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Metrology for THz Communications

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Device Discovery and Beam Tracking

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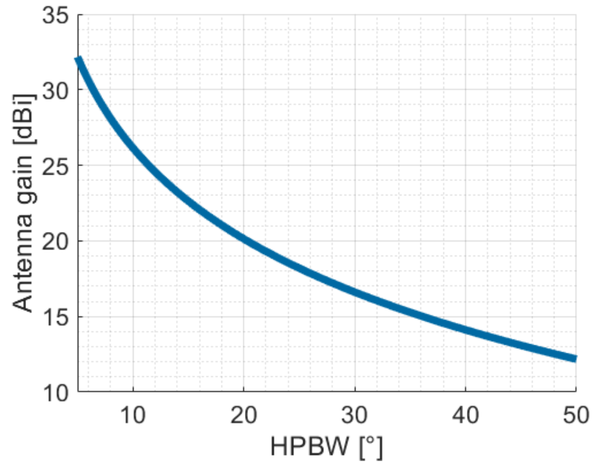
Motivation

- Low THz frequency range (0.1 – 1 THz) foreseen for next generation communication systems due to high available bandwidth
- In this frequency, range systems suffer from currently low output power devices and high losses
- Antenna gain can be increased in order to overcome losses
- Half-power beamwidth decreases if antenna gain is increased

$$P_{\mathrm{RX}} = P_{\mathrm{TX}} \cdot G_{\mathrm{TX}} \cdot G_{\mathrm{path}} \cdot G_{\mathrm{RX}}$$



Continuous antenna alignment crucial!

Two phases of antenna alignment

- Antenna alignment can be separated into two phases: initial alignment and alignment update

Initial alignment

- Called device discovery
- Needed at the beginning of the communication
- Maybe necessary after alignment loss

Alignment updates

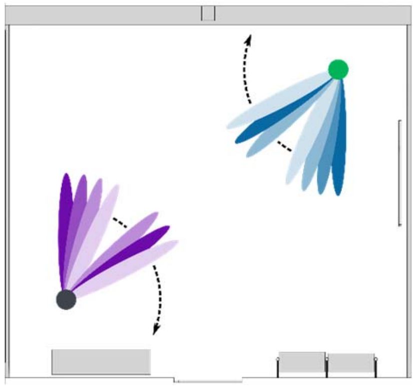
- Necessary in time-variant scenarios
- Among others: beam tracking and beam switching

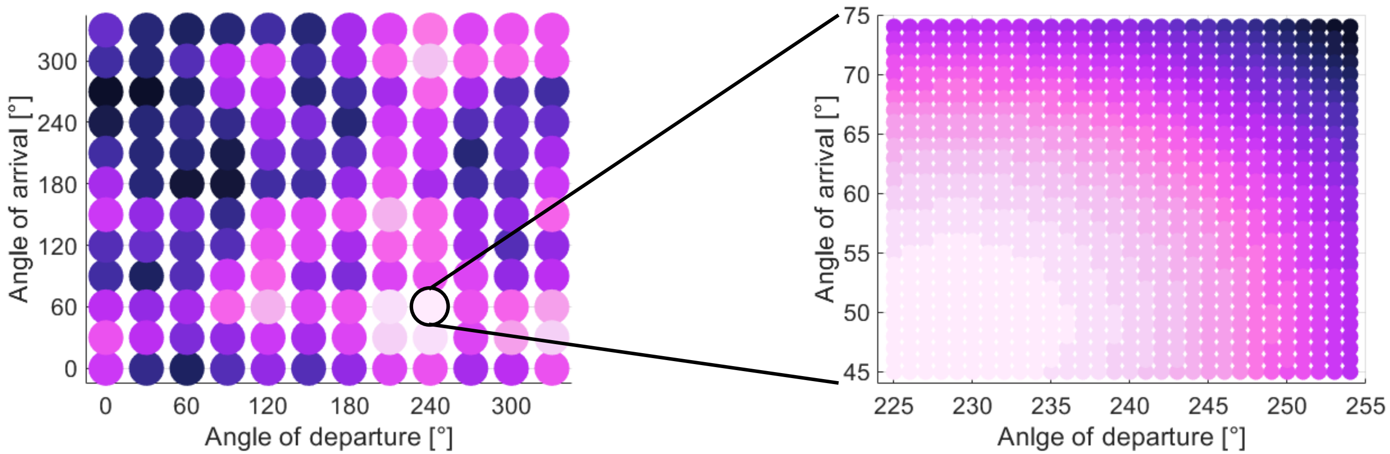
- This work will deal with a novel device discovery and beam tracking approach

Device discovery

- Approaches utilized in lower frequency ranges often fails due to constraints like, for example, need of omni-directional antennas
- Promising approach: two-step scanning approach

$$N = \left\lceil \frac{360°}{\Delta\varphi_{\text{init}}} \right\rceil^2 + \left\lceil \frac{\Delta\varphi_{\text{init}}}{\Delta\varphi_{\text{final}}} \right\rceil^2$$





Compressed sensing

T. Doeker, P. Reddy Samala, P. S. Negi, A. Rajwade and T. Kürner, "Angle of Arrival and Angle of Departure Estimation Using Compressed Sensing for Terahertz Communications," *2021 15th European Conference on Antennas and Propagation (EuCAP)*, Düsseldorf, Germany, 2021, pp. 1-5, doi: 10.23919/EuCAP51087.2021.9411406.

- Power angular profile (PAP) given over two-dimensional grid with resolution $\Delta\varphi_{\mathrm{PAP}}$
- Distribution of multipath components (MPCs) in environment can also be given as two-dimensional grid with resolution $\Delta\varphi_{\mathrm{MPC}}$
- The MPCs are mapped to the PAP through the antenna diagram
- In vectorized form: $\boldsymbol{y} = \boldsymbol{A}\boldsymbol{x}$

$\boldsymbol{y} \in \mathbb{R}^m$ ≙ measurement vector; vectorized form of PAP

$\boldsymbol{A} \in \mathbb{R}^{m \times n}$ ≙ measurement matrix including the antenna diagram

$\boldsymbol{x} \in \mathbb{R}^n$ ≙ signal vector; vectorized form of MPC distribution

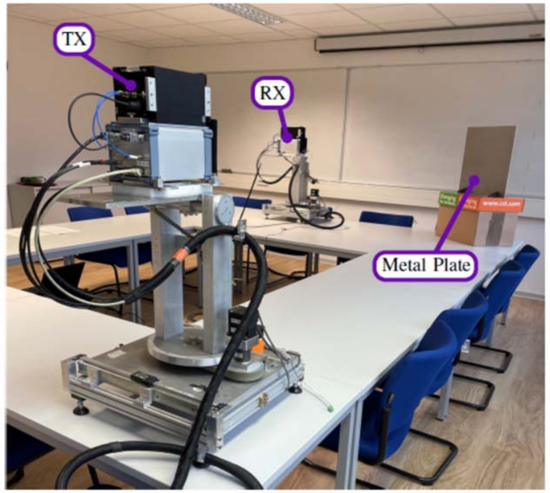
typically: $m \ll n$

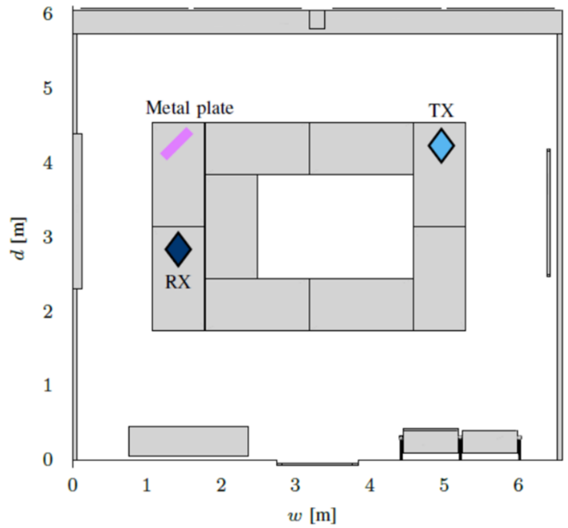
→ Compressed sensing can be used to solve the equation as $\boldsymbol{x}$ can be assumed to be sparse

Benefit & measurements

T. Doeker and T. Kürner, "Compressed Sensing-assisted Device Discovery for Low Terahertz Communications," in *IEEE Transactions on Terahertz Science and Technology*, doi: 10.1109/TTHZ.2025.3591305.

- MPC distribution, i.e. signal vector, can be reconstructed based on PAP with low angular resolution (few measurements)
- PAP can be measured with channel sounder: Each AOD-AOD combination is sum of power of channel impulse response in specific direction
- Available channel sounder:
  - correlation-based time-domain channel sounder
  - Center frequency 304.2 GHz with 8 GHz bandwidth
  - 15 dBi horn antennas with approx. 30° HPBW

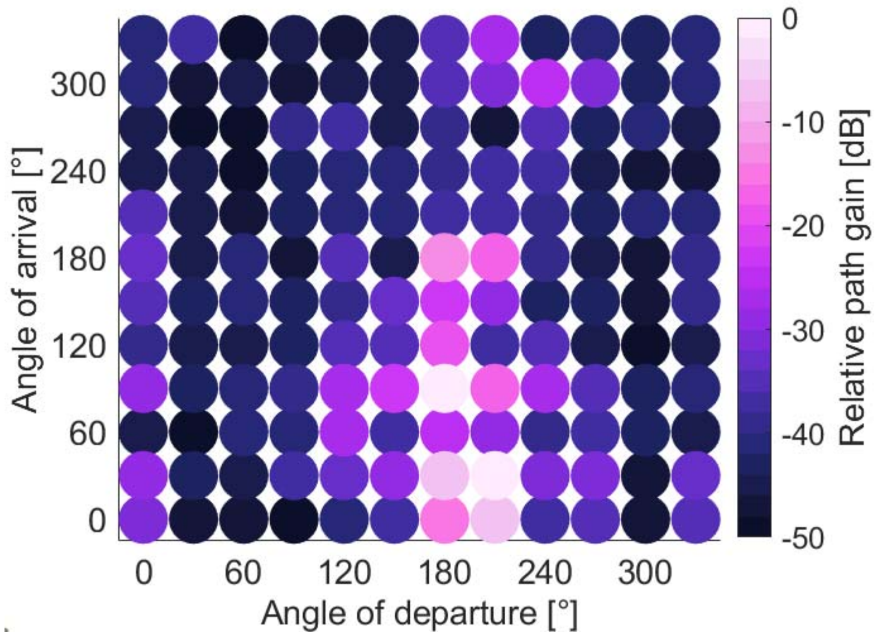




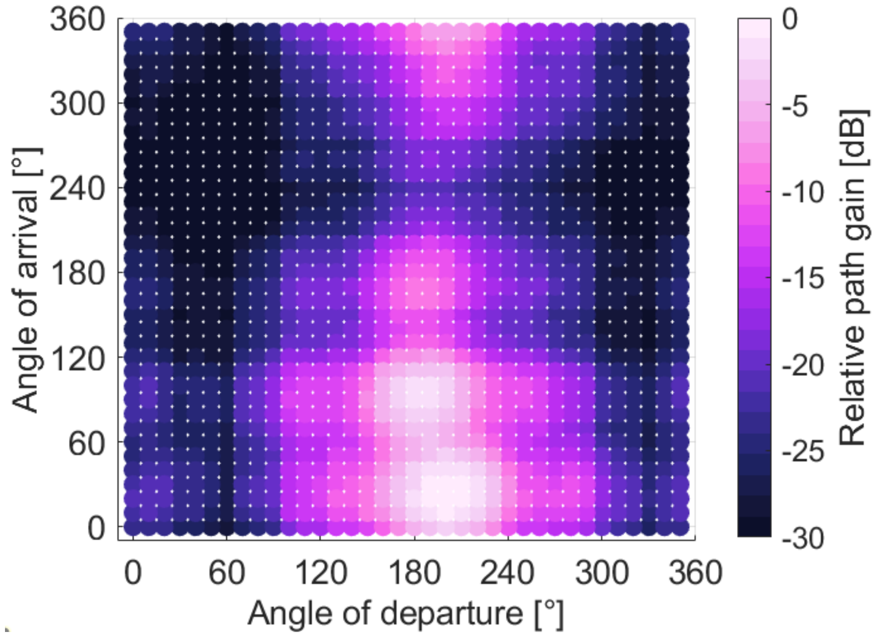
Results

T. Doeker and T. Kürner, "Compressed Sensing-assisted Device Discovery for Low Terahertz Communications," in *IEEE Transactions on Terahertz Science and Technology*, doi: 10.1109/TTHZ.2025.3591305.

Measured PAP with $\Delta\varphi_{\mathrm{PAP}} = 30°$



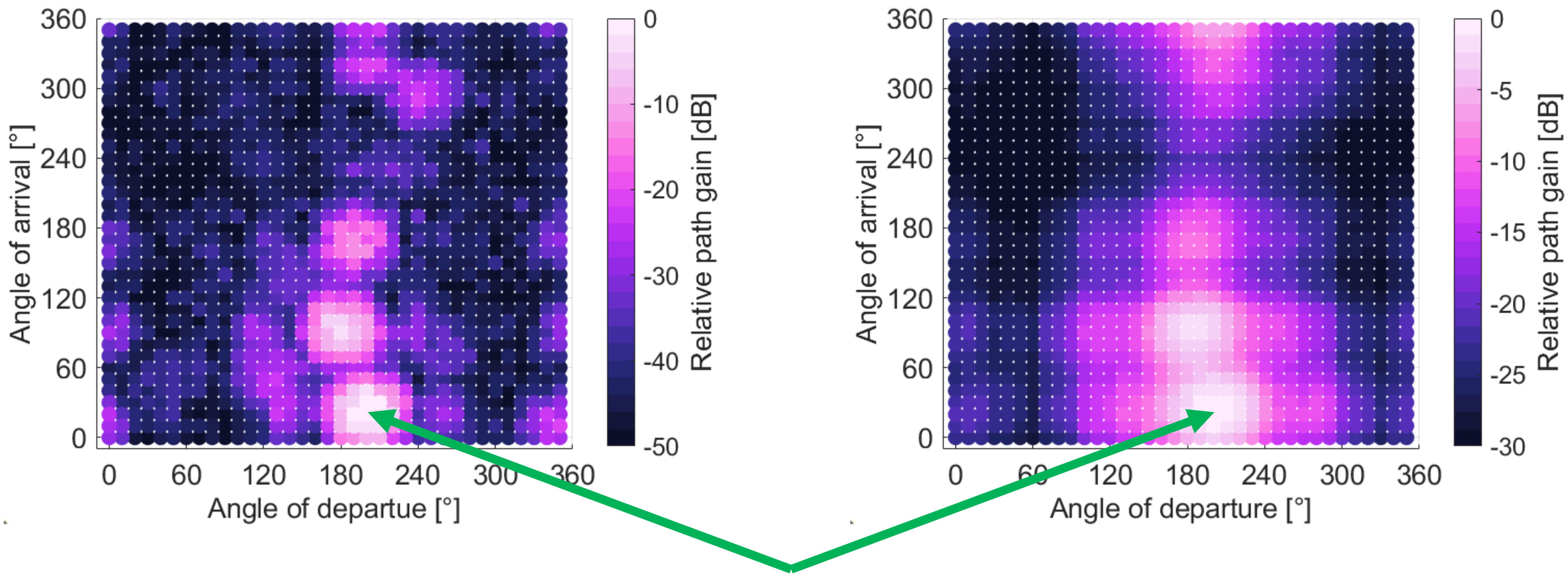
Predicted MPC with $\Delta\varphi_{\mathrm{MPC}} = 10°$



Results

T. Doeker and T. Kürner, "Compressed Sensing-assisted Device Discovery for Low Terahertz Communications," in *IEEE Transactions on Terahertz Science and Technology*, doi: 10.1109/TTHZ.2025.3591305.

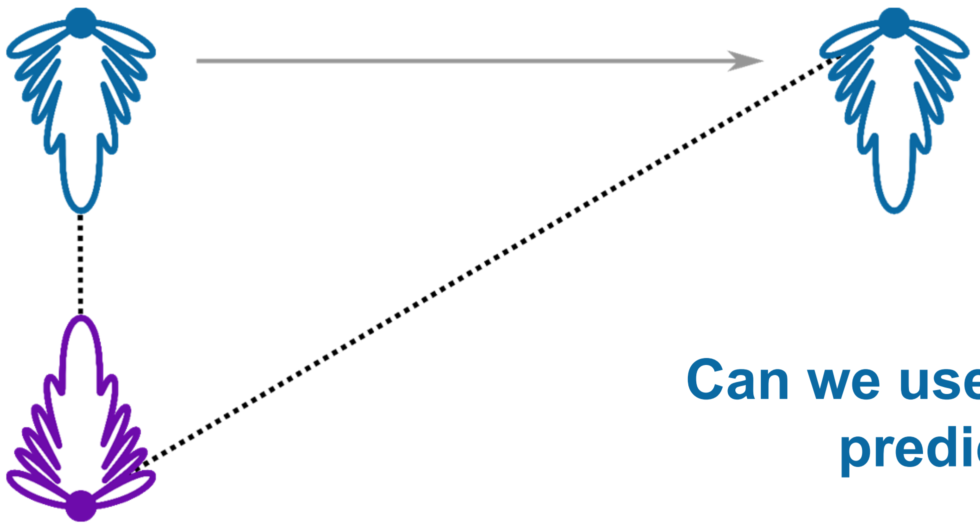
Measured PAP with $\Delta\varphi_{\mathrm{PAP}} = 10°$ | Predicted MPC with $\Delta\varphi_{\mathrm{MPC}} = 10°$



In both cases maximum at $\mathbf{AOD = 220°}$ and $\mathbf{AOA = 20°}$

Beam tracking

- After initial alignment further alignment enabled using horn antennas
- Existing methods always require MIMO setups and antenna arrays or are based on movement predictions
- Assumption that relative orientation of antennas does not change during movement



Can we use the change in the path gain for predicting the angular change?

Change of path gain

- Based on Friis equation (assuming LOS condition here):

$$\frac{P_{\mathrm{RX},1}}{P_{\mathrm{RX},0}} = \frac{P_{\mathrm{TX}} \cdot G_{\mathrm{TX}}(\varphi_{\mathrm{AoD},1}) \cdot G_{\mathrm{FSPL}}(d_1) \cdot G_{\mathrm{RX}}(\varphi_{\mathrm{AoA},1})}{P_{\mathrm{TX}} \cdot G_{\mathrm{TX}}(0°) \cdot G_{\mathrm{FSPL}}(d_0) \cdot G_{\mathrm{RX}}(0°)}$$

- Received power, path loss and antenna gain before movement are known:

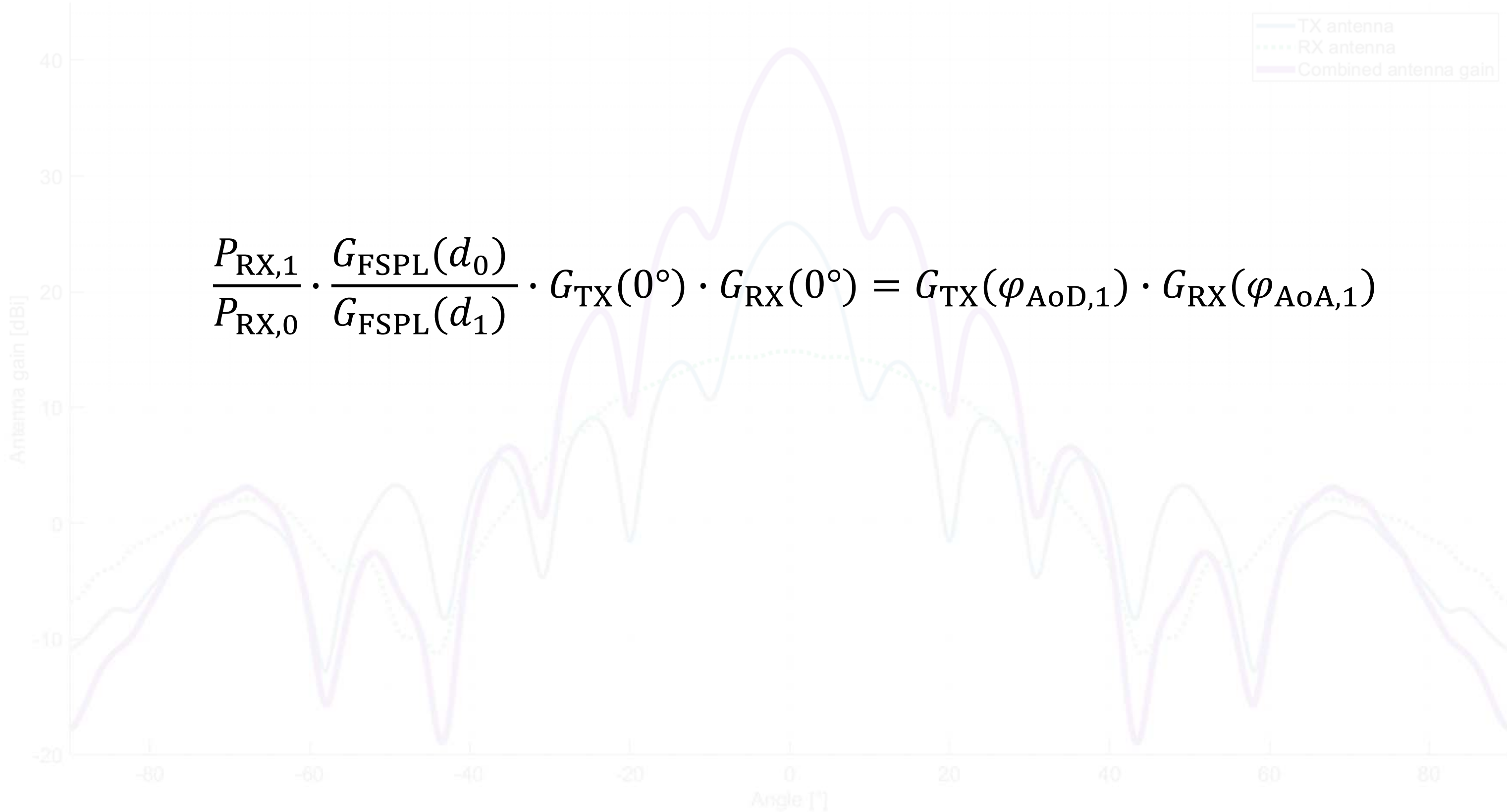
$$\frac{P_{\mathrm{RX},1}}{P_{\mathrm{RX},0}} \cdot \frac{G_{\mathrm{FSPL}}(d_0)}{G_{\mathrm{FSPL}}(d_1)} \cdot G_{\mathrm{TX}}(0°) \cdot G_{\mathrm{RX}}(0°) = G_{\mathrm{TX}}(\varphi_{\mathrm{AoD},1}) \cdot G_{\mathrm{RX}}(\varphi_{\mathrm{AoA},1})$$

- If relative orientation of antennas does not change: antenna gain for each AOD-AOA combination can be calculated

  → *combined antenna gain*

Combined antenna gain

$$\frac{P_{\mathrm{RX},1}}{P_{\mathrm{RX},0}} \cdot \frac{G_{\mathrm{FSPL}}(d_0)}{G_{\mathrm{FSPL}}(d_1)} \cdot G_{\mathrm{TX}}(0°) \cdot G_{\mathrm{RX}}(0°) = G_{\mathrm{TX}}(\varphi_{\mathrm{AoD},1}) \cdot G_{\mathrm{RX}}(\varphi_{\mathrm{AoA},1})$$



Unique solution

- In order to find unique solution: More than one antenna are used with different orientations
- Simulation-based evaluation: 100% accuracy of angle prediction

L. H. W. Löser, T. Doeker and T. Kürner, "Antenna Pattern Tracking Algorithm for Low Terahertz Communications," *2024 18th European Conference on Antennas and Propagation (EuCAP)*, Glasgow, United Kingdom, 2024, pp. 1-5, doi: 10.23919/EuCAP60739.2024.10501488.

- Measurement-based evaluation:
  - ± 1° accuracy for angular changes < 20° in LOS and NLOS cases
  - ± 4° accuracy for angular changes < 70° (LOS) and < 45° (NLOS)

T. Doeker, L. H. W. Loeser and T. Kürner, "Measurements and Verification of an Antenna Pattern-Based Tracking Algorithm at 300 GHz," in *IEEE Transactions on Terahertz Science and Technology*, vol. 15, no. 3, pp. 359-369, May 2025, doi: 10.1109/TTHZ.2025.3555599.

Conclusion

- Antenna alignment crucial for THz communications
- Important for initial alignment as well as continuous alignment in time-varying scenarios

- For initial alignment novel device discovery approach based on iterative search in combination with compressed sensing
- Measurement-based evaluation shows correct prediction for measurements taken with 30° increment

- For continuous alignment, here beam tracking, novel approach based on information of path gain change/ antenna diagram
- Measurement-based evaluation shows prediction ± 1° accuracy for angular changes < 20° for LOS and NLOS

Thank you very much for your attention

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