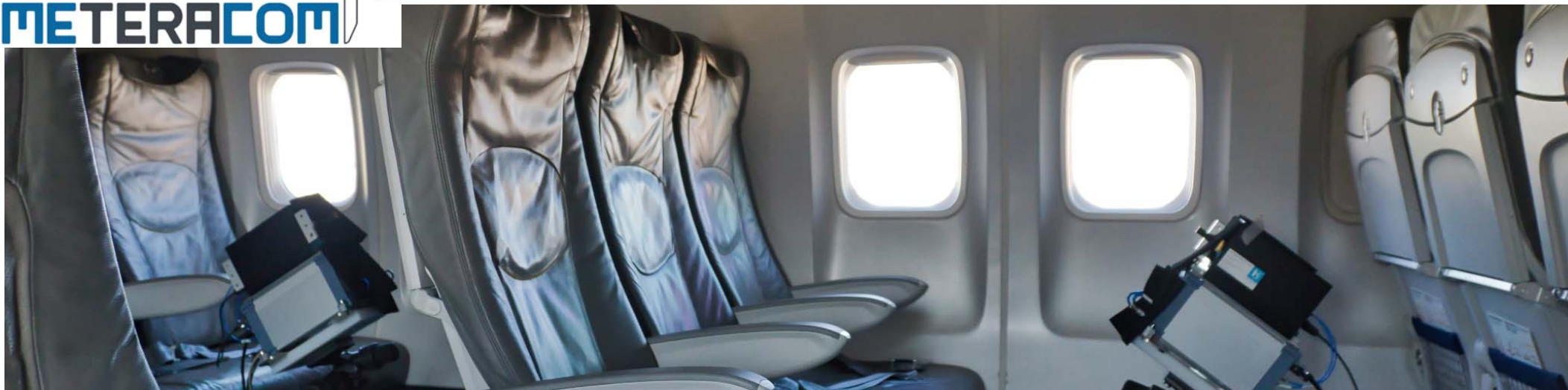




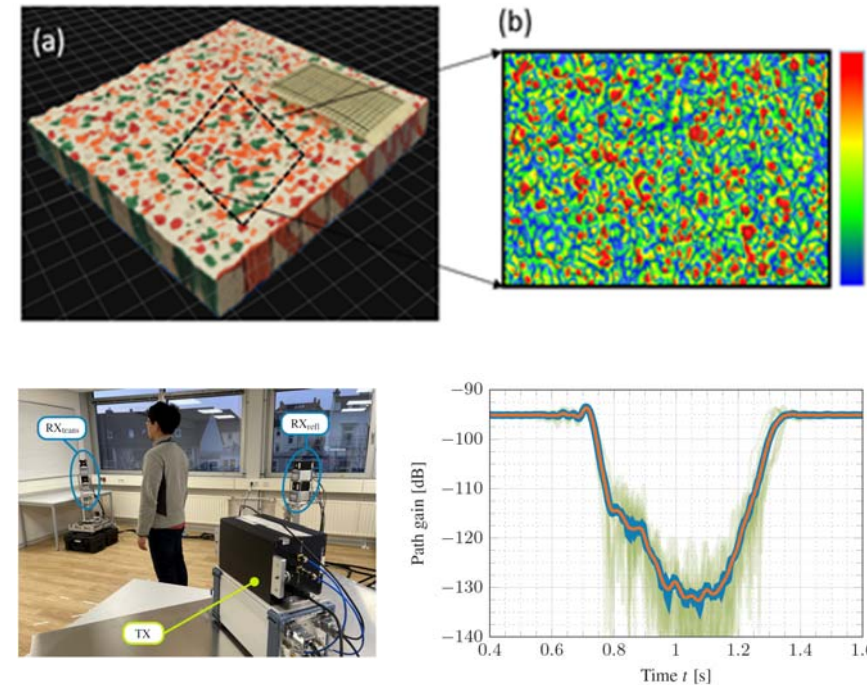
Introduction to DFG FOR 2863 Meteracom

Prof. Dr.-Ing. Thomas Kürner, Spokesman DFG FOR 2863
Institut für Nachrichtentechnik, TU Braunschweig

DFG FOR2863 Meteracom Final Workshop @ IRmmW-THz 2025, 20 August 2025

Outline

- Introduction of the DFG FOR 2863 Meteracom
 - *Why?* Motivation to work on Metrology for THz Communications
 - *What?* Project Structure
 - *Who?* Consortium
- Some exemplary Outcomes*
- Overview on the Workshop Program
 - Talks
 - Poster Presentations
- Overview on regular Contributions by Meteracom @IRmmW-THz 2025
- Introduction of the Meteracom Booth @IRmmW-THz 2025
- Introduction of the Meteracom OpenAccess Book Publication

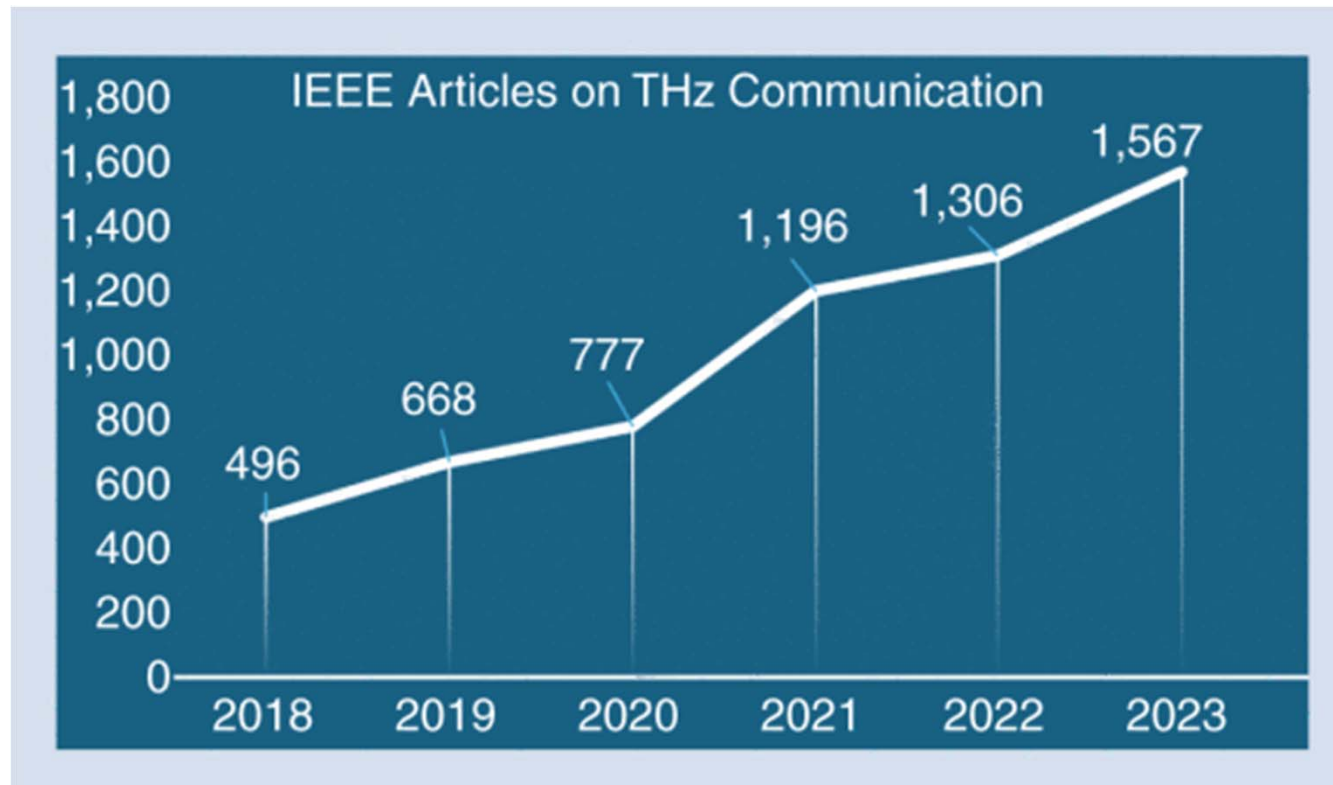


*and not presented elsewhere in the workshop



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Research on THz Communications is booming....



Source: J. M. Jornet, H. Elayan, T. Nagatsuma, M. Juntti, E. T. Pinto, T. Kürner, H. Guerboukha, D. M. Mittleman, E. Knightly, "Mobile Terahertz Communication and Sensing Systems: A Future Look," in *IEEE Vehicular Technology Magazine*, vol. 19, no. 4, pp. 20-35, Dec. 2024,

...and THz Communication has even entered the Phase of (Pre-Standardisation) @ IEEE 802 and ETSI

IEEE STANDARDS ASSOCIATION

IEEE

IEEE Standard for High Data Rate
Wireless Multi-Media Networks

Amendment 2: 100 Gb/s Wireless
Switched Point-to-Point Physical
Layer

IEEE Computer Society

Sponsored by the
LAN/MAN Standards Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 802.15.3d™-2017
(Amendment to
IEEE Std 802.15.3™-2016
as amended by
IEEE Std 802.15.3e™-2017)

IEEE SA
STANDARDS
ASSOCIATION

IEEE Standard for Wireless
Multimedia Networks

IEEE Computer Society

Developed by the
LAN/MAN Standards Committee

IEEE Std 802.15.3™-2023
(Revision of IEEE Std 802.15.3-2016)

IEEE

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STANDARDS

ETSI GR THz 001 V1.1.1 (2024-01)



TeraHertz modeling (THz);
Identification of use cases for THz communication systems

ETSI GR THz 003 V1.1.1 (2024-12)



TeraHertz modeling (THz);
Channel measurements and modeling in THz bands



ETSI GR THz 002 V1.1.1 (2024-03)



TeraHertz technology (THz);
Identification of frequency bands of interest for
THz communication systems

ETSI GR THz 004 V1.1.1 (2025-01)



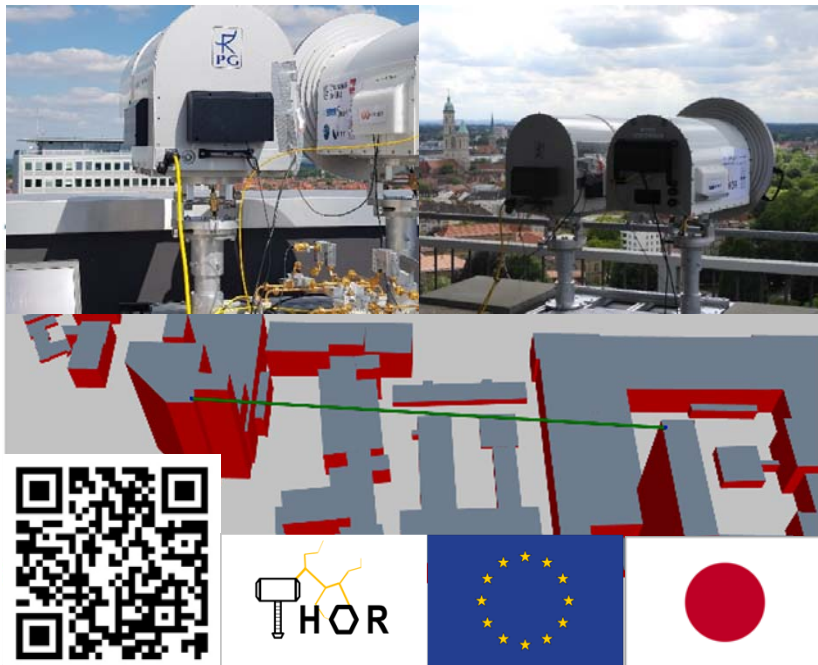
TeraHertz technology (THz);
RF Hardware Modeling



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Numerous Hardware Demonstrators have shown the feasibility of THz Communications

THz Backhaul Demonstrator, Braunschweig, June 2022



Source T. Kürner et al., "THz Communications and the Demonstration in the ThoR-Backhaul Link," in *IEEE Transactions on Terahertz Science and Technology*, vol. 14, no. 5, pp. 554-567, Sept. 2024, doi: 10.1109/TTTH.2024.3415480.

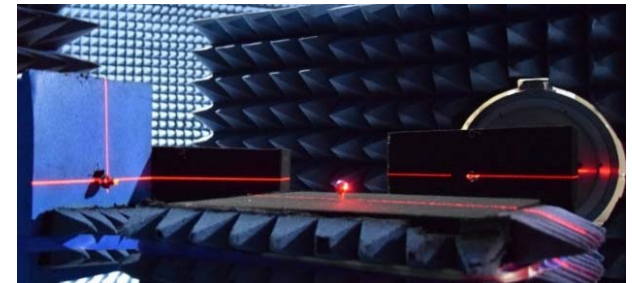
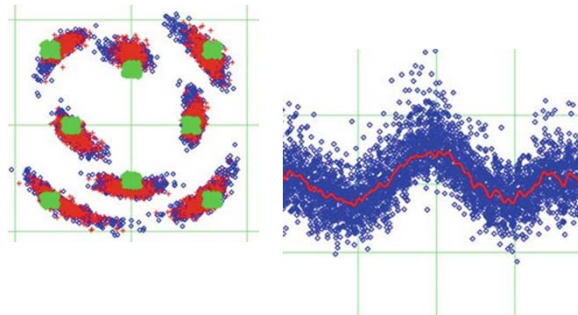
IEEE 802.15 WNG Tech Focus @Kobe/Japan, 15 January 2025



Challenges for Metrology of THz Communications

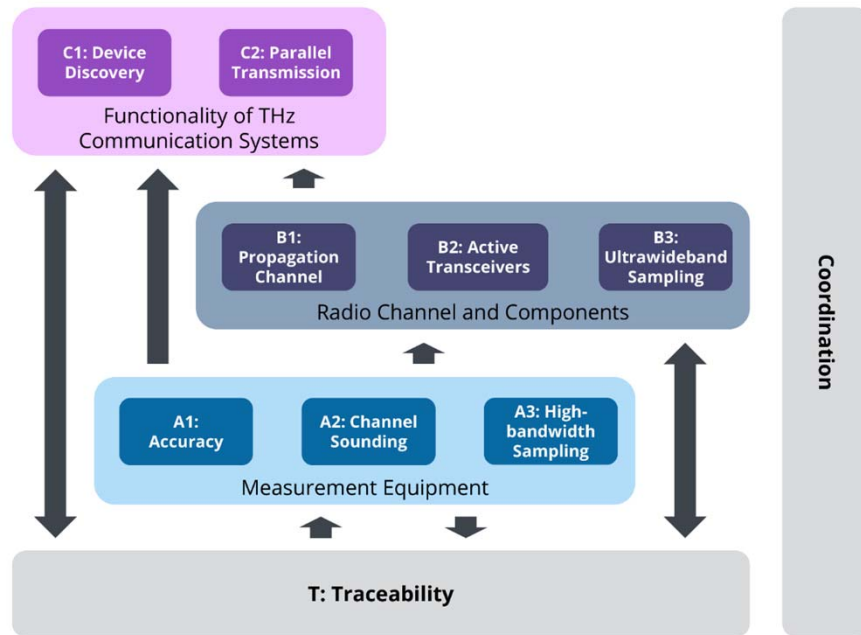
- The **capability to performing measurements** and evaluating measurements in a proper way are **crucial for the advance of THz communication systems**. Meteracom has addressed the **grand challenge of metrology for THz communication measurements** systematically, and in four distinct project areas:

- T: Traceability to the International System of Units (SI)
- A: Characterisation of the measurement system itself
- B: Metrological characterisation of the RF components and the propagation channel
- C: Measurements required for enabling the functionality of THz communications / Systems Metrology.

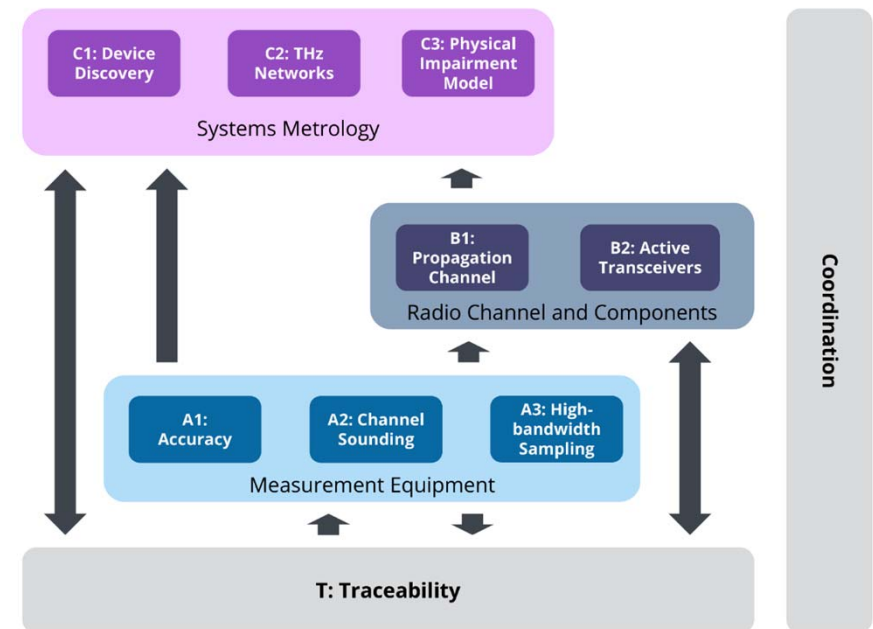


Project Structure

Phase I (2019-2022)



Phase II (2022-2025)



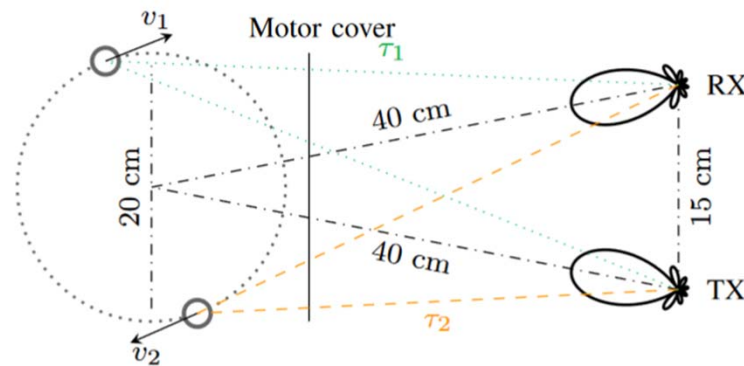
Source: based on T. Kürner, T. Doeker, D. Humphreys, T. Kleine-Ostmann, T. Schneider „Metrology for THz Communications – Findings from DFG FOR2862“, in Springer 2025, to be published; <https://link.springer.com/book/9783032019851>; (Open Access Under a Creative Commons License)

Meteracom Consortium

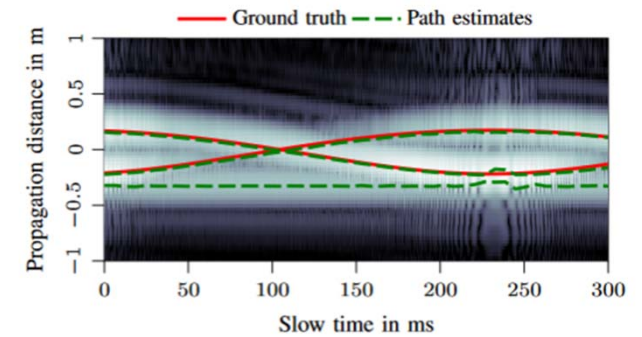
- Interdisciplinary and distributed research unit
- 10 Principal Investigators from 6 universities and PTB
- 2 Mercator Fellows from NPL (UK) and Brown University Rhode Island (USA), respectively
- Spokesman: Thomas Kürner (TU Braunschweig)



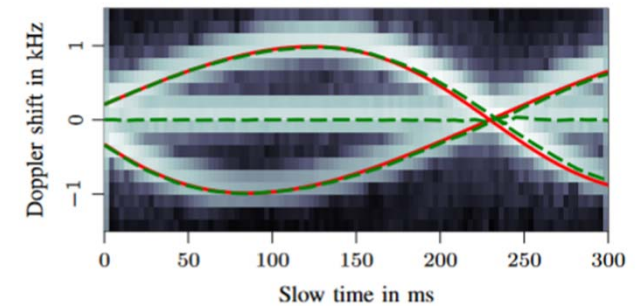
Exemplary Outcome Project Area A: Joint Delay/Doppler Sounding and Resolution Verification via OTA artifact



J. Gedschold *et al.*, "Metrology of Multicarrier-Based Delay-Doppler Channel Sounding for sub-THz Frequencies," in *IEEE Open Journal of Antennas and Propagation*, doi: 10.1109/OJAP.2025.3566473 (Open Access Under a Creative Commons License)



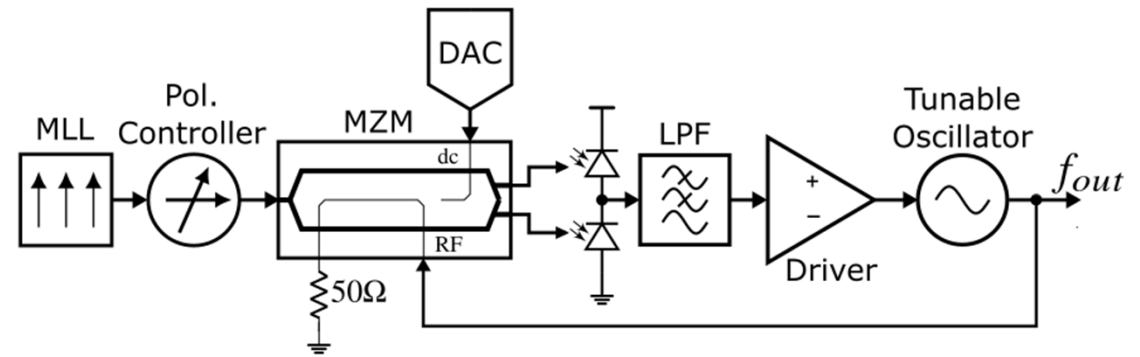
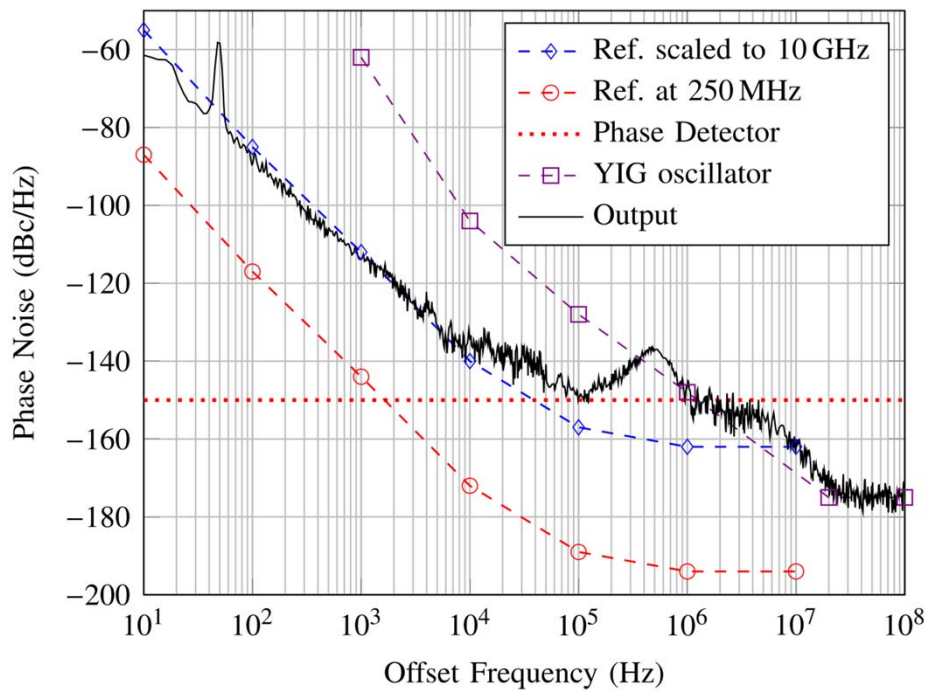
(a) Time-varying power delay profile.



(b) Time-varying power Doppler profile.

FIGURE 9. Experimental measurement and estimation results of the proposed OTA artifact.

Exemplary Outcome Project Area B: Photonic Referenced Oscillator / Optoelectronic PLL (OE-PLL)

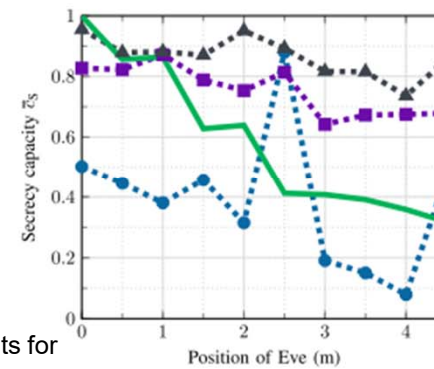
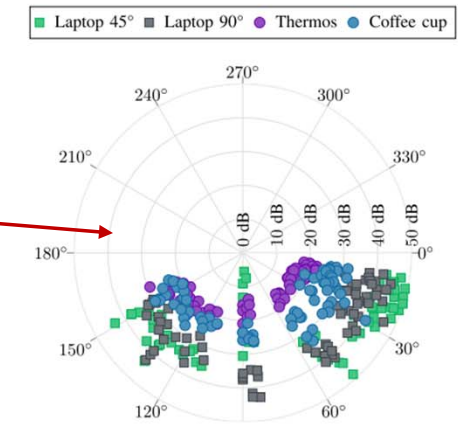
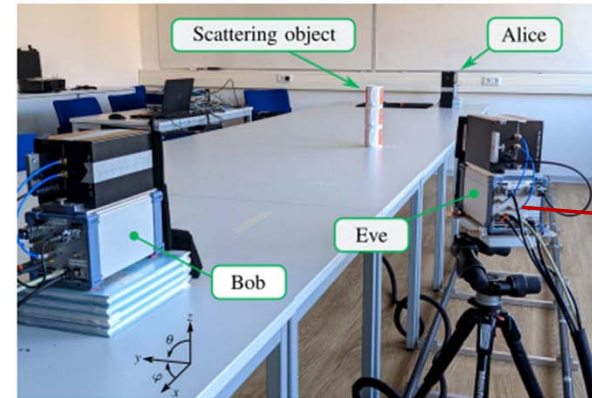
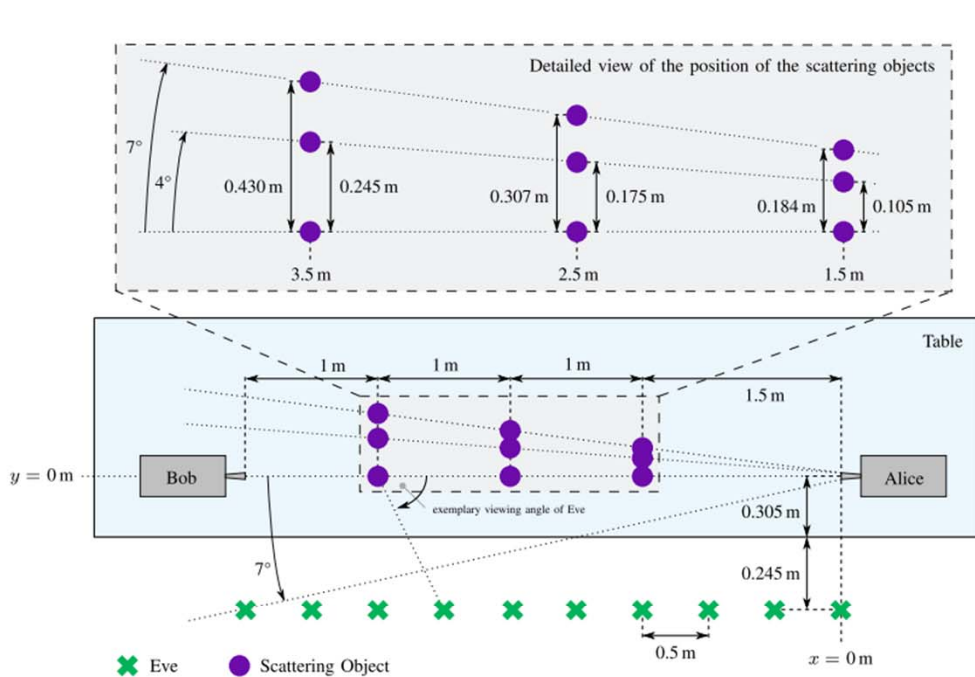


- 2.8 fs rms @ 10GHz
[1 kHz-100MHz]

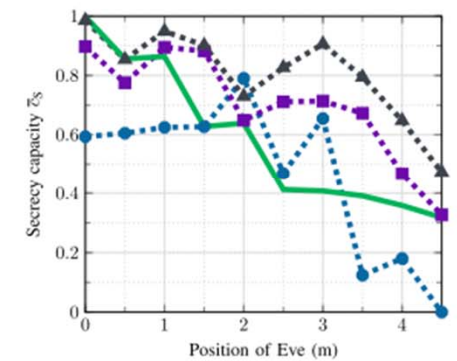
M. Bahmanian and J. C. Scheytt, "A 2–20-GHz Ultralow Phase Noise Signal Source Using a Microwave Oscillator Locked to a Mode-Locked Laser," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 3, pp. 1635-1645, March 2021, doi: 10.1109/TMTT.2020.3047647. (Open Access (Open Access Under a Creative Commons License))



Exemplary Outcome Project Area C: Measurements on Physical Layer Security at 300 GHz



(c) Coffee cup placed at $x_{\text{scat}} = 3.5$ m.



(j) Laptop 90° placed at $x_{\text{scat}} = 1.5$ m.

Source: T. Doeker, C. Herold, J. M. Eckhardt and T. Kürner, "Eavesdropping Measurements for Applications in Office Environments at Low THz Frequencies," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 71, no. 6, pp. 2748-2757, June 2023, doi: 10.1109/TMTT.2023.3236018. (Open Access Under a Creative Commons License)

Overview on the Workshop Program

WORKSHOP PROGRAM – August 20, 2025 / Room M1

10:00 – 11:30

Thomas Kürner, Technische Universität Braunschweig, Germany:
Introduction to DFG FOR 2863 Meteracom

Invited Keynote

Tadao Nagatsuma, The University of Tokyo, Japan:
Effects of Phase Noise and Nonlinearity on Signal Integrity in Photonics-Enabled THz Links

David Humphreys:
Development Considerations for a THz Waveform Traceability for H-band Communication

Younus Mandalawi, Technische Universität Braunschweig, Germany:
Results of Metrology of High-bandwidth Sampling Systems

Lunch

13:30 – 15:00

Invited Keynote

Iwao Hosako, National Institute of Information and Communications Technology (NICT), Japan:
New Use Cases and Strategies for Promoting Terahertz Wave Communications Based on IEEE 802.15.3-2023

Thomas Kleine-Ostmann, Physikalisch-Technische Bundesanstalt, Germany:
Measurement Techniques and Testbeds for Over-the-Air Sub-THz Channel Sounding Systems

Benjamin Schoch, University of Stuttgart, Germany:
Instrumentation for Traceable Distortion Characterization of Terahertz Transceivers

Daniel M. Mittleman, Brown University, USA:
Portable Reference Structure Enabling THz Channel Impulse Response Measurement System Comparisons

Coffee Break

15:30 – 17:00

Martin Koch, Philipps University of Marburg, Germany:
THz Characterisation of Building Materials

Tobias Doeker, Technische Universität Braunschweig, Germany:
Device Discovery and Beam Tracking

Christoph Herold, Technische Universität Braunschweig, Germany:
Link- and System Level Simulation for Metrology

Panel Discussion

Moderator: *Thomas Kürner*

Panelists: *Tadao Nagatsuma, Iwao Hosako, Daniel M. Mittleman, David Humphreys, Thomas Kleine-Ostmann, and Martin Koch*



PDFs of all presentations available @
https://meteracom.de/workshop_irmmw-thz_2025/



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20 August 2025 | Thomas Kürner | Introduction to DFG FOR 2863 Meteracom | 12/17

METERACOM

Measurement $\mu = \frac{1}{\sigma} \sqrt{\frac{1}{N} \sum_{n=1}^N (\hat{x}_n - \bar{x})^2}$

DATA: NUMBER OF CHANNELS MEETING THE REQUIREMENTS FOR EACH BAND IN THE TEST AREA (%)

• 2.5 MHz Band 1	• 2.5 MHz Band 2
• 2.5 MHz Band 3	• 2.5 MHz Band 4
• 2.5 MHz Band 5	• 2.5 MHz Band 6
• 2.5 MHz Band 7	• 2.5 MHz Band 8

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B1: How do objects in the beam affect terahertz communication channels?

*Felix Lippert*¹, *Benjamin Kollmann*², *Andreas Kollmann*², and *Christof Lippert*¹ 
¹Department of Physics, Philipps-Universität Marburg, 35032 Marburg, Germany,
 Institute for Photonics and Quantum Optics (IPQ), Philipps-Universität Marburg,
 35032 Marburg, Germany
²Centre for Investigations on Optics & Lasers (CIOL), EPJ Centre for Excellence, Marburg, Germany

1. Introduction

- Pulse transmission channels in THz and millimeter are attributed to different loss mechanisms, which are not fully understood
- Theoretical models for THz propagation in the atmosphere are available
- Theoretical models for reflection and refraction at dielectric and metallic boundaries
- Theoretical models for scattering at rough surfaces and rough objects
- Theoretical models for scattering at random media

2. Experimental Setup

- Commercial THz-TDS spectrometer was modified for femtosecond measurements
- The THz beam is generated by a femtosecond laser
- The THz beam is focused by a parabolic mirror
- The THz beam is detected by a THz-TDS spectrometer
- The THz beam is detected by a THz-TDS spectrometer

4. Items in the THz Beam



The THz beam is generated by a femtosecond laser and is focused by a parabolic mirror. The beam is then directed towards a sample. The sample is a medium containing objects. The THz beam interacts with the objects, causing scattering and absorption. The scattered and absorbed energy is detected by a THz-TDS spectrometer.

3. Theoretical Modeling

- The experiment can be modeled by using the Finite Difference Time Domain (FDTD) method
- The FDTD method is a numerical method for solving Maxwell's equations
- The FDTD method is based on the discretization of space and time
- The FDTD method is used to simulate the propagation of the THz beam in the presence of objects



5. Person in the THz Beam



The THz beam is generated by a femtosecond laser and is focused by a parabolic mirror. The beam is then directed towards a person. The person is standing in the THz beam. The THz beam interacts with the person, causing scattering and absorption. The scattered and absorbed energy is detected by a THz-TDS spectrometer.

6. Conclusions

- The THz beam is generated by a femtosecond laser
- The THz beam is focused by a parabolic mirror
- The THz beam is directed towards a sample
- The THz beam interacts with the sample, causing scattering and absorption
- The scattered and absorbed energy is detected by a THz-TDS spectrometer

7. References

- [1] F. Lippert, B. Kollmann, A. Kollmann, and C. Lippert, "Terahertz communication channels in the presence of objects," *Optics Express*, vol. 25, no. 1, pp. 1-10, 2017.
- [2] F. Lippert, B. Kollmann, A. Kollmann, and C. Lippert, "Terahertz communication channels in the presence of objects," *Optics Express*, vol. 25, no. 1, pp. 1-10, 2017.
- [3] F. Lippert, B. Kollmann, A. Kollmann, and C. Lippert, "Terahertz communication channels in the presence of objects," *Optics Express*, vol. 25, no. 1, pp. 1-10, 2017.

[illegible][illegible][illegible]

Introduction

Reinforcement learning (RL) has emerged as a powerful paradigm for solving complex decision-making problems. In the context of mmWave/THz networks, RL can be employed for optimizing channel access, beamforming, and resource allocation. However, the high-dimensional and non-stationary nature of these environments poses significant challenges for traditional RL algorithms. This paper proposes a novel adaptive RL framework to address these challenges, enabling efficient learning and optimal decision-making in dynamic mmWave/THz environments.

Adaptive RL Framework

The proposed framework consists of several key components: a multi-agent RL system, a dynamic environment, and a centralized coordination module. The RL agents interact with the environment to learn optimal policies for channel access and beamforming. The dynamic environment simulates the mmWave/THz network, including channel characteristics, user mobility, and resource constraints. The centralized module coordinates the agents, ensuring efficient resource utilization and minimizing interference.

Results and Key Findings

Extensive simulations were conducted to evaluate the performance of the proposed framework. The results demonstrate that the adaptive RL framework achieves superior performance compared to traditional RL algorithms and heuristic-based methods. Key findings include:

- Improved channel access efficiency, leading to higher throughput and lower latency.
- Optimized beamforming strategies, resulting in enhanced signal quality and coverage.
- Robust performance in dynamic environments, maintaining optimal decision-making under changing conditions.

Conclusion

This paper presents a novel adaptive RL framework for mmWave/THz networks. The framework effectively addresses the challenges of high-dimensional and non-stationary environments, enabling efficient learning and optimal decision-making. The results show that the proposed framework outperforms existing methods, achieving improved channel access efficiency, optimized beamforming, and robust performance in dynamic environments. Future work will focus on extending the framework to larger-scale networks and exploring advanced RL algorithms for further performance enhancement.

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Overview on regular Contributions by Meteracom @IRmmW-THz 2025

Wednesday, 20 August, Communication systems I, Hall D	
14.30-14.45	<i>Younus Mandalawi, Souvaraj De, Mohamed I. Hosni, Linjie Zhou, Thomas Schneider</i> Integrated Wideband Wireless Signal Receiver Based On Cascaded Ring Modulators

Thursday, 21 August, Session Metrology and Parameter Estimation, Hall D	
13.45-14.00	<i>Benjamin Schoch, Ingmar Kallfass</i> An In-Situ Time and Frequency Domain Instrumentation for Traceable Distortion Characterization of Terahertz Transceivers
14.00-14.15	<i>Benjamin Schoch, Simon Haussmann, Marc Guenter, Thomas Ufschlag, Philipp Neininger, Dirk Schwantuschke, Ingmar Kallfass</i> Intermodulation Distortion Analysis In Cascaded D-Band GaN Amplifiers

Thursday, 21 August, Communications signal processing and channel modelling, Hall E	
16.45-17.00	<i>Tobias Doeker, Carla E. Reinhardt, Yaseman Shiri, Daniel M. Mittleman, Thomas Kürner</i> Channel Impulse Response Measurements With Time-Domain Spectroscopy In The Low Terahertz Range

Thursday, 21 August, Poster, Hall	
17.00-18.30	<i>David Humphreys, Heiko Fueser, Adam Kuchnia</i> THz waveform traceability for h-band communication
	<i>Martin Koch, Felix Gorka, Daniel Mittleman, Enrique Castro-Camus</i> How Do Objects In The Beam Affect Terahertz Communication Channels?



Introduction to the Meteracom Booth @ IRmmW-THz 2025



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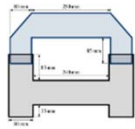

FOR 2863 Meteracom
Metrology for
THz Communications

Exhibits on Display

Exemplary Results from Project Areas A, B and C

A: Portable Reference Structure for Channel Sounding

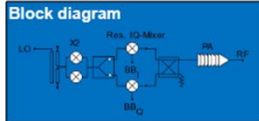
- Portable/small structure enabling comparable measurement results
- Two distinct multipath components
- One component variable due to movable part of structure
- Compatible with channel sounder, vector network analyzer and time-domain spectroscopy systems

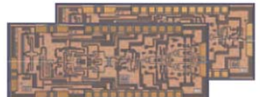



B: MMIC Design - Traceable THz Transceivers Impairments

- Fully integrated electronic Tx / Rx frontend chips

Block diagram

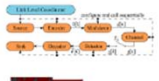
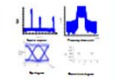




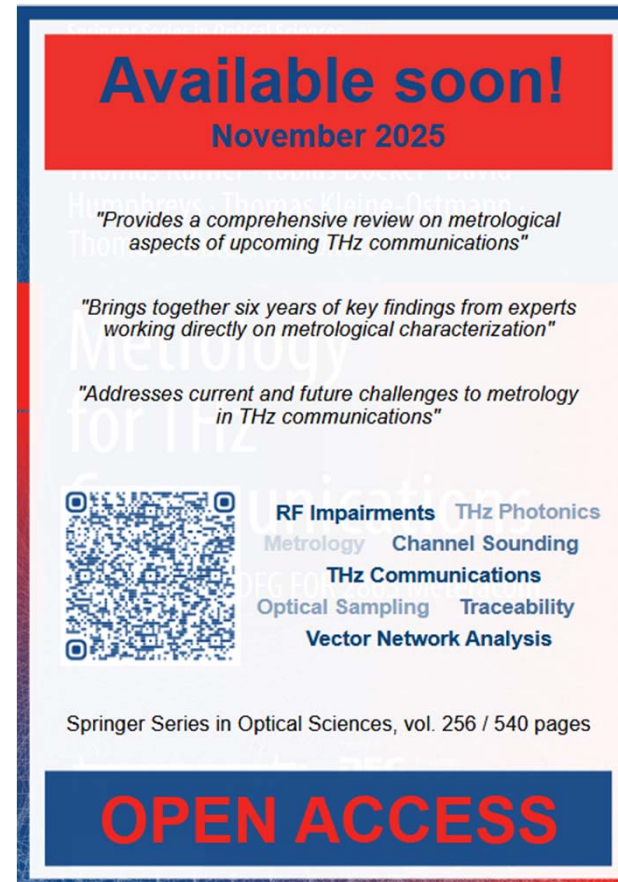
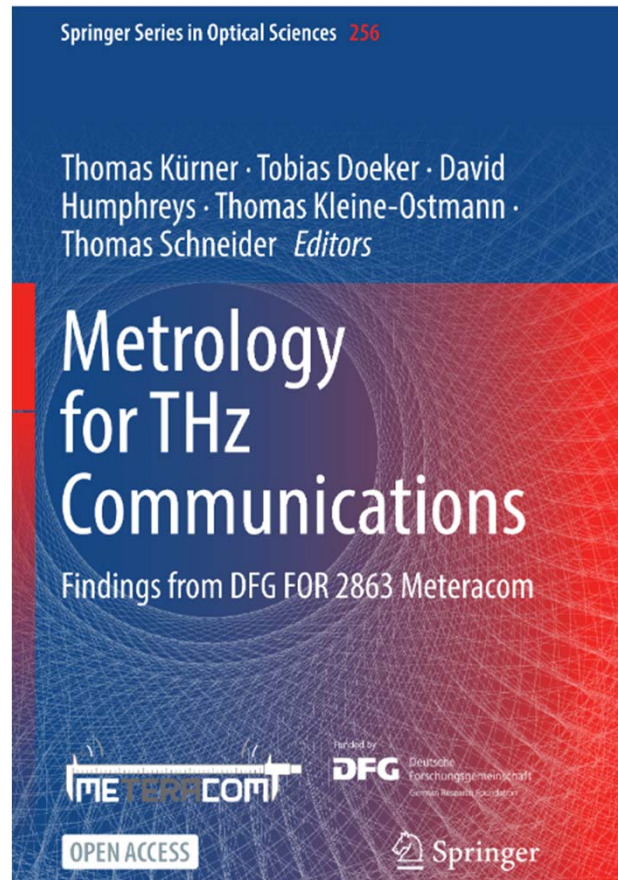
- RF frequency range: 250 ... 325 GHz
- Saturated output power: $P_{sat} \sim 8$ dBm
- Size: 2500 $\mu\text{m} \times 1000 \mu\text{m}$
- LO frequency range: 70 ... 80 GHz
- IF (IQ) frequency range: 0 ... 40 GHz

C: SiMoNe - Simulator for Mobile Networks

- The Simulator for Mobile Networks (SiMoNe) has been extended by a link level simulation module within the Meteracom project. Now, it provides an integrated framework for ray-tracing based propagation predictions, link- and system level simulations for THz communications in accordance with IEEE 802.15.3-2023.
- During the project, it has been used to evaluate possibilities and challenges in various THz communication scenarios. It provided, for example, a closer look at the impact of hardware impairments on communication channels, generated training data for machine learning task and aided in evaluating new coding concepts for THz communications. It will continue to provide valuable insights in application cases such as wireless THz backhaul links, RIS- and relay-assisted communications and V2X communications.

Introduction of the Meteracom OpenAccess Book Publication



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Thank you very much for your Attention



UNIVERSITÄT ZU LÜBECK

HEINZ NIXDORF INSTITUT
UNIVERSITÄT PADERBORN

E-Mail: t.kuerner@tu-braunschweig.de

Funded by
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