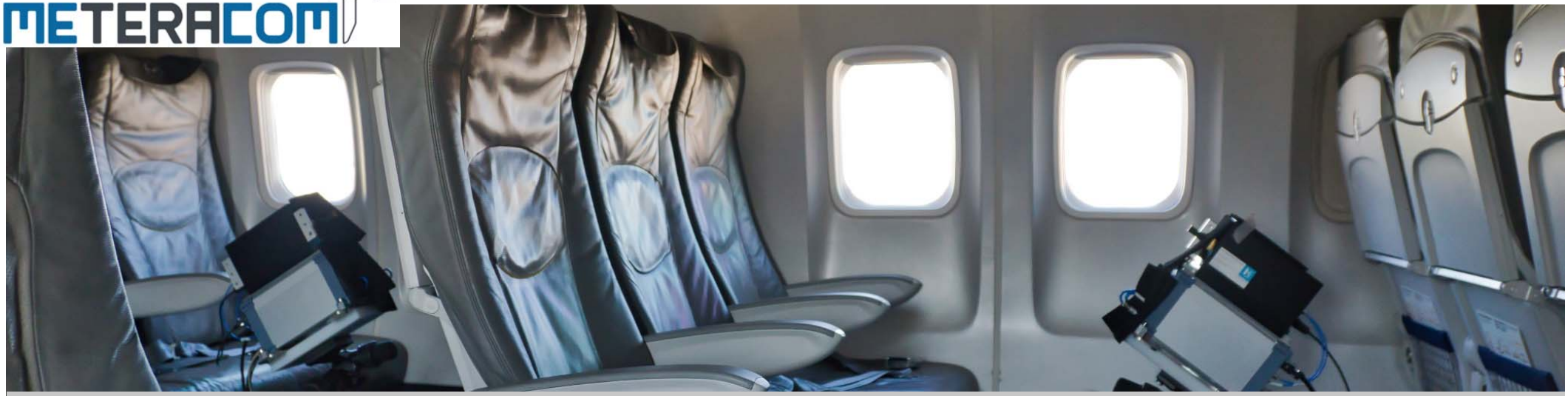
Funded by DFG Deutsche Forschungsgemeinschaft German Research Foundation

FOR 2863 Meteracom
Metrology for THz Communications

The 50th International Conference on Infrared, Millimeter, and Terahertz Waves
17-22 August, 2025

METERACOM



Link and System Level Simulations for Metrology

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Technische Universität Braunschweig

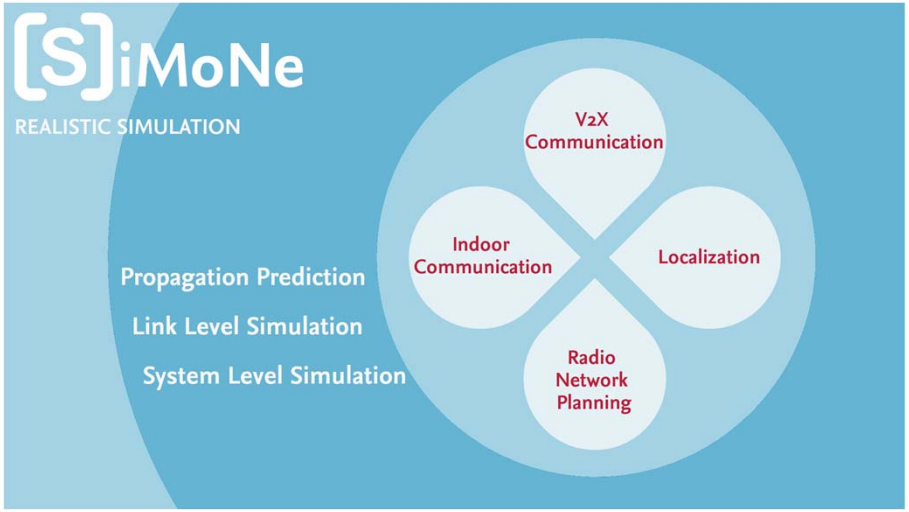
DFG FOR2863 Meteracom Final Workshop @ IRmmW-THz 2025, 20 August 2025

Why do we need simulations at all?

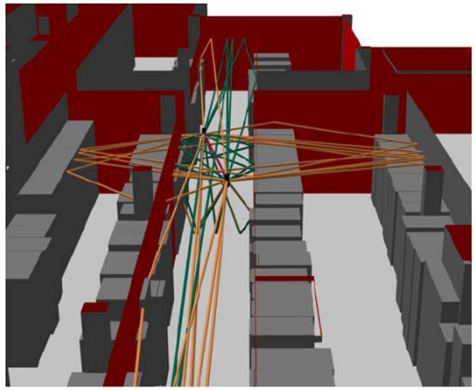
For the development of new technologies, simulations provide a manifold of benefits and opportunities:

- Test new hypothesis
- Explore new designs
- Assess modifications
- Save time by avoiding extensive measurement campaigns
- Recreation of rare conditions (e.g. extreme weather)
- Protect prototypes and assets
- Evaluate scaled systems even with sparse hardware

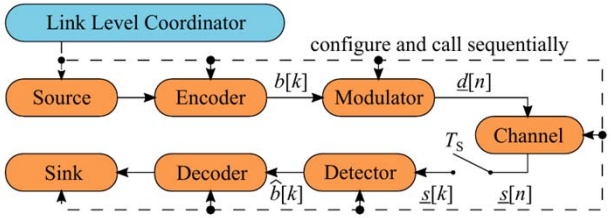
However, a good understanding of the underlying principles is needed for successful and valid simulations.

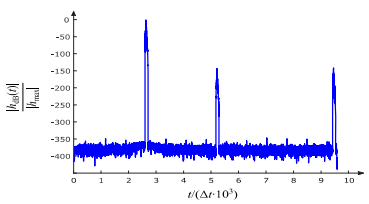


SiMoNe – A few impressions

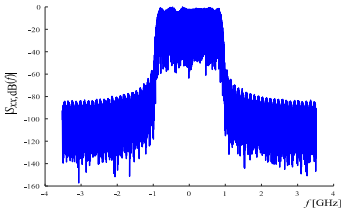


Ray-Tracer

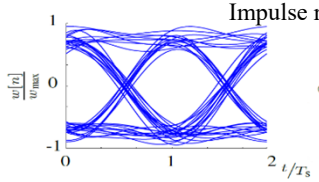




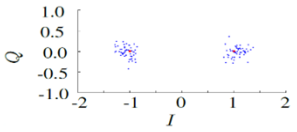
Impulse response



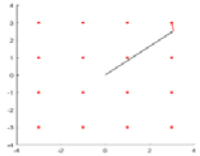
Frequency domain plot



Eye diagram

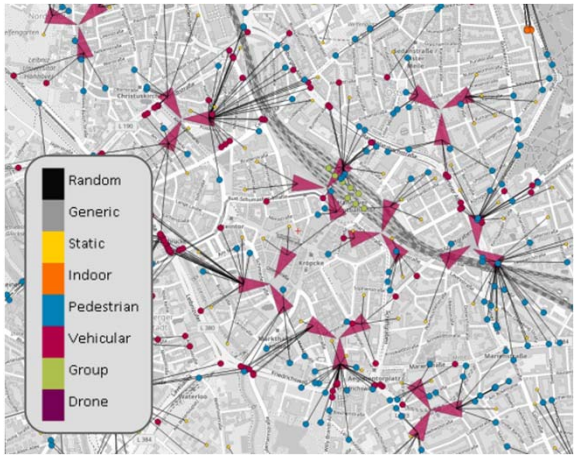


Constellation diagram



Error vector magnitude plot

Link-Level Simulations



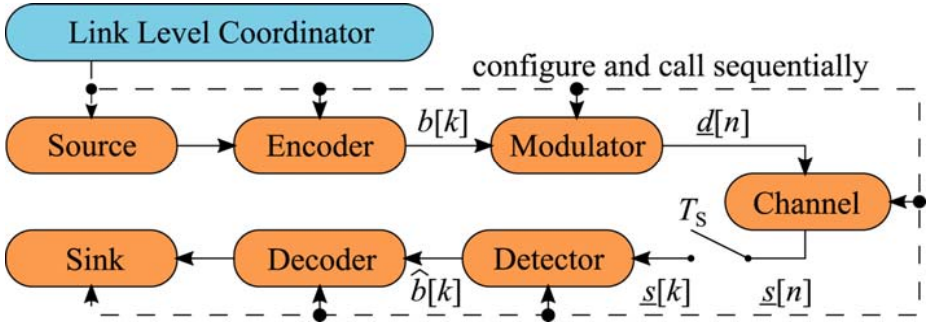
System-Level Simulations

Link Level Simulator - Concept

For Simulation tools to perform effectively, some key concepts are helpful if not required:

- Modular composition and encapsulation of functions
- Iterative computations
- Integration of ray-tracing results
- Visualization of simulation results
- Interfacing with other scientific tools

Schematic of the simulation process



Transmission chain of the Link Level Simulator

Eckhardt, J. M., Herold, C., Jung, B. K., Dreyer, N., & Kürner, T. (2022). Modular link level simulator for the physical layer of beyond 5G wireless communication systems. *Radio Science*, 57, e2021RS007395. https://doi.org/10.1029/2021RS007395

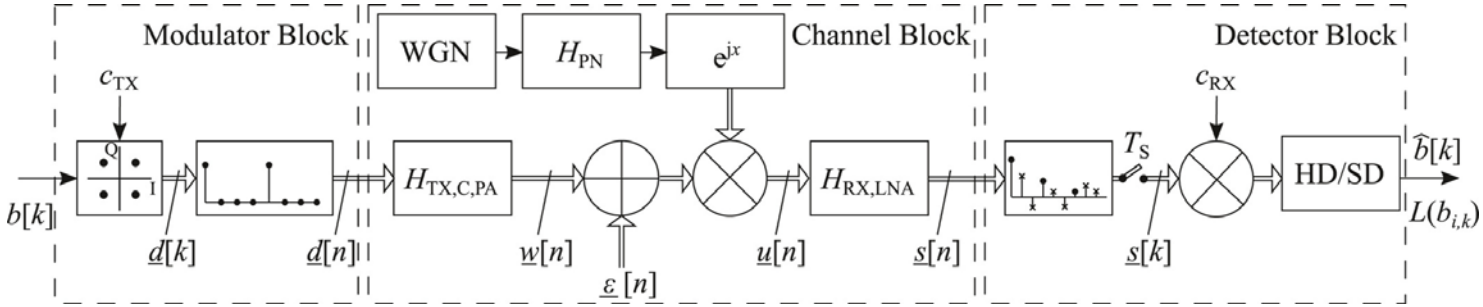
Link Level Simulator – Channel Representation

Amplitude and delay information from ray-tracing are used to create impulse response of the propagation channel:

$$h_c(t) = \sum_t A_i \delta(t - \tau_i)$$

After sampling, the convolution of the propagation channel with the transmit pulse gives the modulation channels impulse response:

$$h_{TX,c}(n) = \sum_i A_i A T_s h_{TX}(n\Delta t - \tau_i)$$

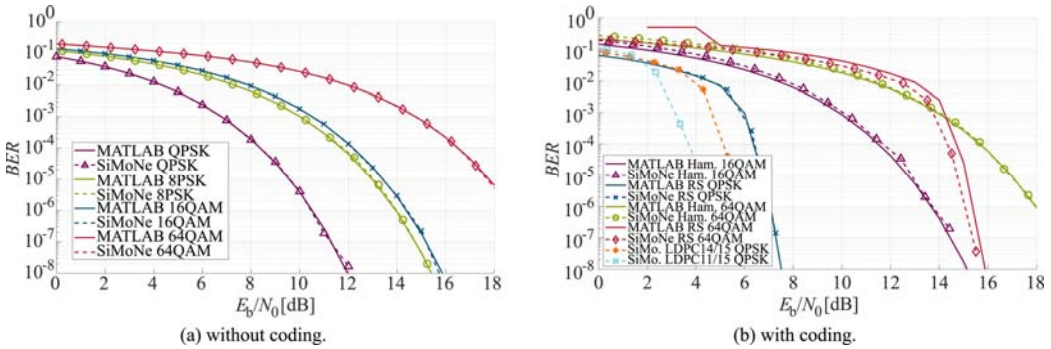


Eckhardt, J. M., Herold, C., Jung, B. K., Dreyer, N., & Kürner, T. (2022). Modular link level simulator for the physical layer of beyond 5G wireless communication systems. *Radio Science*, 57, e2021RS007395. https://doi.org/10.1029/2021RS007395

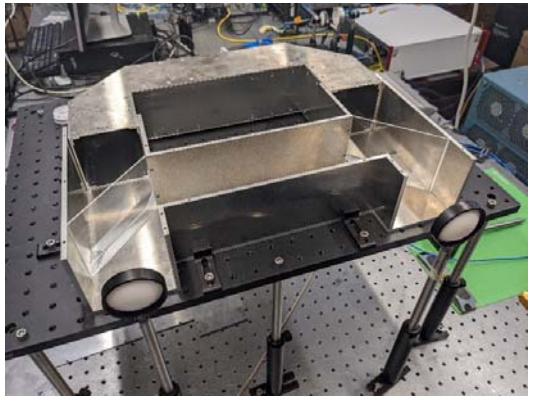
Link Level Simulator - Verification

Verification and Validation are important steps to ensure accuracy and correctness.

- **Unit testing** for single components (such as coding, modulation, filter)
- Simulation of known functions and channels to trace back to **theoretical results** (e.g. AWGN-channels)
- **Modular design** and regression testing allow for continous developement
- Measurements with a **reference structure** in order to compare BER and interference phaneomena.



(a) without coding. (b) with coding.



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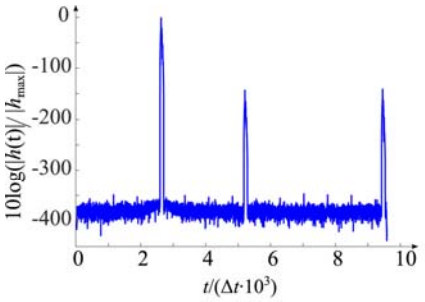
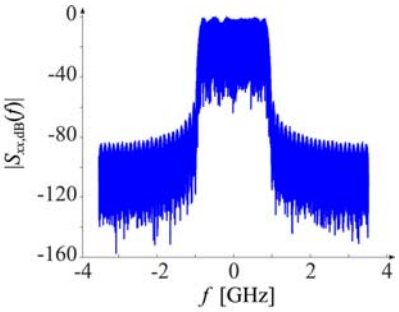
Link Level Simulation - Visualization

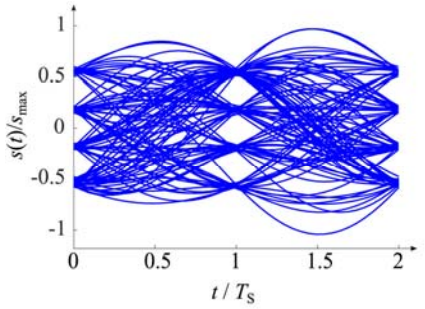
- Visual representation can help to **identify impairments, effects and performance** of various components
- Providing a digital representation of the whole transmission and communication process, simulations and digital twins can access to **data and information that might not be available in a real world system** or prototype.
- Visualizations such as constellation diagrams are often easier to grasp for **non-technical audience** than performance metrics



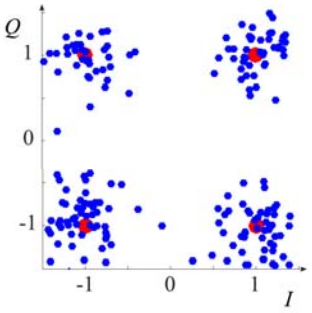
(a) Channel impulse response.



(b) Power spectral density.



(c) Eye diagram.



(d) Constellation diagram.

Eckhardt, J. M., Herold, C., Jung, B. K., Dreyer, N., & Kürner, T. (2022). Modular link level simulator for the physical layer of beyond 5G wireless communication systems. *Radio Science*, 57, e2021RS007395. https://doi.org/10.1029/2021RS007395

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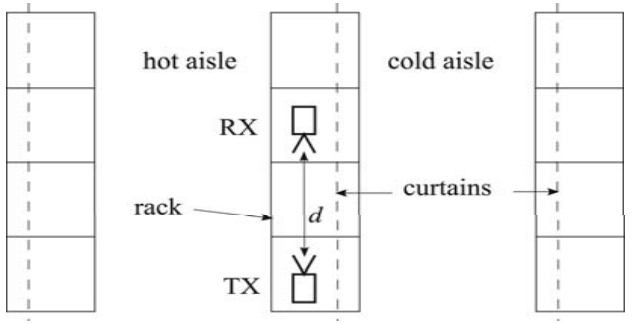
Selected Applications of Link and System Level Simulations

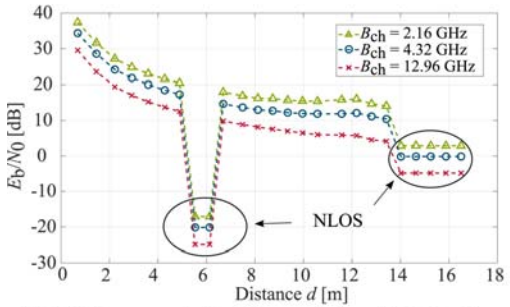
Performance Evaluation in a Data Center Environment

- Communication in a **data center** is one of the key use cases that has been identified for THz communications due to its requirements and characteristics:
  - High data rate transmissions
  - Low latency
  - Clear structured layout with minimal moving obstacles

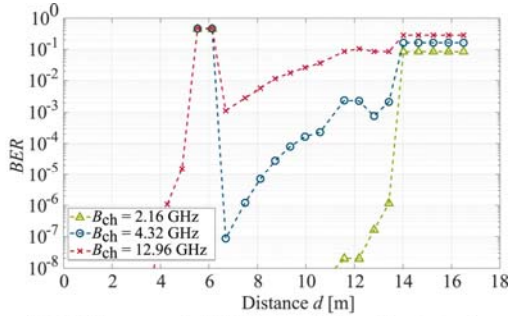
- Ray-Tracing simulation of a **top-of-rack scenario** based on a measurement campaign conducted with the channel sounder

- Simulation campaign to investigate the influence of different **modulation schemes**, **coding schemes** and different **channel bandwidths** and realistic **RF impairments**.





(a) E_b/N_0 for an uncoded BPSK transmission with RRC pulse.



(b) BER for an uncoded QPSK transmission with RRC pulse.

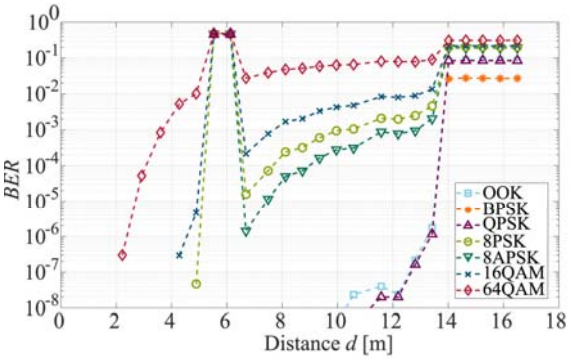
Eckhardt, J. M., Herold, C., Jung, B. K., Dreyer, N., & Kürner, T. (2022). Modular link level simulator for the physical layer of beyond 5G wireless communication systems. *Radio Science*, 57, e2021RS007395. https://doi.org/10.1029/2021RS007395

Performance Evaluation in a Data Center Environment (II)

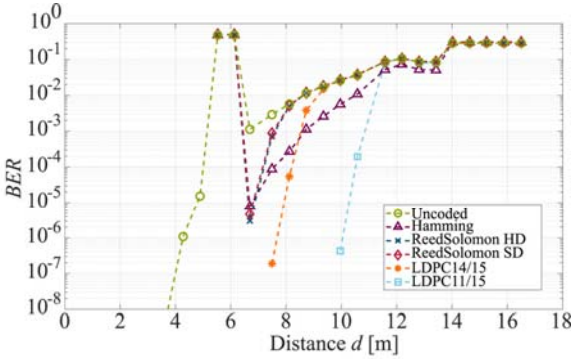
Simulations concluded that:

- Communication in the data center environment is possible
- Line-of-sight conditions are a requirement for successful high data rate communication links
- Channel coding is indespensible in order to reach significant distances
- RF impairments can have a significant impact on the transmission quality of the system.

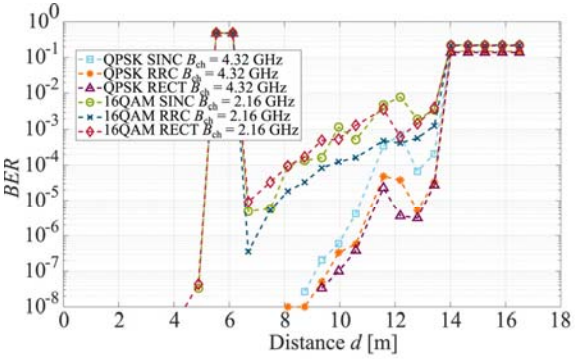
Simulation data has been published and is available for the community.



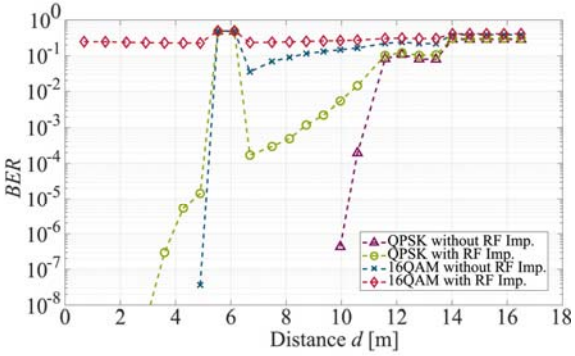
(a) BER of an uncoded transmission with RRC pulse and $B_{ch} = 2.16$ GHz.



(b) BER of a QQPSK transmission with RRC pulse and $B_{ch} = 12.96$ GHz.



(a) BER of different waveforms with Hamming codec.

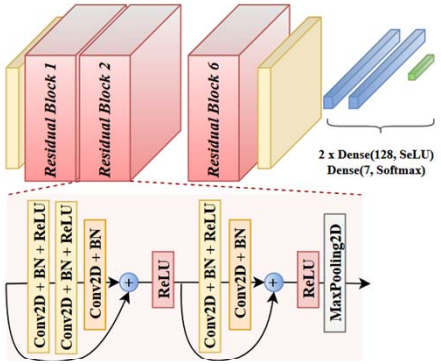


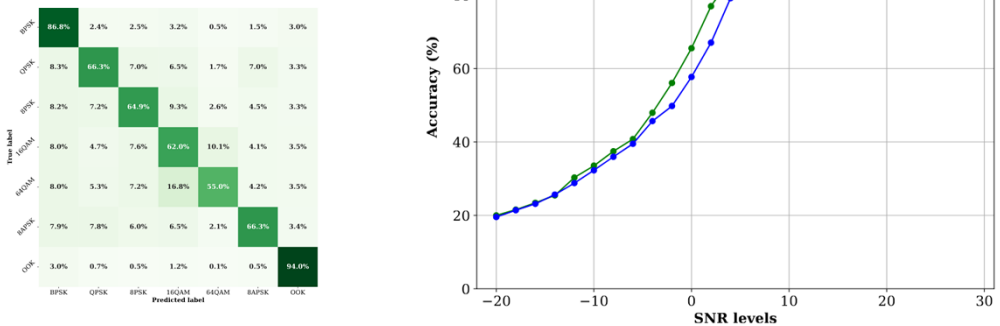
(b) Influence of RF impairments on an LDPC11/15 transmission with RRC pulse and $B_{ch} = 12.96$ GHz.

Eckhardt, J. M., Herold, C., Jung, B. K., Dreyer, N., & Kürner, T. (2022). Modular link level simulator for the physical layer of beyond 5G wireless communication systems. *Radio Science*, 57, e2021RS007395. https://doi.org/10.1029/2021RS007395

Generation of ML-Training Data

- Machine learning and artifical intelligence require a large amount of data to train reliable and efficient neural networks.
- Measurment campaigns for training data are likely costly, therefore simulations can relief the situation and provide values even for rare situations, corner cases and phenomena that are difficult to capture
- For a study of an Automatic Modulation Recognition (AMR) use case, SiMoNe's ray-tracer and link level simulator produced a data set for training purposes.
- At University of Lübeck, a neural network has been developed to solve this task and investigate the trustworthiness of DNNs for this application

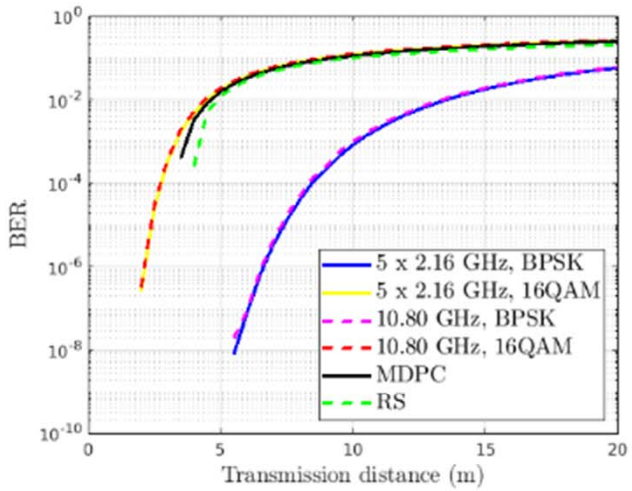


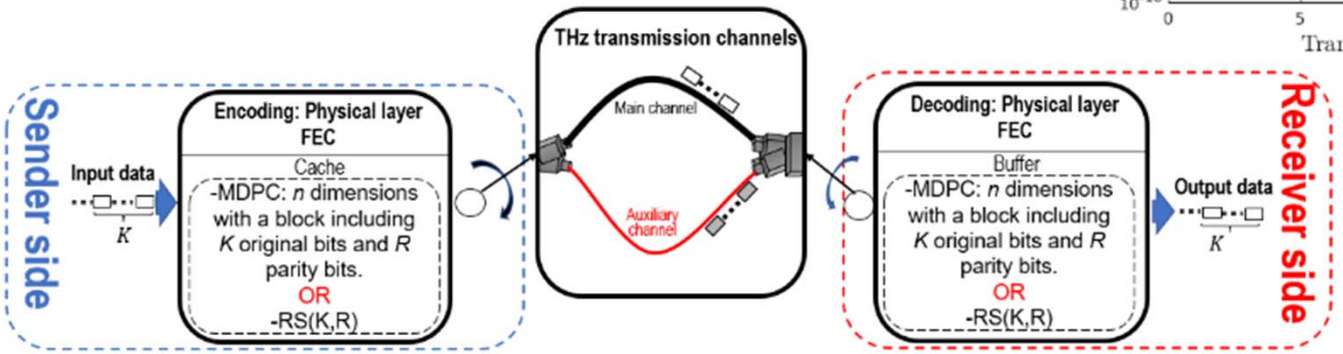


A. Nechi et al., "Practical Trustworthiness Model for DNN in Dedicated 6G Application," 2023 19th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Montreal, QC, Canada, 2023, pp. 312-317

Evaluation of New Coding Concepts

- In order to reach high data rates and low latency, THz communications require efficient and fast coding schemes.
- At the Institute for Computer and Network Engineering of TU Braunschweig, network coding concepts have been developed for THz communications
- SiMoNe's link level simulator provided simulations of the separate channel to investigate and evaluate the performance of this new coding concept.



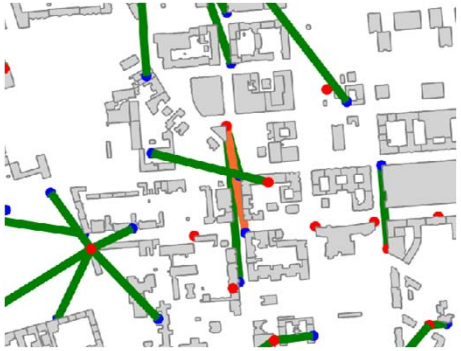


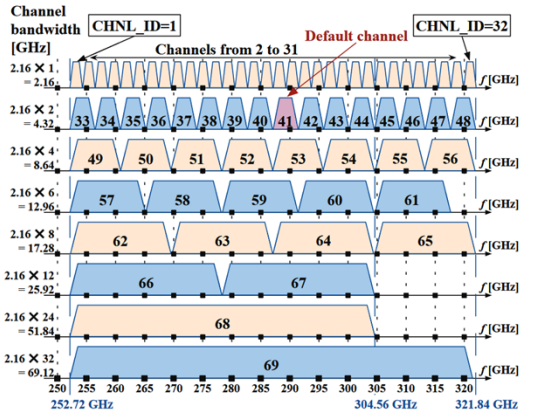
C. V. Phung, C. Herold, D. Humphreys, T. Kürner and A. Jukan, "Performance Analysis of MDPC and RS codes in Two-channel THz Communication Systems," *2022 45th Jubilee International Convention on Information, Communication and Electronic Technology (MIPRO)*, Opatija, Croatia, 2022, pp. 482-487

Evaluation of Interference Situations

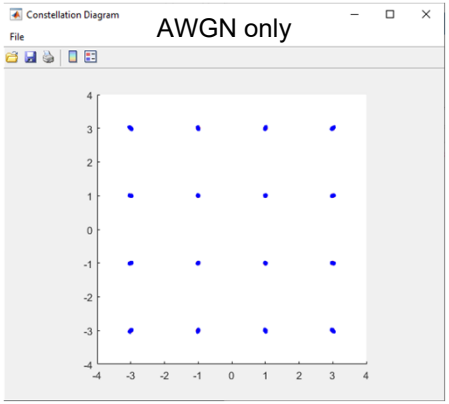
Link level simulations carried in order to investigate various types of interference situations such as:

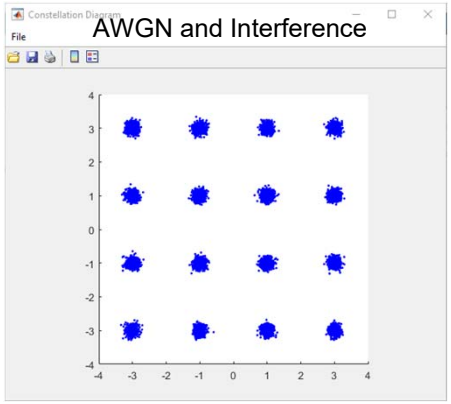
- Inter-carrier interference
- Inter-symbol interference
- Inter-site interference

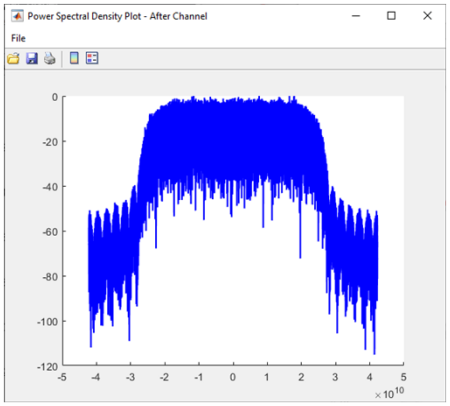


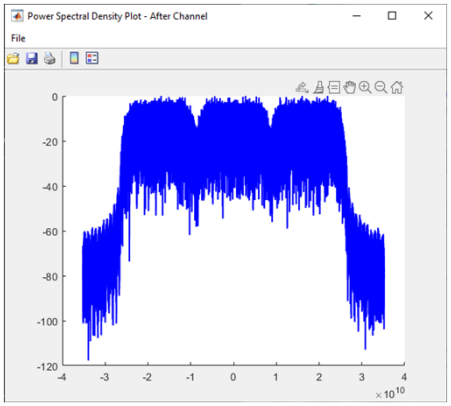


From: "IEEE Standard for Wireless Multimedia Networks," in *IEEE Std 802.15.3-2023 (Revision of IEEE Std 802.15.3-2016)* , vol., no., pp.1-684, 22 Feb. 2024, doi: 10.1109/IEEESTD.2024.10443750.



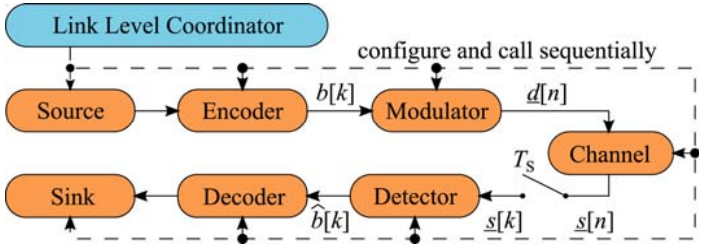


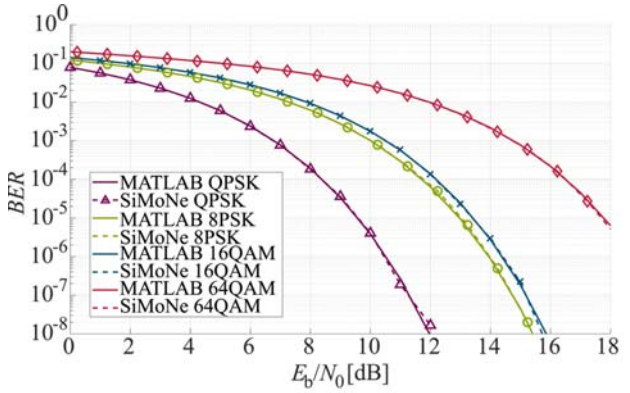




Summary and Conclusions

- Research benefits in various ways from capable simulation tools including **cost-saving, acceleration of development cycles and investigation of rare conditions**.
- Simulators like SiMoNe can investigate the impact of various **parameter configurations, compatibility and hardware combinations** and help to understand the influence of specific components
- SiMoNe provides a framework for simulations using an integrated chain of **ray-tracing, link level and system level simulations**
- Current research benefits from the knowledge and insights gathered during the Meteracom project as **applications and use cases** as well as advanced technologies such as RIS and relays are evaluated.





(a) without coding.

Thank you very much for your Attention

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