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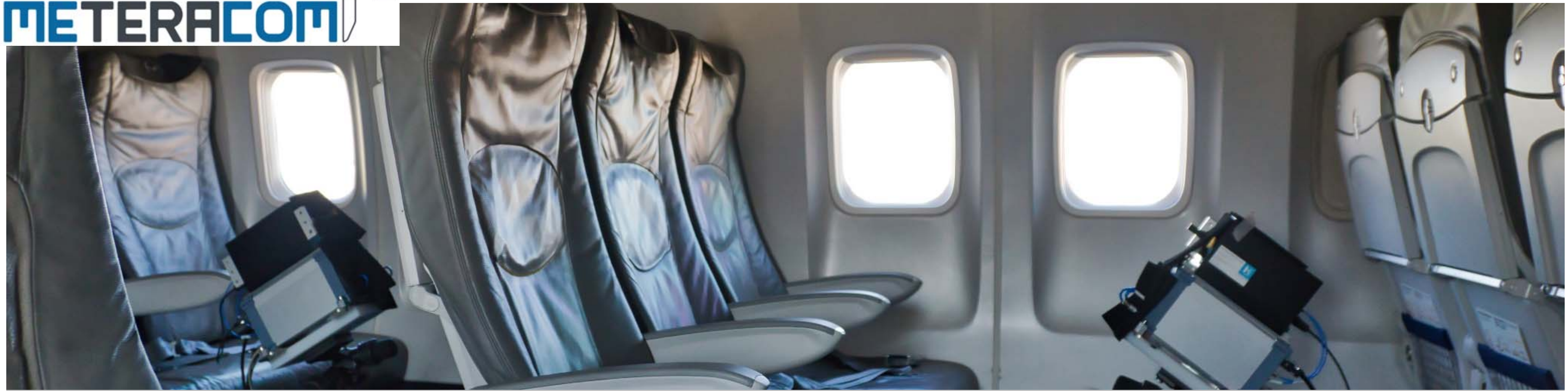
FOR 2863 Meteracom
Metrology for THz Communications

2024 DUISBURG GeMiC German Microwave Conference



Channel Sounder Architectures for Performance Evaluation of THz Systems

Jonas Gedschold, Diego Dupleich, Carla Reinhardt, Tobias Doeker, Giovanni Del Galdo, Reiner S. Thomä, Thomas Kürner

2nd International Workshop on Metrology for THz Communications, Duisburg, 12 March 2024

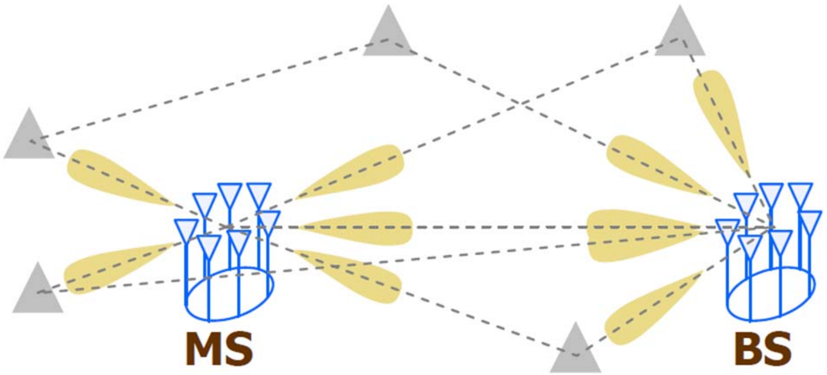
What is this talk about?

SNR and dynamic range of a THz channel sounder

- Baseband Waveform Design
- Automatic Gain Control and its Impact on Directional Channel Sounding
- Real-Time/Time-Variant Sounding

Goal of Channel Sounding

- Characterize the structure of a multipath propagation channel (device independent)



RICHTER, Andreas, 2005. *Estimation of Radio Channel Parameters* [online]. https://nbn-resolving.org/urn:nbn:de:gbv:ilm1-2005000111

- Allows to test performance of THz systems against channel
- System identification problem: excitation at system input and acquisition/processing of system output crucial

- Smaller wavelengths and corresponding antenna designs lead to shrinking effective antenna apertures
- Friis' transmission equation

$$\frac{P_r}{P_t} = \frac{A_r A_t}{d^2 \lambda^2} \quad \text{and} \quad A_{isotr.} = \frac{\lambda^2}{4\pi}$$

P_r, P_t :	received and transmitted power
A_t, A_r :	effective antenna area
λ :	wavelength
d:	distance between antennas

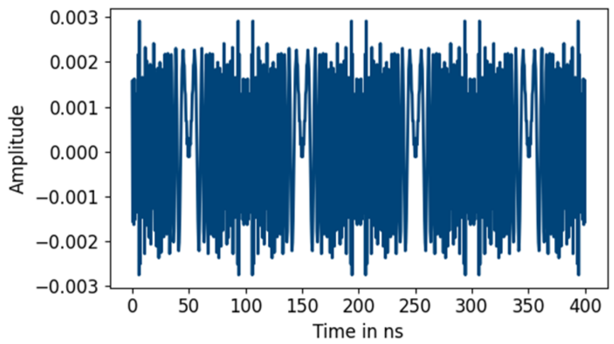
- Building larger antennas/arrays increases gain → antenna orientation is critical
- **Challenge: SNR, dynamic range**

SNR and dynamic range of a THz channel sounder

- **Baseband Waveform Design**
- Automatic Gain Control and its Impact on Directional Channel Sounding
- Real-Time/Time-Variant Sounding

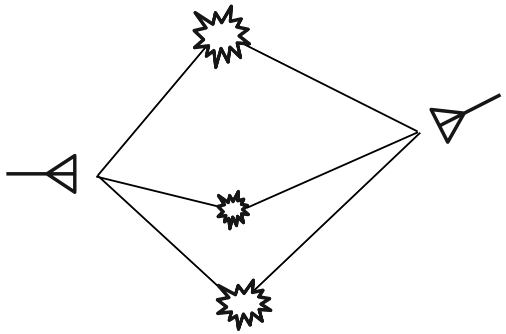
Waveform design for channel sounding

Input

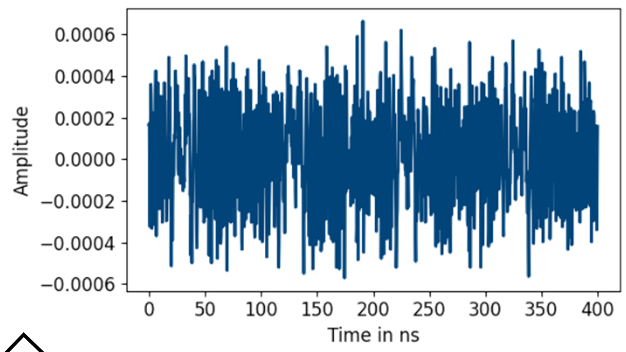


Periodic waveform

Multipath Propagation Channel

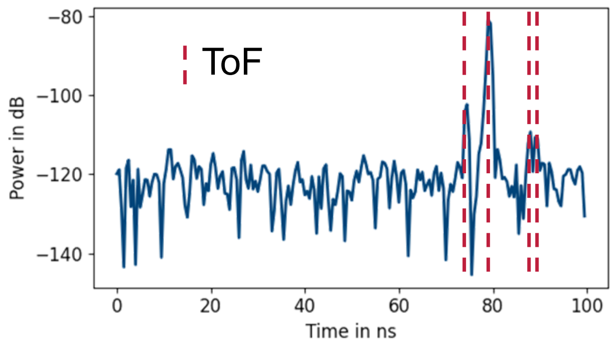


Output



Received signal

Channel impulse response

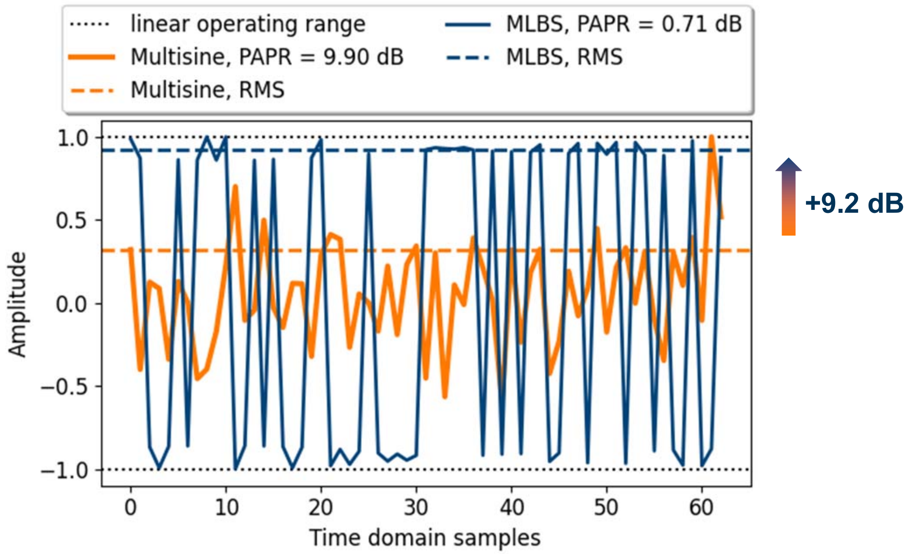


Matched filter output

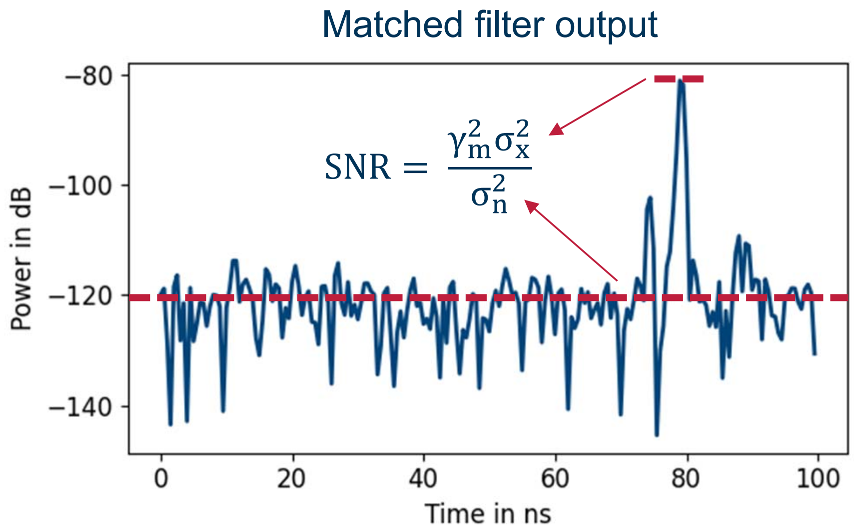
What is a good waveform to estimate parameters of a multipath channel under power constraints?

Waveform design criteria: Peak-to-Average Power Ratio (PAPR)

- Important for nonlinear systems such as amplifiers
- Exploit linear dynamic range of analog components
- A smaller PAPR allows to transmit higher **power**



- ➢ The matched filter SNR only depends on the signal power **irrespective of the actual waveform**
- ➢ Degrees of freedom to optimize waveform for parameter estimation



γ_m^2: path weight, σ_x^2: signal power

σ_n^2: noise power

Power spectrum optimization for parameter estimation

- Use degrees of freedom to maximize how informative the measurements are wrt the model parameters

- Optimize estimator statistics for ToF parameters τ:
  - Bias $= \mathbf{E}[\tilde{\tau}] - \tau = 0$ (assumption)
  - Variance $= \mathbf{E}[(\tilde{\tau} - \tau)^2]$ (for unbiased estimators)

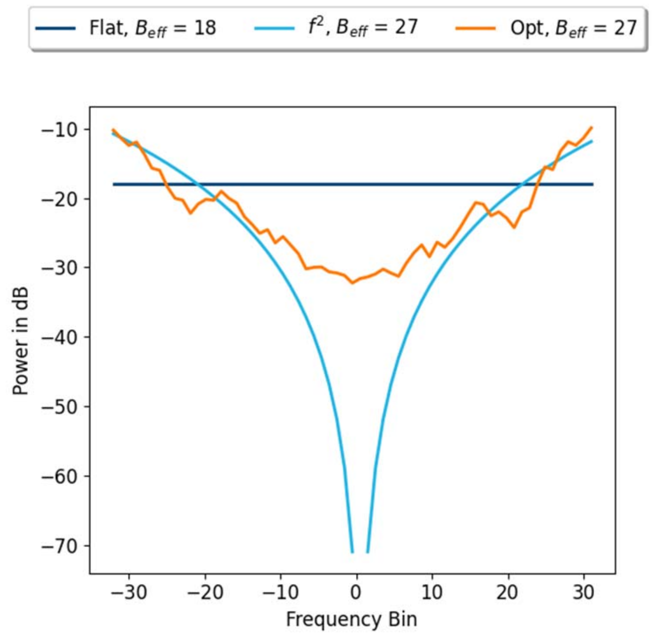
- Inverse Fisher Information (Cramér-Rao bound) defines the lower limit for the variance

$$\mathbf{F}_{\tau_m} \propto \mathrm{SNR} * B_{\mathrm{eff}}^2$$

- Bandwidth can compensate SNR to some degree

➢ **Goal: Waveform with high Fisher information**

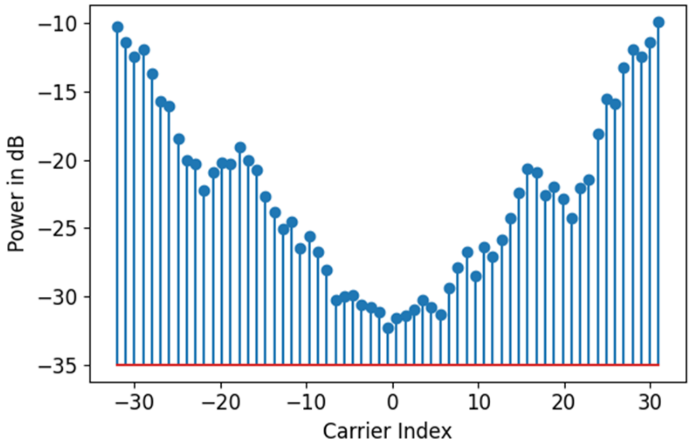
Power spectra



- Orange: iterative optimization of the Fisher information matrix (given initial knowledge about the scenario)

Waveform design with arbitrary power spectra

- Frequency-modulated waveforms are well-known from communications: OFDM-like **multicarrier signal**
- Strictly bandlimited and periodic
- Instead of modulating data onto each carrier, we design power and phase to optimize sounding performance
- Baseband architecture: SDR/AWG



Power spectrum

- Evaluate dispersion function: how much should each carrier be amplified/attenuated

$$\nu[k] = \mathrm{trace}\left(\mathbf{F}^{-1}(\mathbf{X}) \cdot \mathbf{F}(\widetilde{\mathbf{X}}_{\mathrm{k}})\right)$$

k: carrier index, $\mathbf{F}$: Fisher information matrix, $\mathbf{X}$: carrier weights, $\widetilde{\mathbf{X}}_{\mathrm{k}}$: single carrier input

E. Van den Eijnde and J. Schoukens, “On the design of optimal excitation signals,” IFAC Proceedings Volumes, vol. 24, no. 3, pp. 1139–1144, 1991, 9th IFAC/IFORS Symposium on Identification and System Parameter Estimation 1991, Budapest, Hungary, 8-12 July 1991

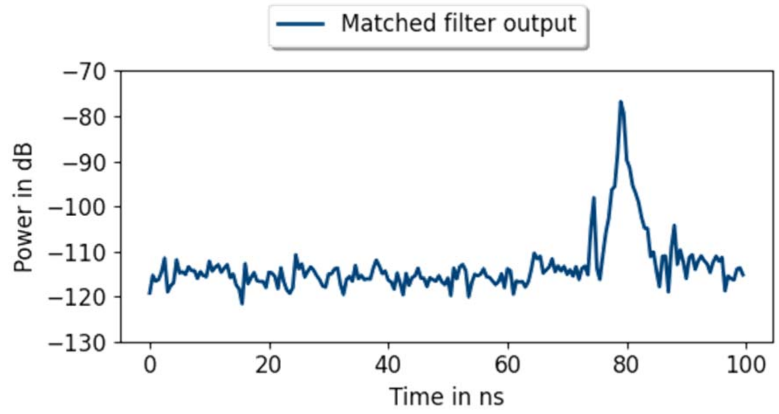
Phase spectrum

- Fisher information only depends on the power spectrum
- Phase spectrum for minimum PAPR: Newman or Schroeder phase design, time-domain clipping, …

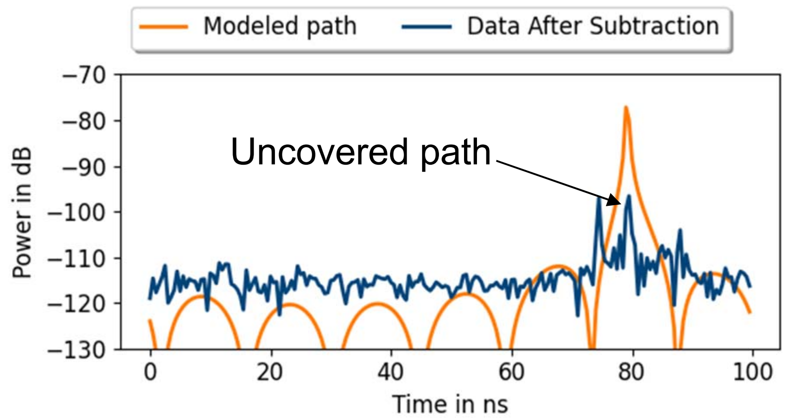
M. Schroeder, “Synthesis of low-peak-factor signals and binary sequences with low autocorrelation (corresp.),” IEEE Trans. Inf. Theory, vol. 16, no. 1, p. 85–89, Jan. 1970

Parameter estimation with optimized waveforms

- Matched filter output depends on waveform ACF
- ACF results from the power spectrum of the waveform
- The ACF may have strong sidelobes which can cover weaker propagation paths
- Signal-interference ratio is degraded



- ➢ Data **model** needs to account for the waveform
- ➢ After the estimation of one propagation path, its influence (full ACF) can be **subtracted** from the data revealing weaker propagation paths
- ➢ Iterative path search (e.g. part of the RIMAX algorithm)



SNR and dynamic range of a THz channel sounder

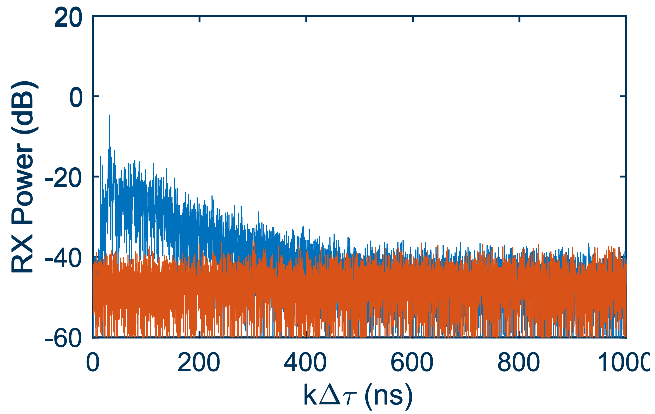
- Baseband Waveform Design
  - Several degrees of freedom for waveform optimization
  - Power spectrum can improve theoretical performance limits for ToF estimation
  - **High effective** bandwidth is beneficial
  - Baseband architecture: SDR/AWG

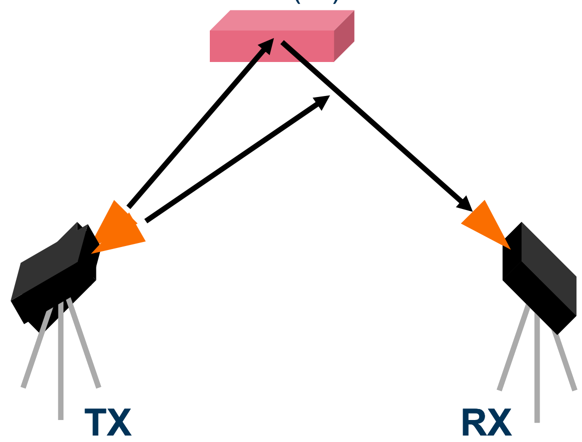
- **Automatic Gain Control and its Impact on Directional Channel Sounding**

- Real-Time/Time-Variant Sounding

Dynamic range in directional channel sounding

- **Goal**: Achieve omnidirectional view on the channel by rotating high-gain antennas
- Channel is **sparse** in the spatial domain
- Large difference on received power from angular-to-angular scan (LOS, strong/weak scatterer, no scatterer)
- Strong requirement on **dynamic range** at the receiver
- AGC is fundamental to avoid non-linearities





Dynamic range in directional channel sounding

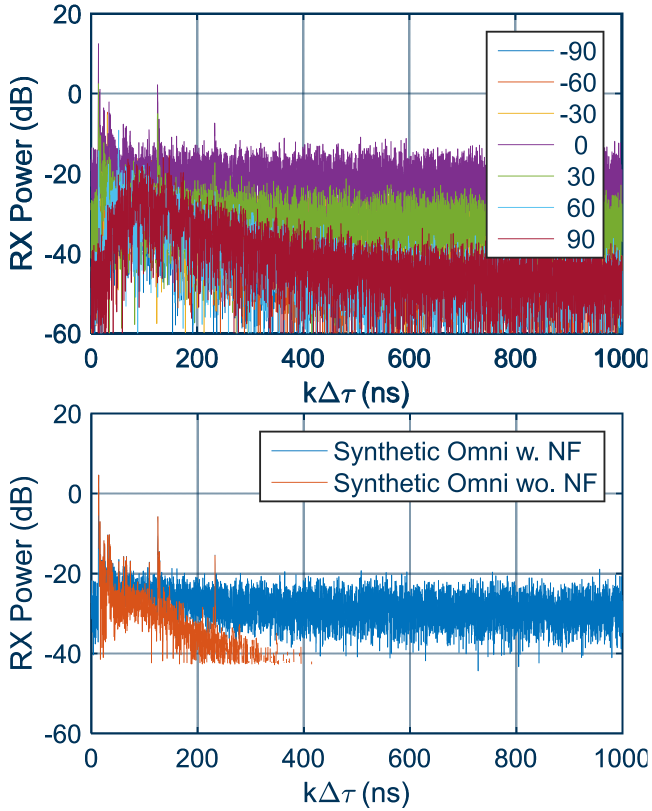
- A compensation of the AGC at the RX is necessary
- This leads to different **noise floor amplifications**
- When synthesizing an omnidirectional pattern from the individual scans, the dynamic range is reduced
- Weak paths could be masked

➢ **Denoising** is required before the synthesis

➢ Signal detection, model-based estimation, …

- Does not increase dynamic range for a single scan

RX



SNR and dynamic range of a THz channel sounder

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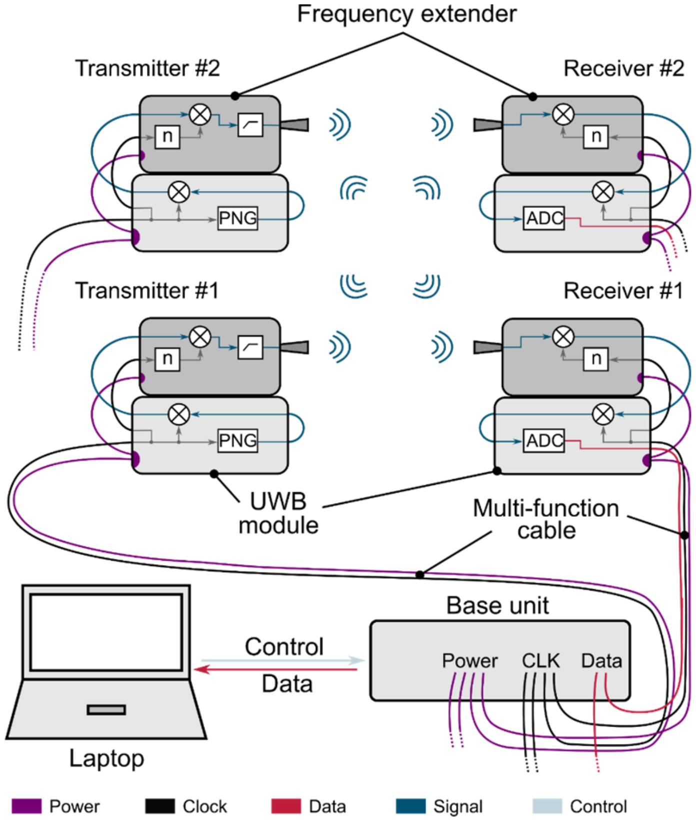
  - Baseband architecture: SDR/AWG
- Automatic Gain Control and its Impact on Directional Channel Sounding
  - AGC compensations leads to varying noise floor amplifications
  - Denoising is necessary for comparison/combination
- **Real-Time/Time-Variant Sounding**

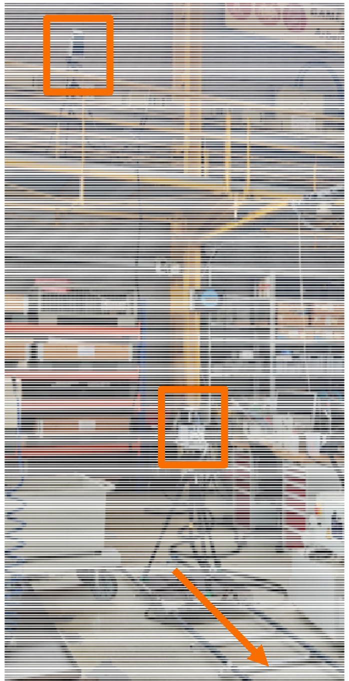
TUBS channel sounder

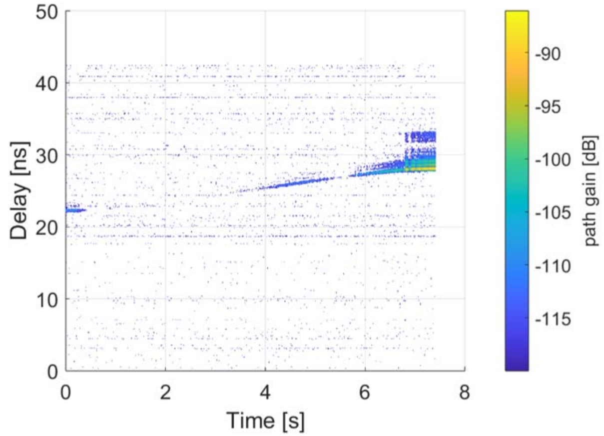


Parameter	Value
Clock	9.22 GHz
Bandwidth	≈ 8 GHz
Chip duration	108.5 ps
Order of M-sequence	12
Sequence length	4095
Sequence duration	444.14 ns
Subsampling factor	128
Measurement time per CIR	56.9 µs
Measurement rate	17,590 CIR/s
Center frequencies	9.2 / 64.3 / 304.2 GHz
SISO/MIMO	Up to 4x4

Real-Time measurements

- Sounder setup allows to measure **dynamic scenarios,** e.g., due to moving TX, RX or objects
- No coherent averaging during the measurement run for maximum time resolution (dynamics unknown)
- SNR is too low for evaluation
- Determination of the **coherence time** of the channel allows averaging in post processing over intervals where the channel behaves WSS
- **Tradeoff** between SNR and velocity in the channel
- Join the poster session for more details: Channel Measurements in an Industrial Environment for Access Point-to-Sensor Communication at 300 GHz





Time-variant power delay profile after averaging 125 CIRs

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- Real-Time/Time-Variant Sounding
  - Averaging only if channel behaves WSS
  - tradeoff between SNR and measurement rate

Thank you very much for your Attention

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References

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2. D. Dupleich, R. Müller and R. Thomä, "Practical Aspects on the Noise Floor Estimation and Cut-off Margin in Channel Sounding Applications," *2021 15th European Conference on Antennas and Propagation (EuCAP)*, Dusseldorf, Germany, 2021, pp. 1-5, doi: 10.23919/EuCAP51087.2021.9411409.
3. Carla E. Reinhardt, Varvara V. Elesina, Johannes M. Eckhardt, Tobias Doeker, Lucas C. Ribeiro, Thomas Kürner „Channel Measurements in an Industrial Environment for Access Point-to-Sensor Communication at 300 GHz" – GeMIC 2024