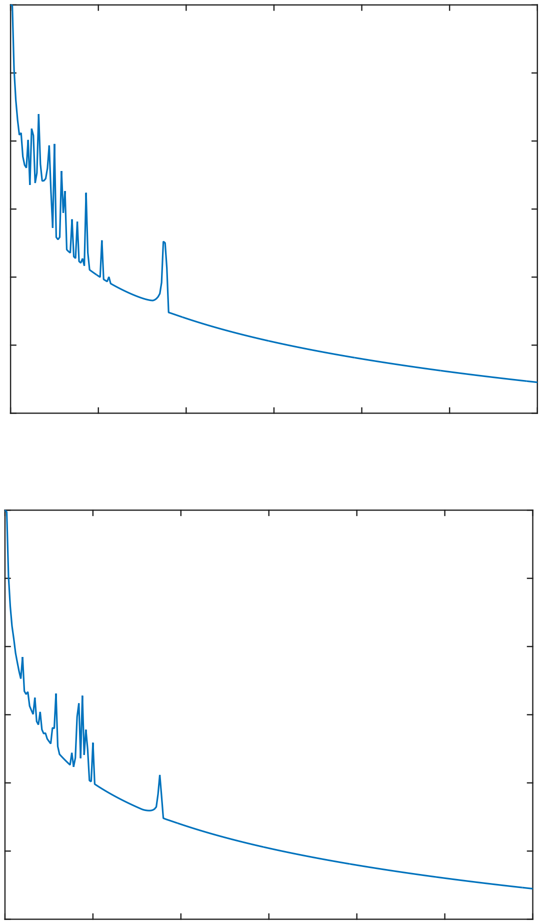
$$PL(d[m])_{total}[dB] = PL_0[dB] + \zeta \cdot d[m] + \chi_g$$

- The parameters of which are

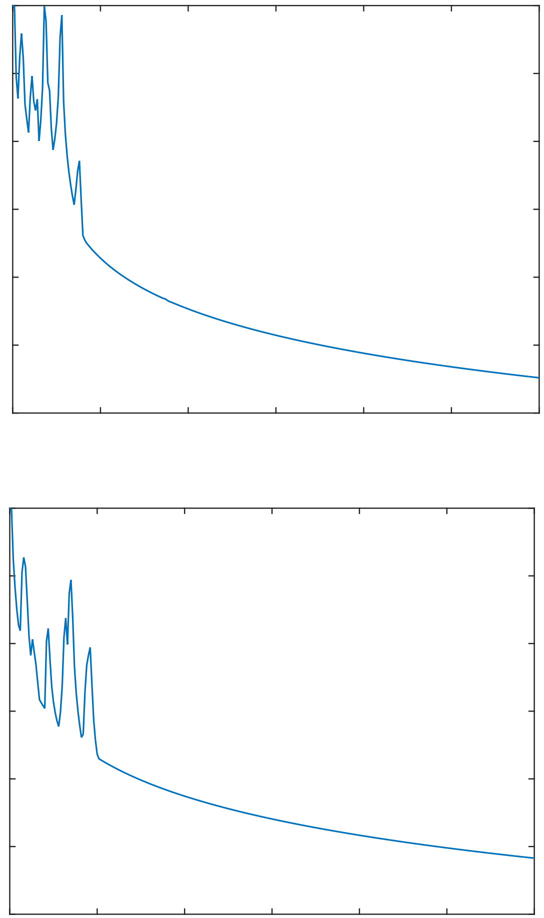
Scenario	PL_{d_0}	d_0	γ	RMSE(χ_g)
Chip to Chip LOS, vertical	44.85	40.64	1.1934	44.85
Chip to Chip LOS, circular	51.49	43.13	1.1020	51.49

Intra-Device Results: Impulse Responses

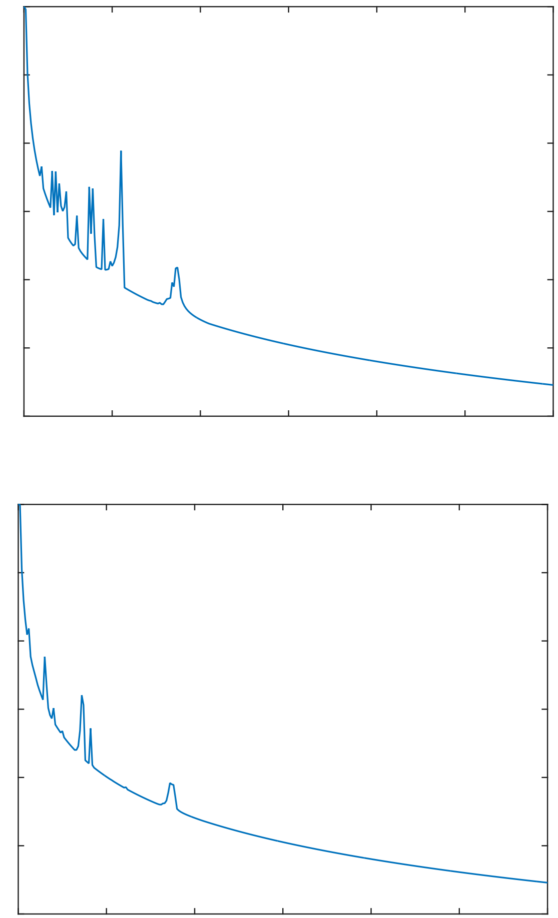
Chip to Chip LOS



Chip to Chip NLOS



Board to Board



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Conclusion

- The characteristics of the channel model are derived from a **ray-tracing approach** for intra-device communications in the THz - range
- These characteristics configure a so-called **channel generator** which is utilized to generate a large **number of realistic channel transfer functions**
- The path loss models and envelopes of the impulse responses have shown that
  - Different application cases lead to **varying channel statistics**
  - **Simple figures of merit** such as mean path loss and exponential decay **are not sufficient**
  - **Antenna characterstics** such as polarization and beamwidth **play a significant role**
- Thus, a **set of realistic channel transfer functions** shall be generated for the application cases and configurations
- In the proposal evaluation process, these **channel transfer functions** shall serve as **foundation for the link-level simulations**, e.g. to provide impulse responses as input to a tapped delay line model

Thank You
for Your Attention