Modular Link Level Simulator for the Physical Layer of Beyond 5G Wireless Communication Systems

Johannes M. Eckhardt, Christoph Herold, Bo Kum Jung, Nils Dreyer, and Thomas Kürner

1Institut für Nachrichtentechnik, Technische Universität Braunschweig, Braunschweig, Germany

Abstract The low THz band is a promising candidate to enable data rates of up to 1 Tbit/s. To develop suitable communications systems, novel simulation approaches are needed that account for the specifics of the evolving technology. This article presents a modular link level simulator for the physical layer of beyond-5G and 6G wireless communication systems in the THz range. The simulator, that is oriented toward the IEEE Std 802.15.3d-2017 is contrasted to the state of the art of physical layer simulation tools. Its concept and basic building blocks are presented and the simulator is validated by channel simulations considering an AWGN channel model. Moreover, it is applied to a top-of-rack scenario in a wirelessly augmented data center. Different parameter sets are compared showing that a LOS condition and sufficient transmit power are a prerequisite in order to profit from the large bandwidth in the low THz range. The extensive data set of simulation results serves as input for future studies with higher layer simulation tools.

Plain Language Summary Terahertz communications are a promising candidate to deliver very high data rates up to 1 Tbit/s for next generation wireless systems. In this paper we present a new simulation module of the Simulator for Mobile Networks (SiMoNe) for the physical layer that considers important effects such as waveforms and impairments of radio frequency devices. The simulator is compared to the state of the art and its principles and basic building blocks are explained. Moreover, the simulator is validated and applied to a top-of-rack scenario in a future data center with wireless links on top of racks. The simulations show the necessity of line-of-sight conditions and high requirements on the electronic devices for a successful transmission over longer distances. The gained data set of simulation results can be used for further investigations on higher layer performance by the community.

1. Introduction

Since the current mobile radio generation cannot answer the needs for data rate and latency of certain use cases such as massive machine-type communications and mission-critical or immersive applications, research and markets drive the development of novel communication systems (Tataria et al., 2021) (Samsung Research, 2020). In recent years, the advances in the development of electronic devices make the terahertz (THz) band (0.1 THz–10 THz) attractive and accessible (Sengupta et al., 2018). Especially, the often called low THz band reaching from 0.1 THz to 1 THz is a promising candidate for the next generation of wireless systems (Latvaa-aho & Leppänen, 2019) providing large frequency bands with limited impact of molecular absorption.

THz communications offer great potentials in terms of data rate but faces a different propagation regime leading to a paradigm shift for the design and deployment of mobile communication systems (Akyildiz et al., 2014). Hence, THz channel modeling and simulation as the point of departure for novel system design are discussed for various applications such as wireless backhaul links (Jung et al., 2021), device-to-device communication (Fu et al., 2020), vehicular environments (Eckhardt, Petrov, et al., 2021), high-speed trains (Guan et al., 2019), wirelessly augmented data centers (DCs) (Cheng & Zajic, 2020) or wireless personal area network (WPAN) in office environments (Ju et al., 2021) (Priebe & Kürner, 2013).

Generally, in THz communications, higher path loss favors point-to-point (P2P) applications with high-gain directional antennas (Akyildiz et al., 2018) that might also lower the interference by spatial filtering. At the same time, beam tracking will be necessary for moving users (Tan & Dai, 2021). It is therefore an obvious approach to start exploring the novel technology for fixed P2P applications with known positions as accounted for in the first standard for THz communications: IEEE Std 802.15.3d-2017 (Petrov et al., 2020).
The DC use case offers great potential and fixed P2P links can be applied well. By integrating wireless links at THz frequencies, the DC experiences a performance improvement because of the new level of flexibility and adaptability (Hamza et al., 2016). In combination with beam switching, the network controller is able to reconfigure the network automatically and to modify the data center layout in a dynamic way (Rommel et al., 2018).

To adapt to the new channel conditions and meet the requirements of the examined applications, novel transmission techniques and protocols have to be developed for the physical layer (PHY) and higher layers (Hossain & Jornet, 2019). New geometry dependent channel models incorporating antenna characteristics and beam forming are necessary to evaluate the system design. In the context of THz communications, especially single carrier (SC) systems are discussed (IEEE Std 802.15.3d-2017, 2017) offering a lower peak-to-average power ratio implying lower demands with regard to challenging THz device development. Since communication systems in the low THz band use cutting-edge hardware devices that are optimized to the limit of technically feasible solutions, the influence of device characteristics and resulting radio frequency (RF) impairments on the signal and the data transmission are of particular interest (Sha & Wang, 2021).

In this paper, we present the novel link level module of the simulator for mobile networks (SiMoNe) (Rose et al., 2015) and analyze the performance of a top-of-rack (ToR) link in a DC. The simulator that addresses the described requirements provides the necessary simulation competences for the simulation of the PHY of high-bandwidth THz systems. It incorporates propagation and channel modeling based on ray-optical channel predictions in complex three-dimensional (3D) scenarios (Dreyer & Kürner, 2019) and enables a fully parameterized simulation of a P2P link. The waveform description as time-discrete signals of the modulation channel allows for a physical interpretation and relation to hardware devices and enables the use of signal and system theory. Thus, the simulator directly contributes to the state of the art of realistic, hardware-near simulations. The complete data set is provided to facilitate fundamental research on higher layers using realistic simulation data (Eckhardt, Herold, Jung, et al., 2021).

The rest of the article is structured as follows. Section 2 presents and summarizes the state of the art of link level simulators (LLSs) identifying the need for new developments. In Section 3, the concept of the new development is outlined and Section 4 presents the detailed models and simulation mechanisms of the whole signal processing chain. The PHY simulator is validated in Section 5 by additive white Gaussian noise (AWGN) channel simulations and in Section 6, the LLS is applied to the DC use case and the performance of a ToR link in a realistic DC model is analyzed. Finally, in Section 7, the key points of the paper are summarized.

2. Current Research

Software simulations are indispensable for the development of novel communication systems. High-performance simulation tools reduce the development costs and speed up the design process. To produce realistic and meaningful simulation results, the simulator and the models have to cover all relevant influence factors. For low THz communication systems relevant modulation and coding schemes (MCs), channel models, waveforms and hardware related impairments have to be supported. In this section, we present the state-of-the-art LLSs and evaluate their properties with regard to THz communications.

The bit error rate (BER) analysis tool from MATLAB's communications toolbox offers three simulation modes (MathWorks, 2021). The theoretical mode provides the BER as a function of the signal-to-noise ratio (SNR), more specifically the bit energy per noise power spectral density (PSD) $E_b/N_0$ for various MCs and AWGN, Rayleigh or Rice channels. The semi-analytic mode considers different modulation schemes and waveforms but is limited to an AWGN channel realization. The Monte Carlo mode serves as an interface for a MATLAB or Simulink model and allows for a simulation of a selected SNR range. The BER analysis tool is a useful but limited tool that could serve as a reference for simple simulation scenarios.

The MATLAB communication toolbox represents a broad collection of signal processing functions including standard-compliant waveform filters, MCs, also comprising multi-carrier systems, statistic channel models, and antenna systems (MathWorks, 2019). The full simulation tool chain for PHY design is well documented but closed source and comes along with an extra license. Hence, the user has limited insights of specific realizations of algorithms and applications. Moreover, the closed design of functions and modules may impede the adaptation
of methods to special customized use cases and applications. The channel is also limited to stochastic descriptions at a high abstraction level without a specific application scenario or specific subscriber interaction.

A commonly used and standard compliant LLS for fifth generation (5G) communication systems is the Vienna 5G Link Level Simulator (Pratschner et al., 2018). It is designed to simulate new concepts in 5G communication systems such as beam forming, multiple input-multiple output (MIMO) techniques or new waveforms and has its main focus on multi-carrier systems. The implemented double-fading and spatial channel models that handle time-discrete signals are detached from any deterministic environment and stay at a general level implementing stochastic functionalities. With regard to future P2P links in the low THz range providing several hundreds of Gbit/s, the system performance heavily depends on the environment of deployment and single carrier systems experience a comeback. Here, the Vienna LLS does not provide the required functionalities.

The Aff3ct library deals with the very efficient implementation of forward error correction (FEC) algorithms in C++ and provides a wide range of FEC codes and various decoders (Cassagne et al., 2019). It is also able to run LLS implementing the whole digital communication chain. Here, the simulator stays at the bit level implementing only digital channels without any waveform generation. Hence, the ability to analyze the impact of signal and waveform related effects on the data transmission such as impairments of the RF devices, inter-symbol interference (ISI), and interference simulation is limited.

The ns-3 extension TeraSim is a system level simulator for network simulations (Hossain et al., 2018). The data transmission is modeled at a packet level and the successful reception of packets is determined based on the received power. The simulator is adapted to THz communications by its channel module that considers a frequency-dependent path loss and takes particularly molecular absorption in the entire THz band into account. However, the realization of signals is limited to the consideration of power density spectra. Thus, inter-symbol interference or the impact of multipath propagation cannot be examined.

As the literature review shows, no currently available LLS is able to meet all of the above mentioned requirements for the simulation of multi-gigabit P2P links at THz frequencies. SiMoNe has been extended with a link level module to close this gap. In accordance with the IEEE Std 802.15.3d-2017, the SiMoNe LLS implements a fully parameterized communication chain. The channel representation includes broadband channel models, the processing of time discrete signals in the equivalent low pass region, and RF impairments. As a result of the integration in the SiMoNe framework, the LLS benefits from an interface to propagation simulations via ray-optical channel predictions in realistic environments and system level functionalities that allow for an easily accessible and realistic interference simulation (Eckhardt, Herold, Friebel, et al., 2021). Moreover, the combination of propagation channels gained from deterministic 3D models, bit transmission over the PHY and context-based system level simulations with realistic user movements enables simulations of real data transmissions and the evaluation of many complex application scenarios in addition to the usual Monte Carlo approach. Table 1 summarizes the properties of the compared LLSs and the next sections give an in-depth insight of the functionalities and implementation of the SiMoNe LLS.

---

| Simulator | MATLAB comms toolbox | Vienna simulator | Aff3ct | TeraSim | SiMoNe |
|-----------|-----------------------|-----------------|--------|---------|--------|
| Reference | (MathWorks, 2019)     | (Pratschner et al., 2018) | (Cassagne et al., 2019) | (Hossain et al., 2018) | This work |
| Language  | MATLAB                | MATLAB          | C++    | C++     | C#     |
| License   | commercial            | free academic, MATLAB required | free academic | free academic | private research project |
| Availability | closed source     | open source     | open source | open source | closed source |
| Waveforms | Yes                   | Yes             | No      | no      | yes    |
| Adaptable to THz | Yes               | No              | No      | yes     | yes    |
| Real data transm. | No               | No              | No      | no      | yes    |
3. Technical Concept

SiMoNe's development has started in 2014 as a tool for system level simulations of mobile wireless networks. Since then, it has developed into a simulation suite for realistic propagation and system level modeling for wireless communication systems. For the LLS, the focus on the signal processing of one link rather than the networks' behavior poses distinct requirements on the development of the components. Due to the large bandwidths and high data rates that are envisioned for THz communications, strict runtime requirements are imposed on LLSs. Statistically significant predictions of the performance of ultra-reliable low latency communication (uRLLC) systems require a significantly larger amount of bits to be simulated compared to less reliable systems, such as an LTE-system. Moreover, the level of detail of the simulated link is much higher compared to system level simulations. Every single transmitted bit is followed on its path between transmitter and receiver and evaluated afterward. In order to ensure that the developed LLS is able to cope with these and further challenges, five main design principles have been identified and followed during the development.

3.1. Modular Composition

As technical developments continue rapidly in the field of THz communication, the simulator must be adaptable and flexible to react upon new concepts, hardware and simulation technology. A modular composition of the simulator allows for that. Functionalities should be bundled in interchangeable and connectable modules. The programming language C# as an object-oriented language which offers concepts such as abstract classes and inheritance. By using parent classes to provide common functionalities to different children (e.g., different types of detectors), code duplicates can be reduced while allowing for interchangeability.

3.2. Iterative Computations

As mentioned above, a low BER requires large amounts of simulated bits. If the communication scenario produces a high BER, though, a lower number of bits is sufficient for the computation of statistics. Running the simulations in an iterative way enables to check for abortion criteria and drastically reduce the runtime for many simulations. As the transmitted bits themselves are often not of interest, they can be discarded after the BER calculation of an iteration, which greatly reduces the memory footprint of the simulations.

3.3. Integration of Ray Tracing Results

The simulator for mobile networks contains a framework for the analysis of 3D scenarios using ray-optical methods (Dreyer & Kürner, 2019). It can be used to predict different communication paths with their delay and amplitude while taking into account positions and orientations of transmitter (TX) and receiver (RX). By implementing an interface to this framework, ray-optical methods can be used in the LLS to derive channel information of realistic 3D scenarios. It thus allows to simulate a variety of scenarios and compare measurement results with the simulations or draw conclusions from scenarios that might not be accessible by measurements. THz communication systems benefit even more from the ray tracing approach since higher frequencies get closer to quasi-optical propagation. Therefore, ray tracing is often applied to model and simulate THz channels. A conceptual overview of the simulation process that combines ray tracing and link level simulator is shown in Figure 1.

3.4. Visualization of Results

The visualization of different stages of the transmission system is important for several reasons: It can help to provide visual aids to spot and interpret phenomena such as I/Q-imbalances in a constellation diagram or timing issues in an eye diagram. Both diagrams are widely used and are standard representations for transmission
systems. The visualization capabilities of the link level simulator include constellation diagrams, eye diagrams, error vector diagrams, spectrum plots and frequency domain plots. Apart from that, the visualization features help and facilitate the scientific communication as exemplarily presented in Figure 2. A metric such as the BER is more tangible when seeing the effect on a constellation diagram than just comparing two numbers to each other for example.

3.5. Interfacing With Other Scientific Tools

SiMoNe is used in several research projects and in collaborations with other research partners. Having appropriate interfaces to enable collaboration and exchange of simulation data with third parties is hence important to consider. The framework offers import and export functionalities in .mat- and .csv-format. While MATLAB is a well-established tool, .csv-files are commonly used to exchange data and allow for a high interoperability and universal usage within many different programs and contexts. By keeping in mind the need of interoperability, it can be assured that the research conducted with SiMoNe can be shared with the research community and have a valuable impact.

4. PHY-Layer Model and Simulator Implementation

After the assessment of requirements for the LLS, a suitable software architecture has been derived and implemented. The architecture and its functional components are briefly introduced in this section. As described in Section 3, the modular composition is one of the most important features of the link level simulator. The simulator is implemented in a design pattern called pipes and filter (Buschmann, 1996) that is commonly used for data processing. All functionalities are kept within defined blocks that only handle their respective tasks and provide states as inputs to other blocks (Rose et al., 2015). The functional blocks that are used within the LLS are explained in the following sections. In addition, an overview of all available blocks and their connections is shown in Figure 3. Note that the variable $k$ flags a discrete quantity.
with bit rate $r_b$ or symbol rate $r_s$ and the variables $n$ and $l$ refer to a time-discrete representation with sampling frequency $f_s$ in time and frequency domain, respectively.

The so-called link level coordinator serves as a control instance of simulation. It holds all configuration parameters and provides them to the actual transmission chain blocks. The coordinator controls the block iteration until a statistically significant number of transmitted bits is reached in the bit sink block. The bit source block creates a configurable number of pseudo random bits each time the block is called by the coordinator. The created bits are provided as a state for the following encoder block.

4.1. Channel Coding

Channel coding for THz communications is a challenging task due to high data rates and the hence implied need to efficiently encode and decode transmitted symbols. The IEEE Std 802.15.3d foresees advanced codecs that allow efficient hardware implementations, namely (240,224)- Reed Solomon (RS), 11/15- Low Density Parity Check (LDPC) and 14/15-LDPC (IEEE Std 802.15.3d-2017, 2017). The Aff3ct coding library is a highly optimized C++-library and provides a fast implementation of a wide variety of coding schemes (Cassagne et al., 2019). Hence, its encoding and decoding functionalities have been integrated in the LLS in order to profit from its efficient channel coding. As the LLS is written in the programming language C# and the Aff3ct coding library partly uses native C++, both software projects are not directly compatible. A wrapper library using a Pointer to Implementation (PImpl) programming technique is added to handle and translate calls between both pieces of software. By employing this wrapper, Hamming, RS and LDPC codes are provided. Hamming and RS codes can be configured using internal library parameters while custom generator and check matrices for the LDPC codes were created according to the standard and imported into the integrated Aff3ct library. The encoded bits $b[k]$ are provided as a state for the modulator block.

4.2. Modulation

One of the main motivations for using THz communication is the large available bandwidth. Hence, the IEEE Std 802.15.3d projects a single carrier system with low order modulation schemes combined with a high bandwidth up to 69.12 GHz (IEEE Std 802.15.3d-2017, 2017). The modulator of the LLS implements the single carrier system and maps the provided bits $b[k]$ to complex symbols $A[k]$ according to the selected modulation scheme. Here, on-off-keying (OOK), binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), amplitude phase shift keying (APSK) and quadrature amplitude modulation (QAM) are implemented. First, the $M$-ary modulation scheme is normalized with the factor

$$c_{TX} = \frac{1}{M} \sum_{m=1}^{M} |d_m|,$$

where $|d_m|$ denotes the amplitude of each possible complex symbol in order to ensure the same average transmit power $P_{TX}$ for all modulation schemes. After the mapping, the complex symbols $d[k]$ are sampled with the sampling frequency $f_s$ resulting in the time-discrete expression

$$d[n] = \sum_{k=1}^{K} d[k] c_{TX} \delta(n\Delta t - kT_s),$$

where $\delta(\cdot)$ denotes the Dirac delta function, $T_s$ the symbol duration and $\Delta t$ the sampling interval. The sampling and the time-discrete signal representation are necessary in order to consider the actual waveform that plays a crucial role in THz communications. The transmit pulse that describes how the waveform unfolds in time allows for incorporating important characteristics of the channel and the RF hardware and thus has to be considered in link level simulations. Since the simulation is performed in the equivalent low pass representation according to (Glover & Grant, 1998), the carrier is omitted.

The signal $d[n]$ is passed on to the transmit filter. In order to model the radio channel as band-limited time-discrete system, the transmit pulse is allocated to the channel block implementing the so-called modulation channel. Accordingly, the transmit pulse is given by
Table 2
Transmit Pulses

| Transmit pulse       | Pulse duration $T_f/T_s$ | Sampling frequency $f_s$ |
|----------------------|--------------------------|--------------------------|
| Sinc pulse           | 128                      | $2 \cdot B_N$            |
| Root-raised cosine pulse | 16                      | $4 \cdot B_N$            |
| Rect pulse           | 1                        | $16 \cdot B_N$           |

where $h_{TX}(t)$ is the impulse response (IR) of the transmit filter realized as root-raised cosine (RRC), rectangular or sinc filter and $A$ the amplitude of the transmit pulse that regulates the transmit power. It has a pulse duration $T_s$ that is a multiple of the symbol duration $T_s$ and given in Table 2. The pulse amplitude $A$ can be derived from the TX power in the equivalent low pass region that is obtained by dividing the energy of a transmit pulse

$$E_g = A^2 T_s^2 \sum_{n=0}^{N} h^2_{TX}[n]$$

by the symbol duration $T_s$ resulting in a pulse amplitude

$$A = \sqrt{\frac{2 \cdot P_{TX} \cdot f_s}{T_s \cdot \sum_{n=0}^{N} h^2_{TX}[n]}}$$

where $P_{TX}$ denotes the bandpass TX power and $f_s$ denotes the sampling frequency. Note that the symbol duration is a multiple of the sampling interval $\Delta t$. The latter is adapted according to the selected transmit pulse and the resulting bandpass bandwidth of the pulses. In order to reduce aliasing effects, the sampling frequency $f_s = 1/\Delta t$ is adapted to the transmit pulse and chosen as a function of the Nyquist bandwidth $B_N$, the minimum bandwidth that allows for a transmission at a certain symbol rate without ISI, as presented in Table 2. In this way, the signal distortion ratio is limited to $SDR = 21.9$ dB (Glover & Grant, 1998). In addition, an oversampling factor allows for an increase of the sampling frequency for visualization purposes.

4.3. Channel Implementation

The challenge of the simulator is to model the time-continuous channel within a time-discrete computer simulation. Based on the results of the ray tracing simulation for the wave propagation and the antenna masking, the multipath components (MPCs) are provided as pairs of amplitude $A_i$ and delay $\tau_i$, where the amplitude is currently assumed as frequency-independent. The IR of the propagation channel can thus be written as

$$h_c(t) = \sum_i A_i \delta(t - \tau_i).$$

In order to transfer this expression to a time-discrete regime, the modulation channel is modeled making use of the transmit pulse presented in the previous section. The band-limited transmit pulse is convolved with the channel impulse response and sampled with the sampling frequency leading to

$$h_{TXC}[n] = (g * h_c)[n] = \sum_i A_i A T_s h_{TX}(n \Delta t - \tau_i).$$

which serves as filter coefficients of a finite impulse response (FIR) filter that is implemented via a fast convolution approach. Thus, the incident signal at the receiver is obtained by the convolution

$$w[n] = d[n] * h_{TXC}[n].$$

In order to serve as an interference signal in other simulations, the incident signal at the RX $w[n]$ can be stored enabling realistic interference simulations based on actual time-discrete signals (Eckhardt, Herold, Friebel, et al., 2021).

A major benefit of the time-discrete and physically meaningful signal representation in the channel block is that quantitative information on various characteristics (e.g., noise or device impairments) from different sources can be taken into account on the basis of the SI units. For instance, the complex AWGN denoted by $\epsilon[n]$ can be simulated in two different ways. One option that is also commonly supported by other simulators is to specify the ratio of the energy per information bit and the noise spectral density $E_g/N_0$. The associated noise power $P_N$ is then calculated as a function of the incident signal power at the RX $P_g$.
\[ P_{RX} = \frac{1}{N} \sum_{n=1}^{N} w[n] \]  

(9)

leading to

\[ P_N = \frac{P_{RX}}{SNR} \]  

(10)

Note that \( E_b/N_0 \) takes into account the code rate \( r_c \) such that the relation between the SNR and \( E_b/N_0 \) is given by

\[ E_b/N_0 = SNR \cdot \frac{B_{BP}}{r_b \cdot r_c} \]  

(11)

Another option offers the generation of actual thermal noise of the RX with a spectral noise density of

\[ N_{0,\text{therm}} = k_B T \]  

(12)

where \( k_B \) denotes the Boltzmann constant, \( T \) the absolute temperature and \( F \) the noise factor of the amplifier chain of the RX. Multiplying the spectral noise density with twice the Nyquist bandwidth \( B_N \) leads to the noise power \( P_N \) that determines the variance of the random noise generator

\[ \sigma^2 = P_N T S f_s, \]  

(13)

For modern communication systems, especially in the low THz band, the characteristics of cutting-edge hardware components have a crucial impact on the performance of the data transmission. Therefore, it is inevitable to model the impairments of RF devices on the signals and waveforms in order to get meaningful simulation results. Based on measurement results from the hardware characterization, the measured PSD of the phase noise (PN), usually given in dBc/Hz, has to be modified for compatibility with the time-discrete signal representation in the channel. First, the given PSD is converted to linear scale

\[ S_{xx}(f) = P_{LO} \cdot 10^{S_{xx,\text{dBc}}(f) \frac{1}{10} \cdot 1 \text{ Hz}}, \]  

(14)

where \( P_{LO} \) denotes the power of the local oscillator. Then, the single sideband spectrum is interpolated, discretized and enlarged to a double side-band spectrum by

\[ S_{xx,\text{PN}}[l] = \frac{1}{2} S_{xx,\text{PN}}(l \Delta f) \cdot \Delta f \]  

(15)

with frequency step \( \Delta f \) determined by the number of filter coefficients. Finally, the PN generator creates a white Gaussian noise (WGN) signal that is filtered by an FIR filter with transfer function

\[ H_{\text{PN}}[l] = \sqrt{S_{xx,\text{PN}}[l]} \]  

(16)

The signal \( u[n] \) considering the phase noise and thermal noise sources can be expressed as

\[ u[n] = u[n] \cdot e^{j \phi_{PN}[n]} + \epsilon[n] \]  

(17)

with \( \phi_{PN}[n] \) denoting the realization of the phase noise signal and \( \epsilon[n] \) denoting the AWGN.
and receive filter, respectively. Therefore, the given sample points of the TF of the device that lie within the simulated frequency band have to be interpolated in order to match the number of filter coefficients of the FIR filter realizing \( h_{\text{TX},C} \). The interpolation is implemented by zero padding in time domain. In further developments, nonlinear effects such as compression will also be considered. Here, the challenge consists in modeling a system of which the characteristics depend on the actual instantaneous power of the input signal.

The signal is finally processed by a matched filter \( h_{\text{RX},\text{LNA}} \) incorporating the characteristics of the LNA.

The detailed signal processing chain of the modulator block, channel block, and detector block is visualized in Figure 4 summarizing the explanations of the respective sections.

4.4. Demodulation and Detection

In order to obtain the received symbols, the received signal \( s[n] \) is resampled with a sampling period corresponding to the symbol duration using the sampling series

\[
s[k] = \sum_{n=-N}^{N} s[n] \text{sinc} \left( \frac{kT_S - (\tau_m \mod T_S) - n\Delta t}{\Delta f} \right),
\]

where \( 2N \) denotes the number of samples that is considered for the interpolation and \( \cdot \) mod \( \cdot \) denotes the modulo operation (Jeruchim et al., 2000). Here, \( N = 100 \) is chosen. The delay introduced by the channel \( \tau_m \) is assumed to be known and gathered from the channel block. In order to account for the channel losses, the received symbols are scaled with the factor

\[
c_{\text{RX}} = \sqrt{\frac{1}{M} \sum_{m=1}^{M} d_m^2} / \sqrt{\frac{1}{K} \sum_{k=1}^{K} w^2[k]}
\]

and additional delays originating from the channel and bit processing are compensated. Finally, a maximum likelihood detector using hard decision (HD) detection provides input for the Hamming and RS decoder. It selects the estimated transmit symbol

\[
d[k] = d_m \quad \text{s.t.} \quad \min_m |s[k] - d_m|,
\]

by minimizing the euclidean norm of the error vector. The LDPC decoder requires and the RS decoder supports a soft decision (SD) detection based on the Log-Likelihood Ratio defined as

\[
L(b_{i,k} | s[k]) = \log \left( \frac{P(b_{i,k} = 0 | s[k])}{P(b_{i,k} = 1 | s[k])} \right),
\]

where \( b_{i,k} \) is the \( i \)th bit of the \( k \)th receive symbol \( s[k] \) (Hagenauer et al., 1996).

4.5. Bit Evaluation

At the sink, several key performance indicators (KPIs) are evaluated for the transmission chain. In order to derive statistically dependable values, a certain number of bits has to be simulated. Three different methods are currently implemented to estimate the required number of bits: A common rule of thumb is that 10–1,000 times
the reciprocal value of the expected BER has to be considered (Jeruchim et al., 2000). For an expected BER of $10^{-6}$, this would mean that $10^7$–$10^9$ bits need to be simulated. In (Mitić et al., 2012), the authors propose a statistical method to estimate the required number of bits. For the same expected BER, their formula

$$K_{\text{sim}} = \frac{1}{\text{BER}} \left[ -\ln(1 - SLC) + \ln \left( \sum_{i=0}^{K_{\text{err}}} \frac{K_{\text{sim}} \cdot \text{BER}^i}{i!} \right) \right],$$

(22)

where $K_{\text{sim}}$ denotes the total number of bits to be simulated, $\text{BER}$ the expected BER, $SLC \in [0, 1]$ the desired level of confidence and $K_{\text{err}}$ the number of already occurred bit errors in the simulation, returns $4.61 \cdot 10^6$ bits to be simulated assuming a confidence of 0.99 and zero errors during the transmission. A third option is to simulate until a certain number of errors is reached. All three of these methods are complemented by another abortion criterion which defines a maximum number of bits that are simulated in order to avoid infinite loops. Once the suggested number of bits is reached, the link level coordinator is notified by the bit sink block and stops the iterating. Finally, KPIs such as BER, data rate and error vector magnitude (EVM) are computed and saved.

5. Simulator Validation via AWGN Channel

The validation of simulation results against measurements of a real-world system is a common method to show that the simulations produce reliable outcome. As THz communication systems with the intended bandwidths of the LLS are not commercially available yet, this practice is not an option for the LLS. In its place, a multi-layer test concept has been used in order to ensure the correct and expected behavior of the simulation tool. At the first and second stage unit-tests and code reviews were used to validate and verify the behavior of single functions (e.g., a function for the computation of the signal’s power) as well as complete blocks (e.g., the modulator block as shown in Figure 3) encapsulating independent tasks. At the third and final tier, simulation results of the LLS were compared to known and theoretically derived reference results that were computed by other well-established and commonly used simulation tools. A later comparison with results of experimental hardware is foreseen once said data is available to the scientific community.

For this task, a comparison of an AWGN channel for different MCSs simulated with SiMoNe’s LLS and MATLAB’s BER tool was drawn. The AWGN has been selected as it provides well-studied results in a time-invariant setting as a reference for the data transmission. The channel delay $\tau$ and amplitude $A$ are set to 0 ns and 1, respectively. The noise power is set accordingly to the predefined $E_b/N_0$. Note that the SNR is dependent on the modulation scheme and the transmit pulse for fixed $E_b/N_0$ and thus not appropriate to compare BERs of different configurations. Four modulation schemes (BPSK, 8PSK, 16QAM and 64QAM) have been simulated and compared to the BER tool’s results for uncoded transmission over the range of $E_b/N_0 = [0, 18]$. A good agreement between the respective values can be observed. Minor deviations between the LLS’s and the BER tool’s curves most likely arise from the statistical variations of the AWGN and are not of concern. The BER graph for uncoded transmission is depicted in Figure 5a.
In order to verify the coded transmission, simulations of different pairs of MCSs have been conducted, namely QPSK modulation and a (255,239)-RS-code, 16QAM and (7,4)-Hamming code, 64QAM and (7,4)-Hamming code and 64QAM and a (255,239)-RS-code. Similar to the uncoded cases, the coded simulation results show a strong agreement with the theoretical data from the BER tool. For reference, a QPSK modulated transmission with the 11/15-LDPC and 14/15-LDPC codes as defined in the IEEE Std 802.15.3d were included. However, no equivalent simulation in MATLAB’s BER tool exists. The $E_b/N_0$ sweeps for coded transmissions are shown in Figure 5b.

After testing of the LLS’s components and comparing the simulated data with theoretical BER-curves, it can be concluded that the simulator is valid and applicable to other scenarios because the digital signal processing within the simulation yields the expected results for traceable cases. Thus, the simulator is applied to analyze the performance of ToR links in a realistic DC model in the next section.

6. **Top-of-Rack Link Analysis in a Data Center Scenario**

Highly efficient data center networks are mandatory to cope with the challenges of the current century and need to provide ultra-low latency, reliability, and flexibility. Additional wireless links will enable a fast reconfigurability that increases the performance and efficiency of a DC. The ToR area is therefore a promising region for inter-rack connections with a high probability for a line-of-sight (LOS) connection. Using a channel model based on ray tracing (Dreyer & Kürner, 2019) in a realistic DC model (Eckhardt et al., 2019), the performance of a single ToR link is evaluated through link level simulations.

The DC under investigation is organized in rows. Plastic curtains above each row of racks are a particularity of this DC that divide the DC into hot and cold regions in order to assure an energy efficient air flow for cooling. The TX and RX are located on the same row in the middle of the DC. TX and RX are initially placed on adjacent racks with a distance of $d = 0.69$ m, that is subsequently increased by one rack up to $d = 16.50$ m. Figure 6 shows a schematic overview of the simulation setup.

At first, the ray tracing simulation is carried out in the DC model for each distance up to second order reflections and transmissions, respectively, presenting a reasonable trade-off between computational effort and level of detail. Figure 7 illustrates the ray tracing in the DC where reflected and transmitted paths are shown in green and yellow, respectively. For reasons of visibility, the direct path is not plotted here. The resulting MPCs from the ray tracing given by amplitude and delay that are part of the published research data (Eckhardt, Herold, Jung, et al., 2021) are fed to the LLS to examine the link performance. Figure 8 illustrates an exemplary discrete IR $h_{TX,C}[n]$ of the channel convolved with an RRC transmit pulse and sampled with a sampling frequency of 3.52 GHz representing 575 filter coefficients.

For a meaningful link evaluation realistic parameters have to be set. According to the THz SC PHY mode of the IEEE Std 802.15.3d, the chip rate is set to 1.76 Gchip/s, 3.52 Gchip/s, and 10.56 Gchip/s with a channel bandwidth of 2.16 GHz, 4.32 GHz, and 12.96 GHz, respectively (IEEE Std 802.15.3d-2017, 2017). The MCSs also comply with the standard and are listed in Table 3. TX powers of up to 0 dBm are available at 300 GHz for unpackaged devices (Al-Khalidi et al., 2020). To compensate for the losses due to packaging and system integration, the TX power is assumed to be $-8$ dBm. The TF of the PA is provided in (John et al., 2020). In the considered frequency band, the forward transmission $S_{21}$ varies between $S_{21 \text{,min}} = 18.21$ dB and $S_{21 \text{,max}} = 23.24$ dB. The values for the PSD of the implemented PN model are taken from (Dan et al., 2020). They show a PSD of the PN of $-70$ dBc/Hz and $-87$ dBc/Hz at an offset frequency of 10 Hz and 10 kHz, respectively. For the mixer and the LNA, including its noise figure $NF$ of 10 dB, characteristics...
The deployed antenna is a simulated antenna pattern of a standard gain horn antenna with a gain of 26 dBi and a half power beam width (HPBW) of 8° that equals the antenna used for the measurements in the DC (Eckhardt et al., 2019). The maximum number of bits to be transmitted is set to 0.3 Gbit resulting in a minimum BER of $1 \cdot 10^{-4}$ that is assumed to be sufficient for a first order analysis. Table 3 summarizes all combinations of simulation parameters that are included in the complete data set. The complete simulation results can be found at (Eckhardt, Herold, Jung, et al., 2021). Due to the multitude of different simulation sets, the following evaluation has been conducted on a subset of simulation results showing the key findings on the P2P link analysis for ToR scenarios.

The BER that is the most important quantity to evaluate the physical layer is closely linked to the $E_b/N_0$ at the RX. Figure 9a reflects the $E_b/N_0$ as a function of the channel impulse response (CIR) mapped to the resulting distance for an uncoded BPSK transmission with varying channel bandwidth. Here, two distances around 6 m have a significantly lower $E_b/N_0$ that is due to shadowing effects and non-line-of-sight (NLOS) conditions caused by lower rack heights at the RX side. NLOS conditions occur also for distances greater than 14 m that are caused by shadowing effects and lower rack height, too.

The $E_b/N_0$ and thus the BER depend on the channel bandwidth since the energy per bit decreases with higher channel bandwidth and constant TX power. Although the symbol rate increases, the $E_b/N_0$ decreases and the BER increases, too. Figure 9b presents the BER for the channel bandwidths under investigation 2.16 GHz, 4.32 GHz, and 12.96 GHz. Data points with a lower BER than $10^{-4}$ did not produce any error during the simulation and therefore are not visualized. Note that for a constant distance and channel bandwidth, different modulation schemes face different values of $E_b/N_0$ although the SNR stays constant. The BER of an uncoded transmission with RRC filter, a channel bandwidth of 2.16 GHz and different modulation schemes is shown in Figure 10a. Although the reflected MPCs seem relatively weak as exemplarily presented in Figure 8, the BER in the DC scenario increases compared to the simulations with the AWGN channel in Section 5. A logical explanation might be the influence of ISI despite the highly directional horn antennas. Obviously, lower order modulation schemes are more robust. However, OOK has a similar BER as QPSK, although OOK performs worse than QPSK on an AWGN channel for constant $E_b/N_0$. As a conclusion, the direct setup in the realistic environment is very significant to evaluate the performance of different system parameters.

Channel coding is indispensable to reach interesting BERs at relevant distances for low THz links in a DC. Different coding schemes with QPSK, RRC and $B_{\text{ch}} = 12.96$ GHz are shown in Figure 10b. As expected, the LDPC11/15 performs best and allows for an error-free simulation up to 10 m in LOS cases.

The strong dependency on the device characteristics is specific for low THz systems that work with the latest generation of RF devices. Therefore, waveforms and RF impairments have to be considered for reliable predictions of the link performance. The impact of the waveform that is presented in Figure 11a for a Hamming coded data transmission shows a higher BER for sinc pulses that are probably more sensitive to ISI because of the longer pulse duration. The RRC shows a better performance especially for QAMs. Moreover, a lower modulation order in combination with a higher bandwidth is more robust than a high order modulation such as 16QAM with a smaller bandwidth providing the same data rate. This observation supports

### Table 3: Simulation Parameters

| Parameter                  | Value                     |
|----------------------------|---------------------------|
| Chip rate $r_{\text{chip}}$| 1.76 Gchip/s, 3.52 Gchip/s, 10.56 Gchip/s |
| Channel bandwidth $B_{\text{ch}}$ | 2.16 GHz, 4.32 GHz, 12.96 GHz |
| Nyquist bandwidth $B_N$    | 0.88 GHz, 1.76 GHz, 5.28 GHz |
| Sampling frequency $f_c$   | given by Table 2          |
| Transmit pulse $g$         | sinc, rect, RRC           |
| Roll-off factor $\alpha$   | 0.7                       |
| Modulation scheme          | BPSK, OOK, QPSK, 16-QAM    |
| Coding scheme              | Hamming, RS, LDPC11/15, LDPC14/15 |
| Max. number of bits        | 0.3 Gbit                  |
| Transmit power $P_{\text{TX}}$ | $-8$ dBm                |
| Antenna type               | standard gain horn        |
| Antenna gain $G_{\text{TX}}$ | $26$ dBi                 |
| Antenna HPBW               | $8^\circ$                 |
| Noise figure $NF$          | 10 dB                     |
| Noise temperature $T$      | 290 K                     |

Figure 8. Impulse response of the modulation channel of the setup $d = 4.89$ m.
the approach of THz communications to profit of the large available bandwidth at THz frequencies along with lower order modulation schemes.

The RF impairments have a significant influence on the data transmission and reduce the maximum transmission distance as visualized in Figure 11b. Here, the amplitude is strongly affected by the TFs of the PA and LNA making a data transmission with QAM impossible. Also the pulse types interact with the RF impairments leading to different BERs. That underlines the absolute necessity to consider RF characteristics in order to reliably predict the performance of the PHY for low THz communication systems.

7. Conclusion

In this paper, we have presented a modular link level simulator for future communication systems that use a high bandwidth and single carrier modulation as defined in the IEEE Std 802.15.3d. Modeling the exact transmit pulse and the channel, incorporating the antenna characteristics and the actual thermal noise of the RX, enables a simulation closely modeling hardware features. The time-discrete model offers the possibility to include hardware characteristics and RF impairments, such as phase noise or compression and expansion effects, having an important impact in simulating cutting-edge hardware development in the low THz band. The simulator has been compared to the state of the art to show the necessity of novel simulation approaches and the benefit of a holistic simulation suite integrating propagation, link- and system-level simulations such as SiMoNe. To prove its operability, the simulator has been validated through AWGN simulations and a comparison with the MATLAB BER tool. Finally, the application to a ToR scenario in a wirelessly augmented DC shows the general system performance of a single link with state-of-the-art hardware parameters. The analysis reveals the influence of RF characteristics on the waveform and on signal transmission and underlines the importance of a LOS condition to

![Figure 9. E_b/N_0 and BER in the DC for different channel bandwidths.](image)

![Figure 10. BER in the DC for different modulation and coding schemes.](image)
provide a fast and reliable data transmission in the low THz band. The results of the simulation campaign with over 20,000 data points are provided to the community as an extensive data set for future research.

Data Availability Statement
The comprehensive simulation data set that was created with SiMoNe v2021.1, 25.09.2021 is available at the research data base of Technische Universität Braunschweig under the [link](https://doi.org/10.24355/dbbs.084-202111032122-0) (Eckhardt, Herold, Jung, et al., 2021).

Acknowledgments
This project has received funding from Horizon 2020, the European Union’s Framework Programme for Research and Innovation, under grant agreement No. 761579 (TERAPOD) and under grant agreement No. 814523 (ThoR). It has also received funding from the German Research Foundation (DFG) under Grant Agreement No. 814761523 (ThoR). It has also received funding from the German Research Foundation (DFG) under Grant Agreement No. 579 (TERAPOD) and under grant agreement No. 100345 (ThoR). It has also received funding from the German Research Foundation (DFG) under Grant Agreement No. 814761523 (ThoR). It has also received funding from the German Research Foundation (DFG) under Grant Agreement No. 814761523 (ThoR). It has also received funding from the German Research Foundation (DFG) under Grant Agreement No. 814761523 (ThoR).

References
Akyildiz, I. F., Han, C., & Nie, S. (2018). Combating the distance problem in the millimeter wave and terahertz frequency bands. *IEEE Communications Magazine*, 56(6), 102–108. [https://doi.org/10.1109/mcom.2018.1700928](https://doi.org/10.1109/mcom.2018.1700928)

Akyildiz, I. F., Jornet, J. M., & Han, C. (2014). Terahertz band: Next Frontier for wireless communications. *Physical Communication*, 12, 16–32. [https://doi.org/10.1016/j.phycom.2014.01.006](https://doi.org/10.1016/j.phycom.2014.01.006)

Al-Khalidi, A., Alharbi, K. H., Wang, J., Morariu, R., Wang, L., Khalid, A., et al. (2020). Resonant tunneling diode terahertz sources with up to 1 mW output power in the J-Band. *IEEE Transactions on Terahertz Science and Technology*, 10(2), 150–157. [https://doi.org/10.1109/TTHZ.2019.2959210](https://doi.org/10.1109/TTHZ.2019.2959210)

Buschmann, F. (1996). *Pattern-oriented software architecture, A system of patterns*. Wiley.

Cassagne, A., Hartmann, O., Léonardon, M., He, K., Leroux, C., Tajan, R., et al. (2019). AHT3ct: A fast forward error correction toolbox. *SoftwareX*, 0710, 100345. [https://doi.org/10.1016/j.softx.2019.100345](https://doi.org/10.1016/j.softx.2019.100345)

Cheng, C.-L., & Zajic, A. (2020). Characterization of propagation phenomena relevant for 300 GHz wireless data center links. *IEEE Transactions on Antennas and Propagation*, 68(2), 1074–1087. [https://doi.org/10.1109/tap.2019.2949135](https://doi.org/10.1109/tap.2019.2949135)

Dan, I., Ducournau, G., Hisatake, S., Szriftgiser, P., Braun, R.-P., & Kallfass, I. (2020). A superheterodyne 300 GHz wireless link for ultra-fast vehicular communications. *IEEE Journal on Selected Areas in Communications*, 39(5), 1572–1595. [https://doi.org/10.1109/jlsac.2020.3071843](https://doi.org/10.1109/jlsac.2020.3071843)

Dreyer, N., & Kürner, T. (2019). An analytical raytracer for efficient D2D path loss predictions. In *2019 13th European conference on antennas and propagation (EuCAP)* (p. 5). Krakow.

Eckhardt, J. M., Doeker, T., Rey, S., & Kürner, T. (2019). Measurements in a real data centre at 300 GHz and recent results. In *Proc. Of European conference on antennas and propagation (EuCAP)* (p. 5). Krakow.

Eckhardt, J. M., Herold, C., Friebel, B., Dreyer, N., & Kürner, T. (2021). Realistic interference simulations in a data center offering wireless communication at low terahertz frequencies. In *2021 international symposium on antennas and propagation (ISAP)* (pp. 1–2). [https://doi.org/10.23919/isap47258.2021.9614511](https://doi.org/10.23919/isap47258.2021.9614511)

Eckhardt, J. M., Herold, C., Jung, B. K., Dreyer, N., & Kürner, T. (2021). Link-level simulations of the physical layer for low THz communications systems: Validation and analysis of a data center use case. *IEEE Transactions on Terahertz Science and Technology*, 11(3), 1590–1603. [https://doi.org/10.1109/tjsc.2021.3071843](https://doi.org/10.1109/tjsc.2021.3071843)

Fu, J., Juyal, P., & Zajic, A. (2020). Modeling of 300 GHz chip-to-chip wireless channels in metal enclosures. *IEEE Transactions on Wireless Communications*, 19(5), 3214–3227. [https://doi.org/10.1109/twc.2020.2971206](https://doi.org/10.1109/twc.2020.2971206)

Glover, I., & Grant, P. (1998). *Digital communications* (1st ed.). Prentice Hall Europe.

Guan, K., Peng, B., He, D., Eckhardt, J. M., Rey, S., Al B., et al. (2019). Channel characterization for intra-wagon communication at 60 and 300 GHz bands. *IEEE Transactions on Vehicular Technology*, 68(6), 5193–5207. [https://doi.org/10.1109/tvt.2019.2907606](https://doi.org/10.1109/tvt.2019.2907606)

Hagenauer, J., Offer, E., & Papke, L. (1996). Iterative decoding of binary block and convolutional codes. *IEEE Transactions on Information Theory*, 42(2), 429–445. [https://doi.org/10.1109/18.485714](https://doi.org/10.1109/18.485714)

Hamra, A. S., Deogun, J. S., & Alexander, D. R. (2016). Wireless communication in data centers: A survey. *IEEE Communications Surveys & Tutorials*, 18(3), 1572–1595. [https://doi.org/10.1109/comst.2016.2521678](https://doi.org/10.1109/comst.2016.2521678)

Hossain, Z., & Jornet, J. M. (2019). Hierarchical bandwidth modulation for ultra-broadband terahertz communications. In *ICC 2019 - 2019 IEEE international conference on communications (ICC)* (pp. 1–7). IEEE.

---

**Figure 11.** BER in the DC evaluating waveforms and RF impairments.
Hossain, Z., Xia, Q., & Jornet, J. M. (2018). Terasim: An ns-3 extension to simulate terahertz-band communication networks. *Nano Communication Networks, 17*, 36–44. https://doi.org/10.1016/j.nancom.2018.08.001

IEEE Std 802.15.3d-2017 (2017). *IEEE standard for high data rate wireless multi-media networks–amendment 2: 100 Gb/s wireless switched point-to-point physical layer (standard)*. IEEE.

Jeruchim, M. C., Balaban, P., & Shanmugan, K. S. (2000). *Simulation of communication systems: Modeling, methodology, and techniques* (2nd ed.). Kluwer Academic/Plenum Publishers.

John, L., Tessmann, A., Leuther, A., Neininger, P., Merkle, T., & Zwick, T. (2020). Broadband 300-GHz power amplifier MMICs in InGaAs mHEMT technology. *IEEE Transactions on Terahertz Science and Technology, 10*(3), 309–320. https://doi.org/10.1109/tthz.2020.2965808

Ju, S., Xing, Y., Kanhere, O., & Rappaport, T. S. (2021). Millimeter wave and sub-terahertz spatial statistical channel model for an indoor office building. *IEEE Journal on Selected Areas in Communications, 39*(6), 1561–1575. https://doi.org/10.1109/jsac.2021.3071844

Jung, B. K., Herold, C., Eckhardt, J. M., & Kürner, T. (2021). Link-level and system-level simulation of 300 GHz wireless backhaul links. In *2020 international symposium on antennas and propagation (ISAP)* (pp. 619–620). IEEE.

Latva-aho, M., & Leppänen, K. (2019). *Key drivers and research challenges for 6G ubiquitous wireless intelligence (white paper)*. 6G Flagship, University of Oulu. Retrieved from http://jultika.oulu.fi/files/isbn9789526223544.pdf

MathWorks (2019). *Bridging wireless communications design and testing with Matlab (White Paper)*. The MathWorks Inc.

MathWorks (2021). *Bit error rate analysis*. Retrieved from https://de.mathworks.com/help/comm/ref/biterrorrateanalysis-app.html

Mitc, D., Lebl, A., & Markov, Ž. (2012). Calculating the required number of bits in the function of confidence level and error probability estimation. *Serbian Journal of Electrical Engineering, 9*(3), 361–375. https://doi.org/10.2298/sjee1203361m

Moro-Melgar, D., Cojocari, O., Oprea, I., Hofde, H., & Rickes, M. (2018). High power discrete Schottky diodes based 275-305 GHz transceiver for FMCW-radar. 29th IEEE International Symposium on Space THz Technology (Vol. ISSTT2018, pp. 233–235).

Petrov, V., Kürner, T., & Hosako, I. (2020). IEEE 802.15.3d: First standardization efforts for sub-Terahertz band communications toward 6G. *IEEE Communications Magazine, 58*(11), 28–33. https://doi.org/10.1109/mcom.001.2000273

Priebe, S., & Kürner, T. (2013). Stochastic modeling of THz indoor radio channels. *IEEE Transactions on Wireless Communications, 12*(9), 4445–4455. https://doi.org/10.1109/twc.2013.072313.121581

Pratschner, S., Tahir, B., Marjani, L., Mussbah, M., Kirev, K., Nissel, R., et al. (2018). Versatile mobile communications simulation: The Vienna 5G link level simulator. *EURASIP Journal on Wireless Communications and Networking, 2018*(1), 226. https://doi.org/10.1186/s13638-018-1239-6

Rommel, S., Raddo, T. R., & Monroy, I. T. (2018). Data center connectivity by 6G wireless systems. In *2018 photonics in switching and computing (PSC)* (pp. 1–3). IEEE.

Rose, D. M., Baumgarten, J., Hahn, S., & Kürner, T. (2015). SiMoNe - simulator for mobile networks: System-level simulations in the context of realistic scenarios. In *2015 IEEE 81st vehicular technology conference (VTC spring)* (pp. 1–7). IEEE.

Samsung Research. (2020). *6G: The next hyper-connected experience for all (White Paper)*. Samsung Electronics Co., Ltd.

Sengupta, K., Nagatsuma, T., & Mittleman, D. M. (2018). Terahertz integrated electronic and hybrid electronic–photonic systems. *Nature Electronics, 1*, 622–635. https://doi.org/10.1038/s41928-018-0173-2

Sha, Z., & Wang, Z. (2021). Channel estimation and equalization for terahertz receiver with RF impairments. *IEEE Journal on Selected Areas in Communications, 39*(6), 1621–1635. https://doi.org/10.1109/jasc.2021.3071824

Tan, J., & Dai, L. (2021). Wideband beam tracking in THz massive MIMO systems. *IEEE Journal on Selected Areas in Communications, 39*(6), 1693–1710. https://doi.org/10.1109/jasc.2021.3071817

Tataria, H., Shafi, M., Molisch, A. F., Dohler, M., Sjöland, H., & Tufvesson, F. (2021). 6G wireless systems: Vision, requirements, challenges, insights, and opportunities. *Proceedings of the IEEE, 109*(7), 1166–1199. https://doi.org/10.1109/jproc.2021.3061701