Ref. Ares(2022)5046642 - 11/07/2022

Horizon 2020 Grant Agreement no: 814523

Terahertz end-to-end wireless systems supporting ultra-high data Rate applications

ThoR

Deliverable D6.5

Software Simulation Results (DEMO – 4)

Coordinator (EU): Thomas Kürner
Organisation: Technische Universität Braunschweig

Coordinator (Japan): Tetsuya Kawanishi
Organisation: Waseda University

Start date of project: 01-Jul-2018

Date of issue: 20-06-2022
Due date: 31-03-2022
ThoR Ref:
ThoR_TUBS_2021117_E_WP6

Leader in charge of deliverable: Bo Kum Jung
TU Braunschweig

Project co-funded by the European Commission within the Horizon 2020 programme and the National Institute of Information and Communications Technology in Japan (NICT)		
Dissemination level		
PU	**Public**	**X**
PP	**Restricted to other programme participants (including the Commission Services)**	
RE	**Restricted to a group specified by the consortium (including the Commission Services)**	
CO	**Confidential, only for members of the consortium (including the Commission Services)**	

Contents

1. **STATEMENT OF INDEPENDENCE** 3
2. **ABBREVIATIONS** 3
3. **EXECUTIVE SUMMARY** 4
4. **INTRODUCTION** 5
5. **SIMULATION SCENARIOS FOR DEMO-4** 7
6. **DEMONSTRATION OF SYSTEM LEVEL SIMULATION** 11
7. **DEMONSTRATION OF LINK LEVEL SIMULATION** 16
   7.1. Concept of Link Level Simulations 16
   7.2. Network Link Level Simulations 16
   7.3. Relay Simulations for Multicarrier Scalability 19
8. **CONCLUSION** 24
9. **REFERENCES** 25

Change register

Version	Date	Author	Organisation	Changes
A	17-11-2021	Jung	TUBS	First draft, added structure and system level simulation
B	01-06-2022	Eckhardt	TUBS	Editing of link level simulation parts
C	05-06-2022	Herold/ Eckhardt	TUBS	Adding simulation results
D	09-06-2022	Eckhardt	TUBS	Final draft
E	20-06-2022	Jung	TUBS	Final version

Reviewed by Akihiko Hirata Chiba Institute of Technology E 20-06-2022

1. Statement of independence

The work described in this document is genuinely a result of efforts pertaining to the ThoR project. Any external source is properly referenced.

Confirmation by Authors:	Bo Kum Jung	TU Braunschweig
	Christoph Herold	TU Braunschweig
	Johannes M. Eckhardt	TU Braunschweig

2. Abbreviations

AWGN	Additive white Gaussian noise
BER	Bit error rate
CCDF	Complementary cumulative density function
CDF	Cumulative density function
CIR	Channel impulse response
FDM	Frequency division multiplex
ICI	Inter-carrier interference
ISI	Inter-symbol interference
KPI	Key performance indicator
LLS	Link level simulation
MCS	Modulation and coding scheme
MPC	Multipath component
PSD	Power spectral density
RF	Radio frequency
RX	Receiver
SINR	Signal-to-interference-plus-noise ratio
SNR	Signal-to-noise ratio
SLS	System level simulation
TX	Transmitter

3. Executive summary

This deliverable provides the simulation results of the software demonstration (DEMO-4) with respect to the link-level simulation (LLS), as well as system-level simulation (SLS). Through DEMO-4, the scalability of IEEE Standard 802.15.3d will be proven by taking into account the experimentally obtained characteristics of the wireless communication system including radio frequency (RF) impairments.

4. Introduction

On behalf of ThoR project, totally four demonstrations as seen in Figure 1 are outlined to show the feasibility of the wireless transmission utilizing carrier frequency at 300 GHz, so called THz frequency spectrum range, over more than hundreds meters. Unlikely the others, the final demonstration (DEMO-4) is explicitly planned to a fully software based simulation in terms of the system level's and the link level's point of view within a tool simultaneously. By doing this, the scalability of IEEE Standard 802.15.3d into the new concept of the wireless communication system will be proven to provide over 100 Gbit/s data rate considering the measured characteristics of the entire system including RF impairments and phase noise.

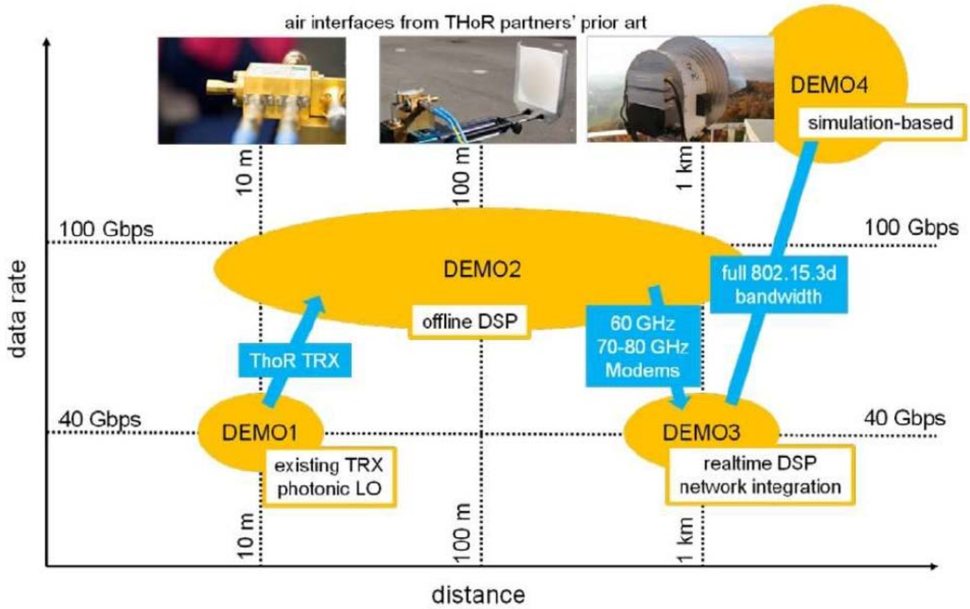

Figure 1: Demonstratopm concept of ThoR project

To achieve this goal, the software simulation (DEMO-4) are completed incorporating with two methodology, namely LLS and SLS. In general, both LLS and SLS are individually considered depending on the focus (e.g., if the target is to check the signal-to-interference-plus-noise ratio (SINR) values of the entire network then only SLS is interested), even though both results are clearly correlated and can synergize to comprehend the competence of the communication system. Therefore, a solid simulation tool has been developed on behalf of ThoR, which draws and visualizes the simulation results combining LLS and SLS together. This coupling concept of LLS and SLS is completed in such a way that the channel impulse response (CIR) of the network generated by SLS is used for an essential input data to run LLS.

SLS provides the possibility to check the performance of the entire mobile network, which is THz backhaul links. To draw the reliable simulation results corresponding to the actual propagation consequence, a realistic simulation scenario considering environmental information, 3D antenna diagram and propagation properties is used. As a results of SLS, multiple types of outcomes such as CIR and received power level can be generated. By post processing received power levels, SINR values of each links within the entire network is possible to achieve which gives the insight of the network's channel quality.

While SLS focus on the channel property of the entire network, LLS rather concentrates on channel states of a targeted single link, where the channel states can be evaluated through the use of multiple key performance indicators (KPIs) incorporating with Monte-Carlo-Simulations. To complete this task, LLS initiates the simulation process with the use of the target link's CIR as an initial input that is outcome from SLS and it applies various coding and modulation schemes defined in IEEE Standard 802.15.3d while considering the hardware impairments of the system that can be mathematically approximated based on the measured characteristics of the used devices. Once the simulation is completed, diverse indicators in form of statistical numbers and visual aids including bit error rate, eye diagram and I/Q imbalance can be drawn to instruct the channel state.

In DEMO-4, both SLS and LLS results is visualized simultaneously within a common frame. It will be provisionally seen as shown in Figure 2, where the results of SLS such as SINR values of THz links will be visualized within a map including building information. The LLS results will be instantly triggered to display once a certain THz link is chosen by user, in which bit error rate (BER), error vector magnitude (EVM), eye diagram, achievable data rate and any other results pop up on the side to indicate the channel quality of the chosen THz link

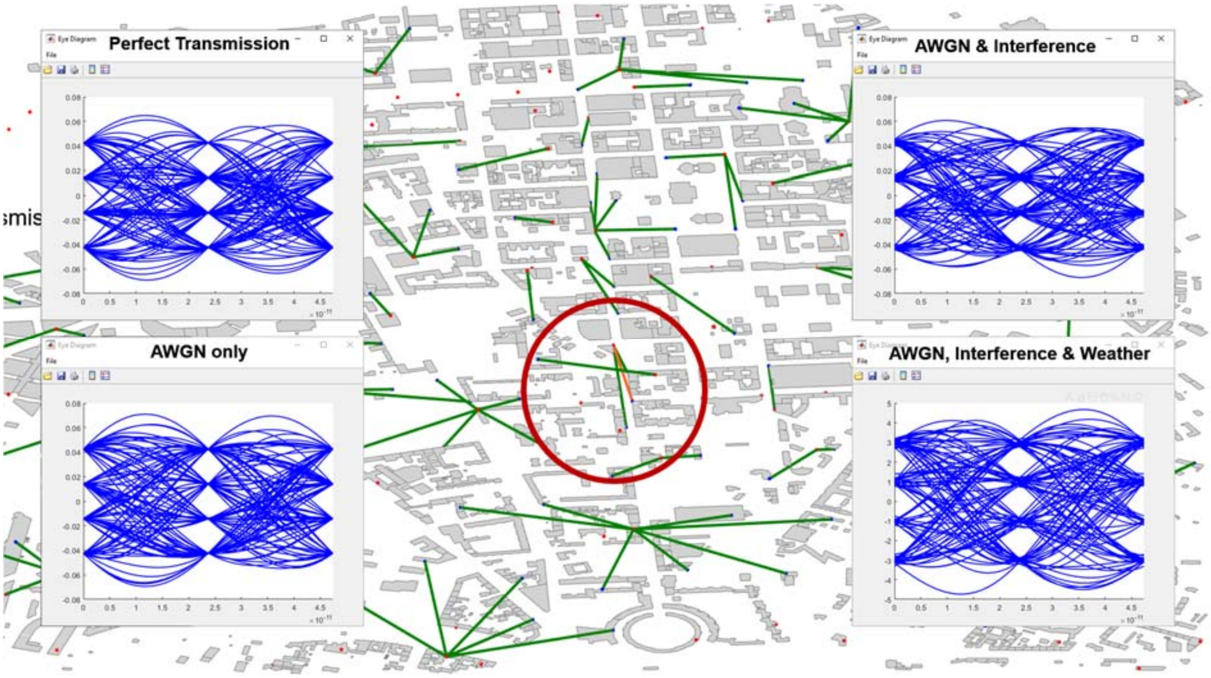

Figure 2: Mock-up of the software demonstrator.

5. Simulation Scenarios for DEMO-4

Within DEMO-4, two scenarios covering mobile data transmission with carrier frequency at 300 GHz are considered and their system's performance will be investigated in terms of at the system level, as well as link level.

One scenario is a typical cellular network case defined in [6], where the backhaul links of the base stations are planned to feed in hybrid modus by both cables and THz links. It covers the traffic hungry area in the middle of Berlin, where sightseeing attractions, shopping promenades, business and residential areas are located and thus the numerous traffics of pedestrians, inhabitants and commuters through days and nights are expected. In Figure 3, the sketch of the scenario in the middle of Berlin (2.5 km x 2.5 km) is visualized, where the locations of the fixed base stations in this scenario are categorized in two types: macro cell site and small cell site. Totally 62 macro cell sites can be found, which are represented by red dots and these serve to cover the mobile network while whose backhaul links are provided via fibre. Their locations are artificially modified while protecting statistical properties on the basis of the antenna deployment data provided by Deutsche Telekom AG. On the contrary to this, no statistical facts are applied to arrange the locations of small cell sites. They were determined in accordance with the internal design rule based on a certain random process. In total, 176 small cell sites are considered to implement for the mobile access with high data rate that are visualized as black dots in Figure 3, whose backhaul links are not determined yet neither via fibre nor via wireless option. A half of them is regarded to implement at the rooftop of the buildings while the other half is regarded as a lamp site case.

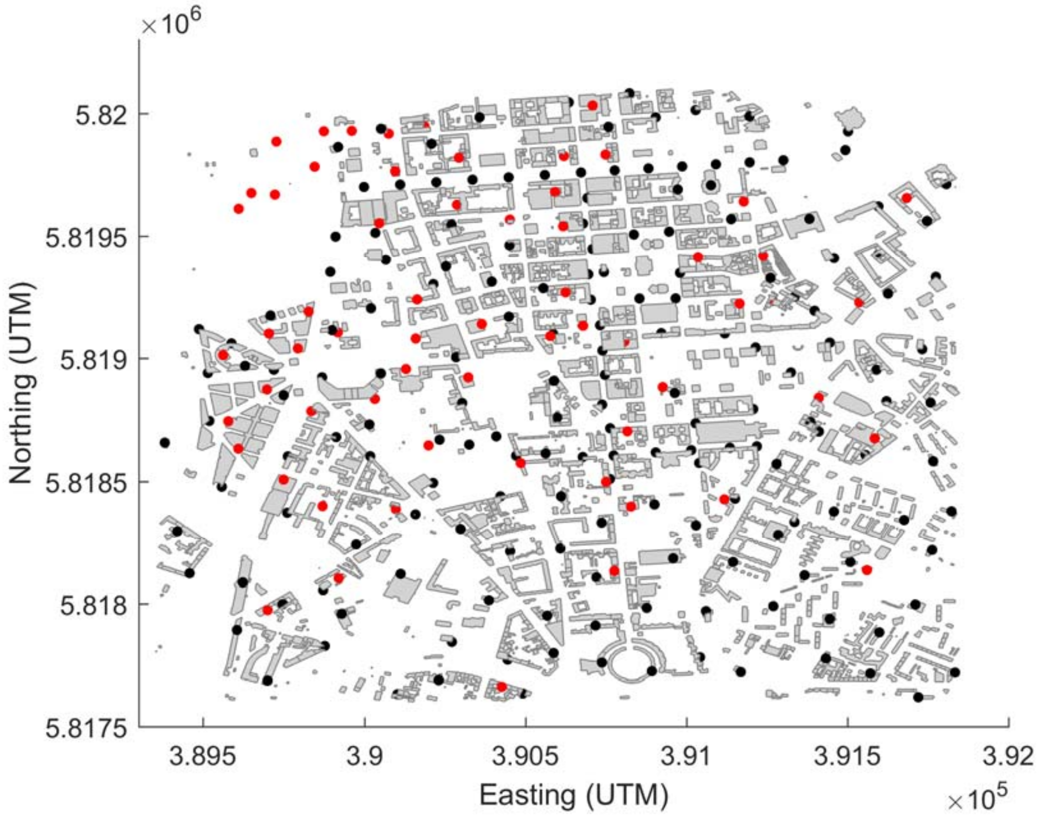

Figure 3: A sketch of the simulation scenario to cover the mobile network in the middle of Berlin (2.5 km x 2.5 km) including macro cell sites (red) and small cell sites (black).

The other scenario represents a special data transportation scenario that requires high data traffic exclusively between two access points whose communication channel can be established either directly or via multi-hobs according to the demand of the required data rate. For this, Messe Berlin and Olympic stadium are assumed as the access points where the high data transmission should be supported via THz link for a live broadcast of such an international football match. Figure 4 represents the corresponding sketch of the simulation scenario that the goal of this is to transport data with the high volume from Olympic stadium to Messe, and vice versa whose link distance amounts to nearly 2197 m (blue line in Figure 4). In this case, a wireless communication via a direct path is a challenging task abiding by the transmission's regulations since the state of art wireless communication system does not successfully operate between two access points whose straight line distance exceeds two kilometres. Thus, the data transmission will be performed favourably via three hops with additional two distinct relay points (relay 1 and relay 2) to mitigate too long link distance (green line in Figure 4). The link distances of the transmission paths are given in Table 1.

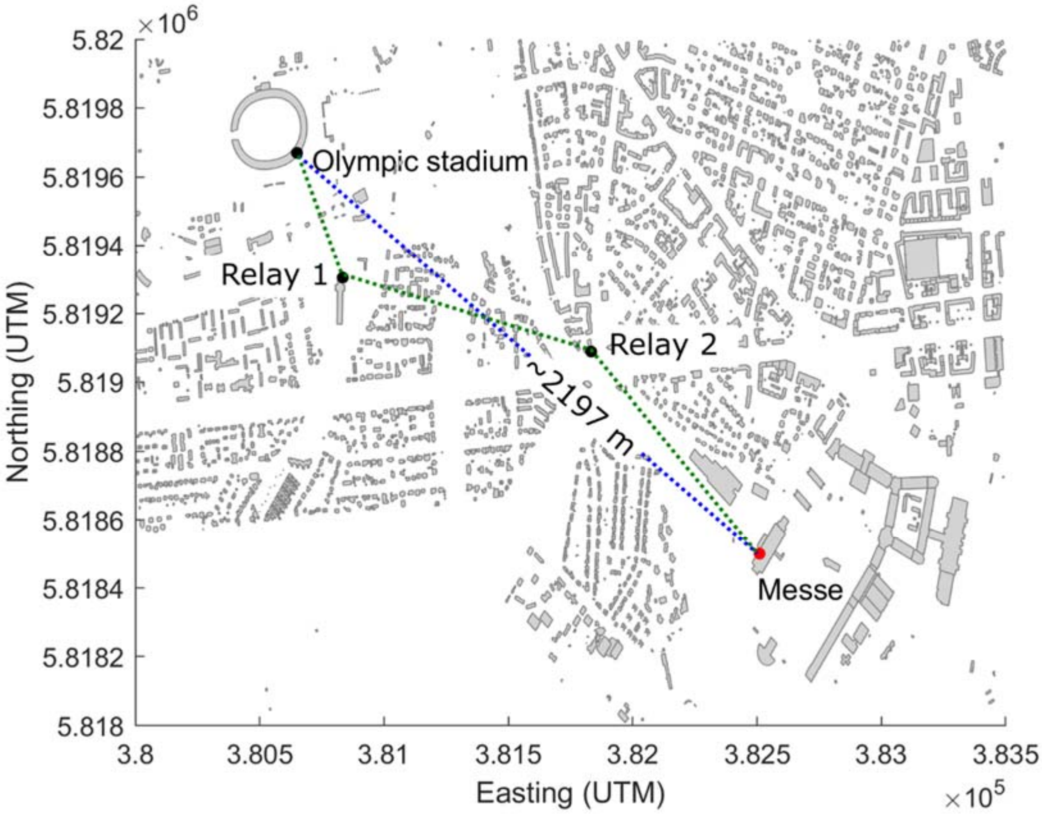

Figure 4: A sketch of the simulation scenario for a data transmission with a high volume between two access points via relay points.

Table 1: Link distance of the transmission paths

Transmission path	Link distance in m
Olympic stadium ↔ Relay 1	409.72
Relay 1 ↔ Relay 2	1023.01
Relay 2 ↔ Messe	897.36

For achieve the real-like simulation results, a 3D radiation pattern of antenna is taken into account for the simulation process whose value is mapped on the propagation prediction results considering the angle of arrival, as well as the angle of departure of the rays. For DEMO 4, a Cassegrain reflector antenna with 48 dBi antenna gain is assumed both at transmitter (TX) and receiver (RX).

The equivalent far-filed 3D radiation pattern of the antenna is visualized in Figure 5 (left). The given radiation pattern is so called a semi-measurement value since the far-filed radiation pattern is not a directly measured value but it is mathematically converted from a near-field measurement value using Fourier transform that is provided by Gifu university [2]. The measurement is completed only for the frontal part of the antenna since it is Cassegrain reflector antenna with high antenna gain so that the backwards radiation pattern may not be interesting or comparably small to neglect. Therefore, the backwards radiation pattern of the antenna is assumed as the same value of the lowest value from the measurement.

As it is apparently identifiable in Figure 5 (left), the centre of antenna is pointing the angles at zero theta and zero phi. The basic coordinates used for the simulations are illustrated in in Figure 5 (right). Here, the theta describes the elevation angles where the positive sign means downwards direction up to 90° (bottom) on the basis of the antenna's centre while the negative sign means upwards direction up to -90° (top). The phi describes the azimuth angles where the positive sign describes clockwise rotation on the basis of the positive y axis (north) in Figure 5 (right) while the negative sign describes counter clockwise rotation. This means that 180° of phi corresponds to the negative y axis, which is valid exactly same for -180° of phi.

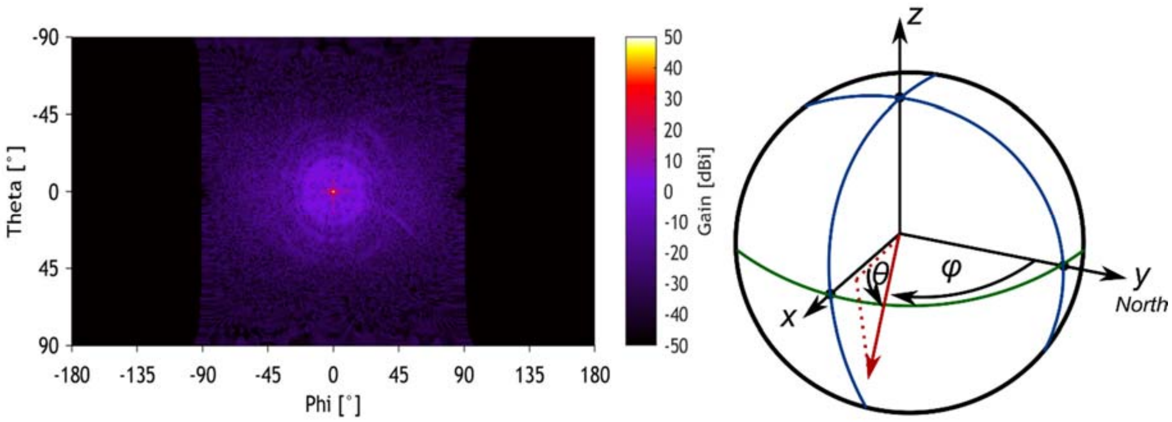

Figure 5: Radiation pattern of the Cassegrain reflector antenna with 48 dBi gain (left), the basic coordinates of the simulation (right).

Apart from the 3D radiation pattern, both simulation scenarios share the identical hardware parameters and they are provided in Table 2.

Table 2: Hardware parameters for simulations.

Parameter	Value
RF centre frequency	300 GHz
Transmission power	0 dBm
Tx antenna gain	48 dBi
Rx antenna gain	48 dBi
Rx antenna noise temperature	290 K

6. Demonstration of System Level Simulation

To do the system level simulation in terms of seeing the feasibility of the THz backhaul links within the mobile network, the backhaul links of the entire mobile network should be firstly designed. This is accomplished by the automatic algorithm based on the star topology [5] that has been developed by TUBS. Determining a networking solution is a non-deterministic polynomial problem. Furthermore, the given automatic planning algorithm contains certain random decision stages. Therefore, finding a global optimum solution of the wireless backhaul network requires enormous computational effort using heuristic way. Thus, a practical solution to find a local optimum solution is to do the simulation iterative. The total iteration number of algorithm is set to 10.000 times and the best planning result (i.e., the optimization factor is set to provide as possible as many THz backhaul links) is visualized in Figure 6, where the red dots represent the cell sites that require backhaul links via fibre option, while the blue dots represent the cell sites whose backhaul links can be wireless provided via one hop by cell sites with fibre backhaul links (red dots). Here, each THz link is visualized in the green line between cell sites.

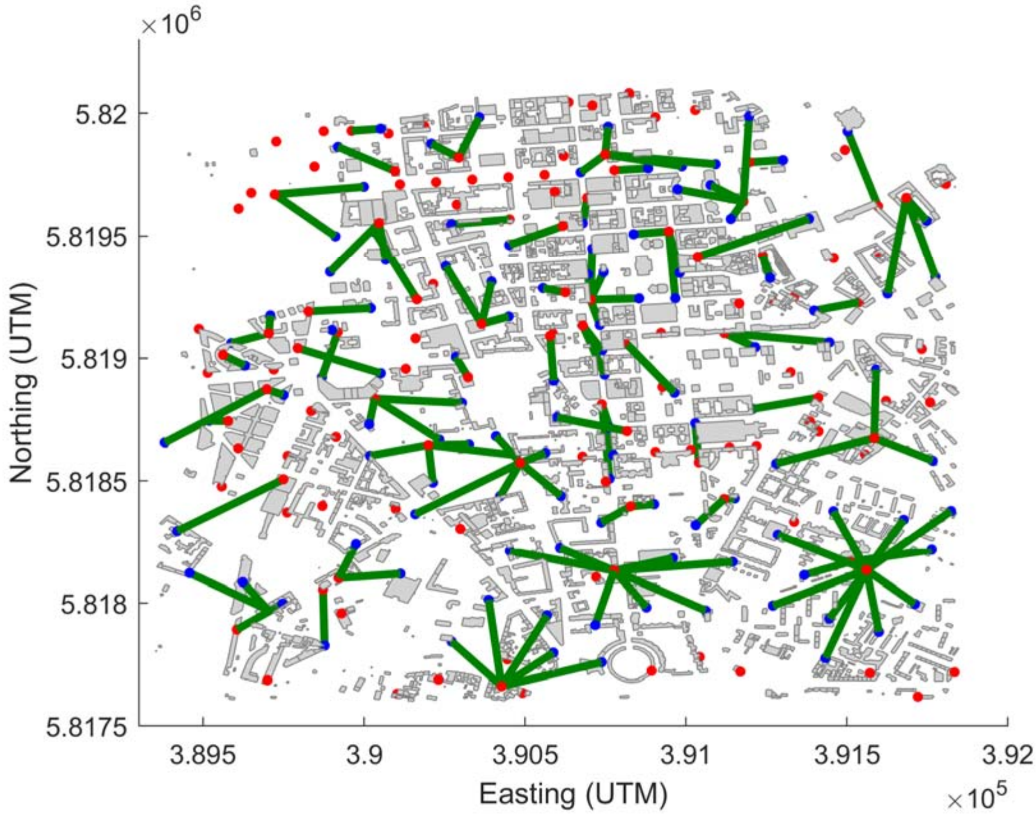

Figure 6: A sketch of the hybrid backhaul network with THz links (green lines) in the middle of Berlin including cell sites with fibre backhaul (red dots) and with wireless backhaul (blue dots).

Using the automatic planning algorithm, 113 cell sites from 176 SCSs are feasible to replace fibre backhaul links with THz links that amounts to around 64 % of the required backhaul links. This is to say that extra 113 THz links and 63 fibre connections are required to serve the backhaul network in the entire area of the simulation scenario.

Four different SLSs taking into account for distinctive configurations have been conducted for the performance assessment of the automatic planning algorithm, as well as for verifying the feasibility of the THz backhaul links within the mobile network.

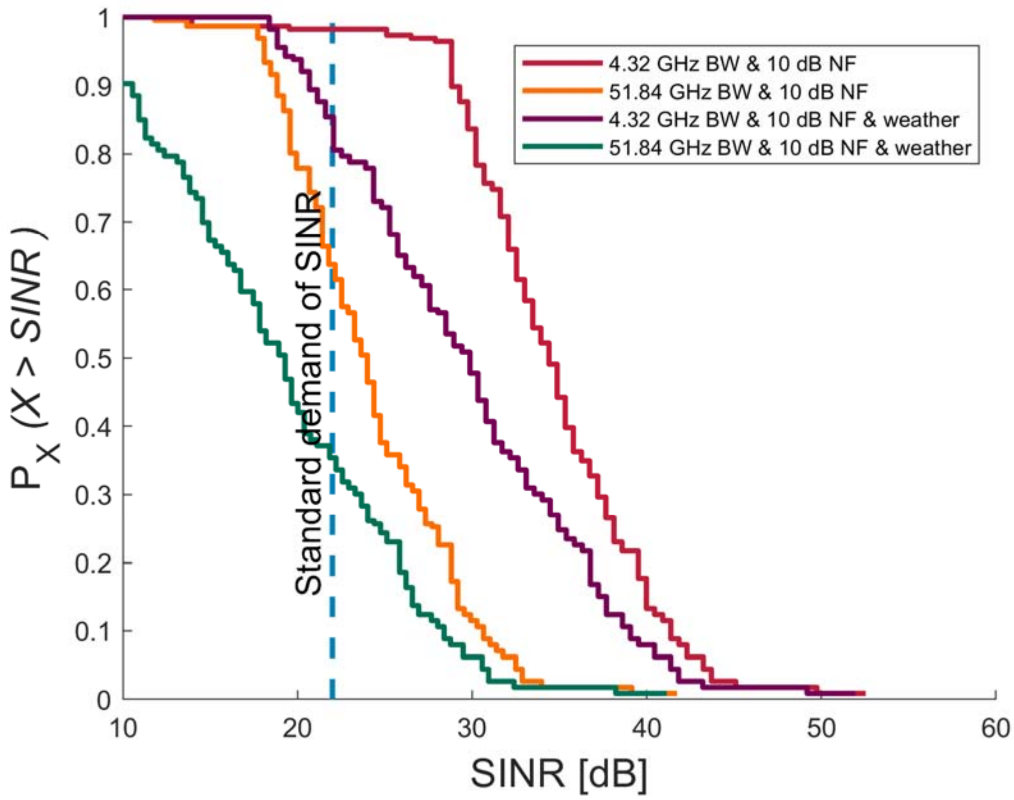

Figure 7: SINR values of the THz backhaul links considering two transmission bandwidth (4.32 and 51.84 GHz) with extra 10 dB noise figure and weather condition based on the automatically planned network in the middle of Berlin scenario.

Figure 7 shows the SINR values of the THz links resulted by SLSs with four diverse configurations which are classified by the transmission bandwidth and the influence of the weather condition. Here, the bandwidth serves to determine the mathematical thermal noise generated by the electrical circuits of system's hardware. The mobile transmission with larger bandwidth produces larger value of thermal noise. Out of the thermal noise, noise figure is additionally assumed as 10 dB that is generated by the electrical circuits of the entire system. For investigating the influence of the weather condition, the weather condition is set as the worst weather condition (i.e., the highest attenuation) measured within the last 25 years whose indicators correspond to 1008,5 hPa air pressure, 31,7 $\mathrm{mm/h}$ rain rate, 18,3 $°\mathrm{C}$ temperature and 15.32 $\mathrm{g/m^3}$ watervapour density. The corresponding data is public accessible and provided by the Deutscher Wetterdienst (DWD).

The red and orange curves represent the SINR values that are derived by taking into account for the wave propagation of only theoretical free space path loss with 4.32 GHz and 51.84 GHz bandwidth respectively, while the violet and green curves consider the additional attenuation at wave propagation figured by using the given weather indicators. A horizontal strip line positioned at 22 dB refers to the standard demand of SINR which is a threshold value for the use of the highest modulation and coding scheme (64 QAM and 14/15 FEC) defined in [3].

According to the simulation results, 1.77 % of the THz links (four links) in case of using 4.32 GHz bandwidth without considering weather impact do not exceed 22 dB while 18.58 % (42 links) of links using larger bandwidth with 51.85 GHz do not exceed this value. Once the weather condition is considered to evaluate SINR value, less links become exceed 22 dB. 37.16 % of links with 4.32 GHz bandwidth considering weather condition do not exceed the given value while 64.6 % using 51.84 GHz bandwidth.

However this does not indicate that the planned THz links go suddenly link failure as soon as whose SINR values are inferior to 22 dB. Those links will however operate normally with use of the reduced modulation and coding scheme unless the link's SINR value goes considerably bad so that the reliable wireless communication is not feasible at all.

In DEMO-4, it is also planned to show the possibility of data transmission with massive volume within a single transmission route, where the low data traffic is anticipated an ordinary day but some events that attract public attention are occasionally held in this area. This leads to the demand of the infrastructure that can support the data transmission with high volume only for special event cases such as broadcasting of FIFA World Cup soccer matches that requiring huge transmission capacity. For this, a transmission route is assumed as between two access points: Olympic stadium where the backhaul link should be provided and Messe Berlin where the backhaul link is previously set up with secured large capacity.

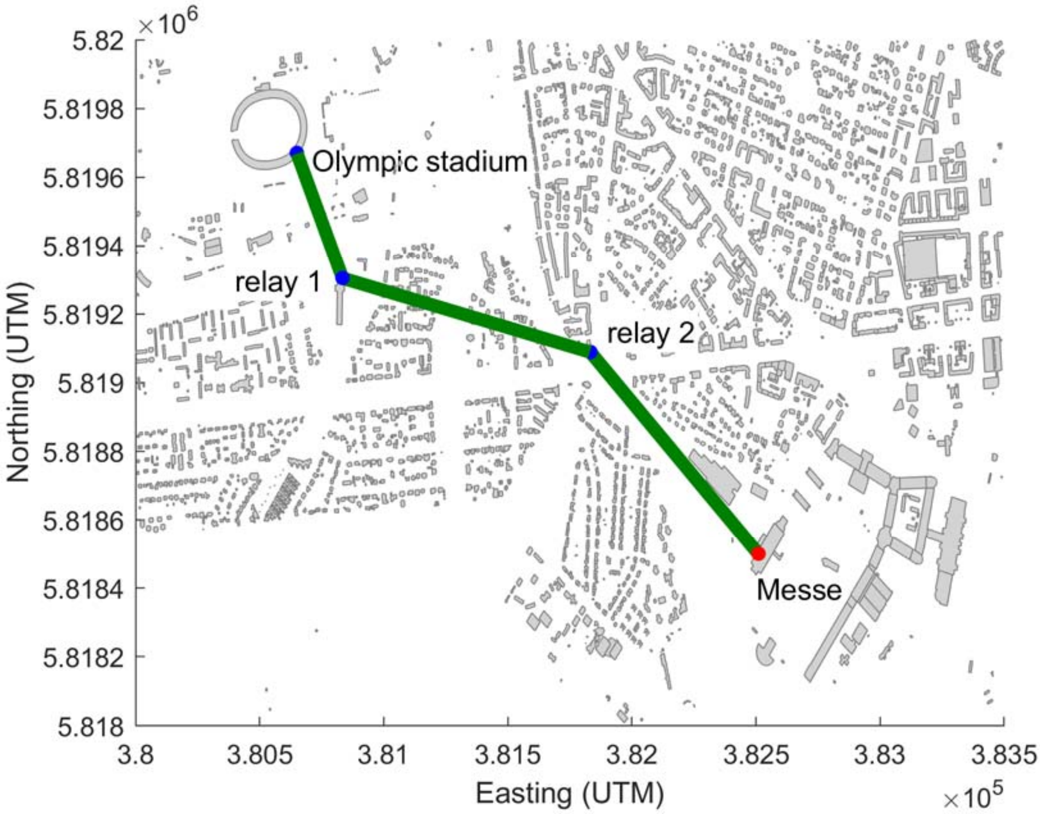

Figure 8: A sketch of the THz links in Berlin for high volume data transmission between two access points assisted by two relay points.

In Figure 8, an overview of the THz transmission scenario with large volume is visualized, where the red point represents the cell site of Messe Berlin with the fibre backhaul link, while the blue points represent the cell sites including Olympic stadium that require THz backhaul links provided by Messe Berlin. A direct transmission route between the Olympic stadium and Messe Berlin limits its applicable modulation and coding scheme due to long distance around 2197 m and thus low achievable data rate is resulted, which is not fulfilling the purpose of wireless communication at THz frequencies (i.e., Short range wireless communication enabling high data transmission). This is the reason why two additional relay points labelled with relay 1 and relay 2 are considered to enable relaying data transport with high volume between Olympic stadium and Messe Berlin. All of access/relay points are positioned top of the each buildings and possessing the LoS condition. The corresponding THz links between each of access/relay points are visualized as green lines in Figure 8.

The SINR values [dB] of the relay scenario's THz links depending on the bandwidths and impact of the weather are given in Table 3, where standard weather denotes the standard weather condition defined in [4] (1013,25 hPa air pressure, 15 $°\mathrm{C}$ temperature and 7.5 $\mathrm{g/m^3}$ watervapour density) and extreme weather denotes an extreme weather conditions in this area within last 25 years (i.e., 1008,5 hPa air pressure, 31,7 $\mathrm{mm/h}$ rain rate, 18,3 $°\mathrm{C}$ temperature and 15.32 $\mathrm{g/m^3}$ watervapour density).

Table 3: SINR values in dB of THz backhaul links for high data transmission via multi relay points considering bandwidths and weather conditions.

	Olympic stadium ↕ (~409 m) relay 1	relay 1 ↕ (~1023 m) relay 2	relay 2 ↕ (~897 m) Messe
Standard weather with 4.32 GHz bandwidth & 10 dB noise figure	26	14.9	16.6
Standard weather with 51.84 GHz bandwidth & 10 dB noise figure	15.2	4.1	5.8
Extreme weather 4.32 GHz bandwidth & 10 dB noise figure	17.4	-6.4	-2.0
Extreme weather 51.84 GHz bandwidth & 10 dB noise figure	6.6	-17.2	-12.9

The simulation results show that data transmission with the highest modulation and coding scheme (≥ 22 dB) is only feasible at the link between Olympic stadium and relay 1 under the standard weather condition using 4.32 GHz bandwidth. While the other links will be operated with the comparably reduced modulation and coding scheme. In case of the extreme weather condition, a THz link between Olympic stadium and relay 1 is expected to transmit high data while the other links potentially do not support the high volume data transmission due to low SINR values.

A remarkable point to perceive in Table 3 is that the difference of SINR values between distinct bandwidths is almost exactly 10.8 dB (i.e., A very first different value is noticed at 10^{-14} decimal point in linear scale that is negligible magnitude in dB scale), which indicates that the thermal noise dominates interference signals since the interference between THz links is previously regulated by avoiding the in-line alignment of the THz links. This means, the SINR values of THz links are exclusively determined by the received power of the signal and the thermal noise.

To achieve required SINR values for the seamless high volume data transmission under the extreme weather condition, an additional remedy is compulsory. Needless to say, amplifying transmission power yields the increased received power of the signal which results consequently advanced gain of SINR values. The amplification of TX power should be however done with caution since it can violate the local regulation, as well as global regulation.

Another way to increase SINR value is to arrange more relay points. As the data transmission is done via more relay points, statistically the distance of each THz links is decreased. This is but only when the positions of the relay points are cogently chosen. The attenuation grad of the wave propagation is positive correlated with the link distance. This means that more attenuation is expected at the link with farther distance than at the one with closer distance, which leads consequently high received power of the signal. As a consequence, SINR values of the THz links are potentially improved. Therefore, the positions of the relay points should be considerably selected to ensure the stable operation of the data transmission via THz links.

7. Demonstration of Link Level Simulation

7.1. Concept of Link Level Simulations

Link level simulations (LLSs) model the transmission of information over a single link from a transmitter (TX) to a receiver (RX). Compared to system level simulations that examine multiple links and their interaction, the LLS models the physical layer in a highly detailed manner in order to predict the link performance via the BER and the data rate.

The link level simulator in SiMoNe is based on a modular block concept. A block encloses dedicated functionalities such as bit generation, encoding, modulation etc. Figure 9 illustrates the main building blocks. The basic concept, validation and the influence of RF hardware characteristics are described in [1].

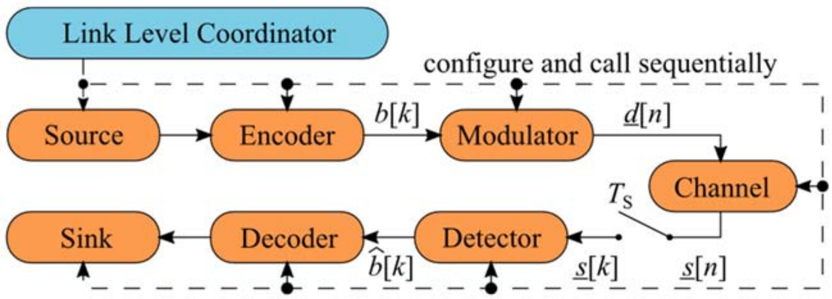

Figure 9: Schematic overview of the link level simulator in SiMoNe [1].

To simulate the backhaul links, we made use of existing models in SiMoNe that were developed within the H2020 Terapod project. However, a major redesign of the configuration of the blocks was done in ThoR as well as a significant extension for multi-carrier systems. In addition, the simulator was enhanced by an import option of configuration parameters from a csv file that allows for an effective processing of multiple simulations with different configuration parameters in a batch execution mode. This enables the link level simulations of a whole backhaul network with different characteristics as presented in Section 7.2

In order to realize the simulation of fully independent links in a multi-carrier frequency division multiplex (FDM) system, a concept of parallel blocks was implemented that is described in Section 7.3

7.2. Network Link Level Simulations

The usage of LLSs allows for the evaluation of a backhaul networks performance under various circumstances without extensive field testing. Using SiMoNe's Link Level Simulation module, realistic link characterizations are possible providing KPIs such as RX power, BER, data rate and goodput.

For this evaluation process, several previous steps have to be executed. Based on LLSs simulating a transmission over an additive white Gaussian noise (AWGN) channel, the expected BER of a backhaul link without inter-symbol interference (ISI) for various modulation and coding schemes (MCSs) is estimated. Figure 10 shows the BER as a function of the signal-to-noise ratio (SNR). Here, the MCSs are compared based on the SNR rather than the most commonly used bit energy per noise power spectral density (PSD) E_b/N_0 because the SNR is given by the scenario whereas the E_b/N_0 varies as a function of the MCS. Therefore, the E_b/N_0 is not an appropriate quantity for an MCS selection. Based on the given results, an SNR – MCS mapping is implemented such that the MCS with the highest effective data rate is chosen that provides a BER below 10^{-7}. For the network simulations, the selected MCS mapping is shown in Table 4.

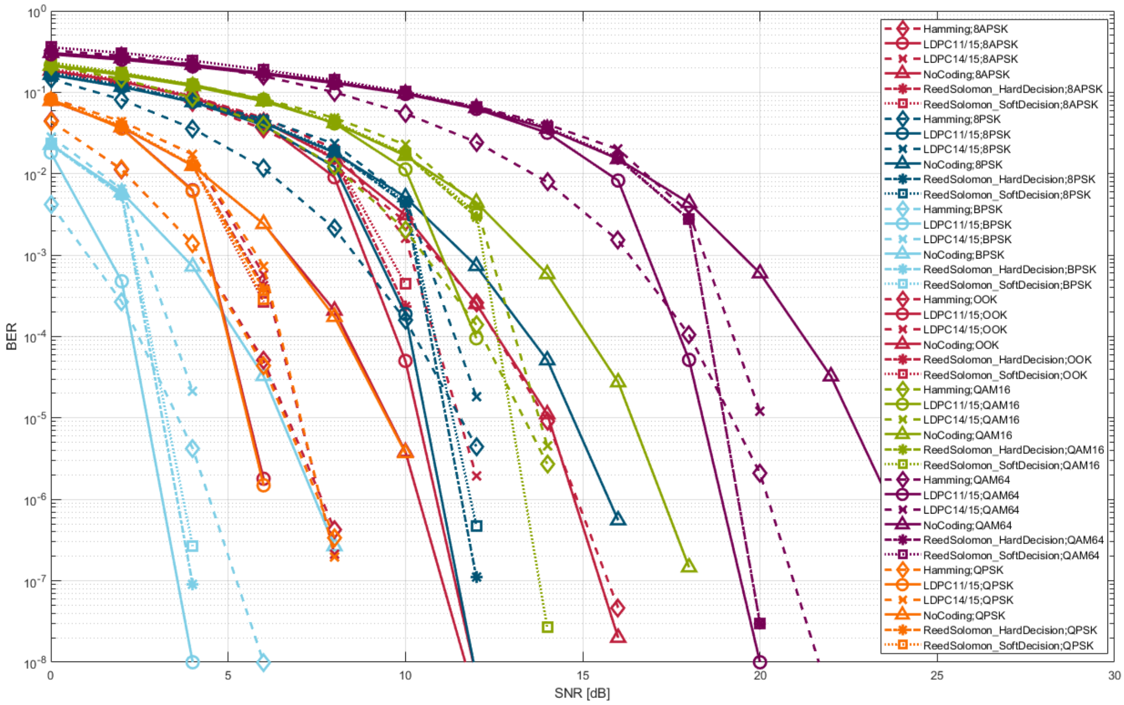

Figure 10: BER of an AWGN simulation for various MCSs.

Table 4: SINR to MCS mapping.

SINR	MCS
< 2.2 dB	BPSK, Hamming
< 5 dB	BPSK, LDPC11/15
< 7 dB	BPSK, LDPC14/15
< 9 dB	QPSK, LDPC11/15
< 12 dB	QPSK, LDPC14/15
< 14 dB	8-APSK, LDPC11/15
< 16 dB	16-QAM, LDPC11/15
< 20 dB	16-QAM, LDPC14/15
< 22 dB	64-QAM, LDPC11/15
< 28 dB	64-QAM, LDPC14/15
> 28 dB	64-QAM without coding

In the next step, channel impulse responses have to be extracted from the ray-tracing results of the backhaul network simulation [7]. The multipath components (MPCs) of each backhaul link are stored together with the RX power and the interference power of the respective link. The associated thermal noise for a channel bandwidth of 4.32 GHz and 51.84 GHz taking a noise figure of 10 dB into account is added to the interference power leading to the resulting SINR shown in Figure 7. Note that the LLS models the interference as AWGN for reasons of reduced computational effort representing a good first order approach.

Based on the previously performed SNR- MCS mapping, the resulting E_b/N_0 values in the network scenario are presented as a complementary cumulative density function (CCDF) in Figure 11. The conditions vary a lot for the four examined scenarios: For a channel bandwidth of 4.32 GHz and a symbol rate of 3.52 GBd without weather phenomena 97 % of all links (dark blue dotted curve) have an E_b/N_0 higher than 22 dB. This value reduces to 62 % if extreme weather phenomena are taken into account (orange dashed curve). Regarding the case with larger bandwidth and without weather phenomena, the E_b/N_0 reduces again to 31 % of all links (red dot-dashed curve) that assure an SINR of 22 dB. Since the curve meets the case with small bandwidth at P = 0.9867, we can derive that only 1.33 % of the links are dominated by interference

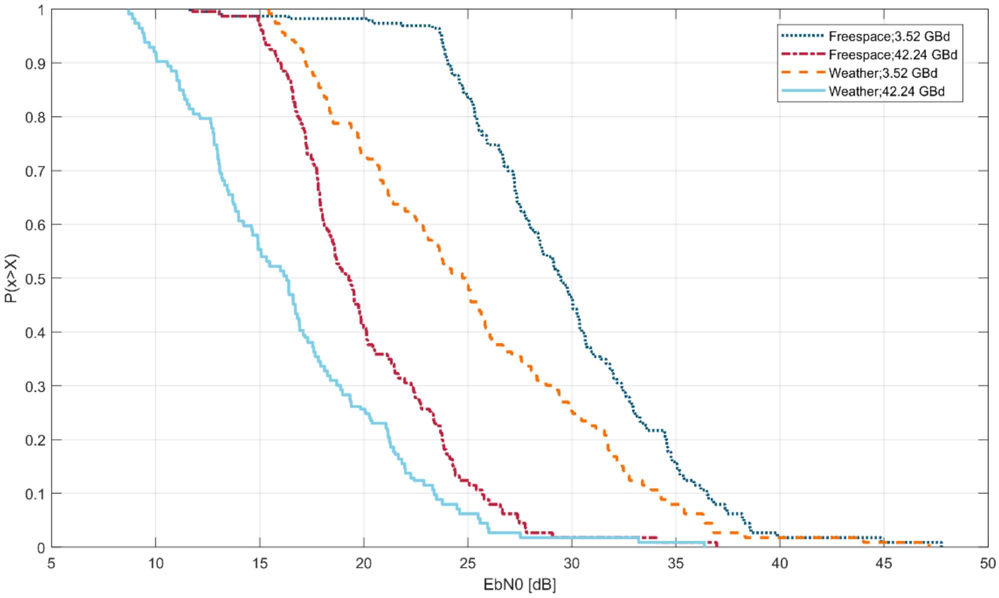

Figure 11: CCDF of the bit energy per noise PSD of the backhaul network.

Regarding the cumulative distribution function (CDF) of the BER in Figure 12, we notice a constant level of all four cases from $3 \cdot 10^{-7}$ to $1 \cdot 10^{-4}$. If we interpret this zone as a threshold for a successful link classification, 78.76 %, 83.19 %, 53.1 % and 73.01 % of the links provide a successful transmission in the free-space scenario with small bandwidth, the weather scenario with small bandwidth, the free-space scenario with high bandwidth and the weather scenario with high bandwidth, respectively. Since we expect only BERs lower than $1 \cdot 10^{-7}$ due to the SINR – MCS mapping, the resulting BER curves might be surprising. Especially the fact that the scenarios with extreme weather conditions perform better than the free-space scenario. However, there are two aspects that need to be considered in the evaluation and provide a possible explanation. First, the SINR does not account for inter-symbol interference (ISI) that may be an additional source of misinterpreted symbols. Second, the links in the free-space scenario are mapped to higher MCSs and provide a higher effective data rate as shown in Figure 13.

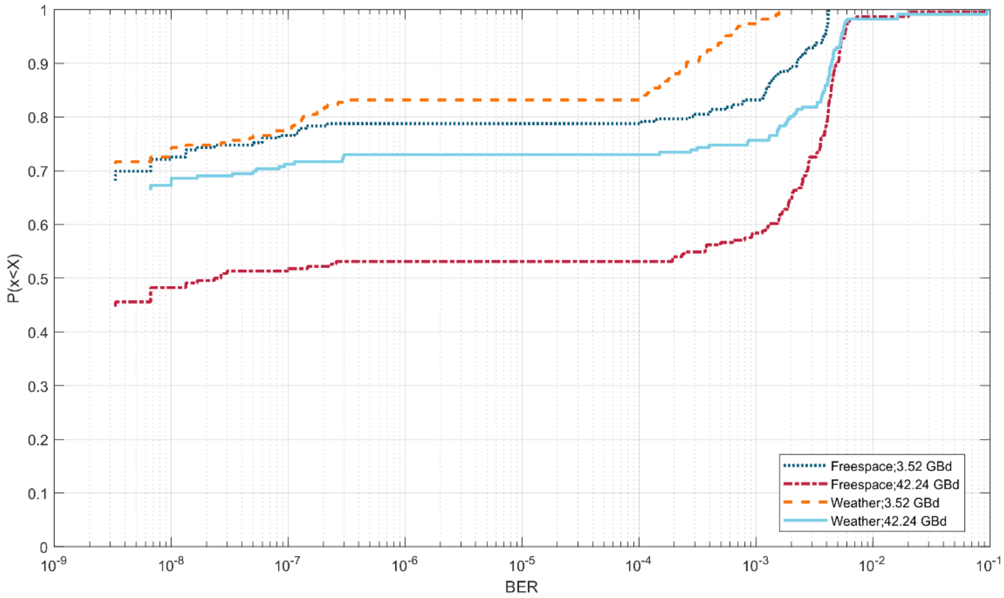

Figure 12: CDF of the BER of the backhaul network.

Based on the given SINR-MCS mapping 96.46 %, 56.64 %, 77.88 % and 42.04 % of the links achieve the maximum effective data rate in the in the free-space scenario with small bandwidth, the weather scenario with small bandwidth, the free-space scenario with high bandwidth and the weather scenario with high bandwidth, respectively. We expect that the adaption of the SINR-MCS mapping would improve the link performances by reducing the effective data rate only in a marginal way. Since the links are more reliable in the extreme weather scenario, the MCS selection might also be expanded to 128-QAM with forward error correction instead of using a 64-QAM without coding to tackle the influence of ISI.

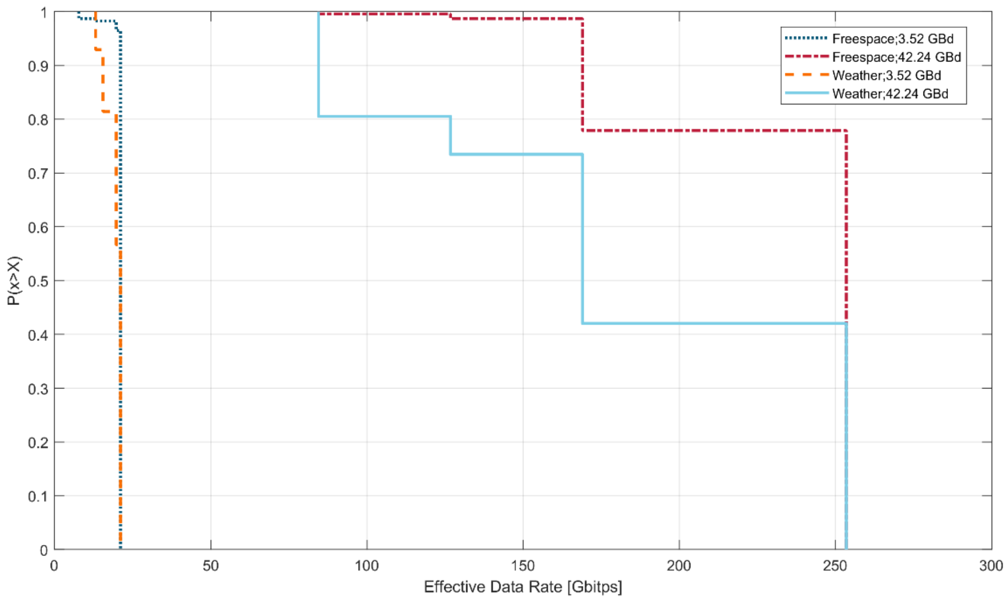

Figure 13: CCDF of the effective data rate of the backhaul network.

7.3. Relay Simulations for Multicarrier Scalability

The IEEE Std 802.15.3d-2017 defines multiple bands for the spectrum range from 252.72 GHz to 321.84 GHz as illustrated in Figure 14. Since electronic devices with a huge bandwidth of up to

69 GHz are very challenging to build, the ThoR project investigates in the link level simulator of SiMoNe [1] the scalability of multiple frequency bands that are used in parallel.

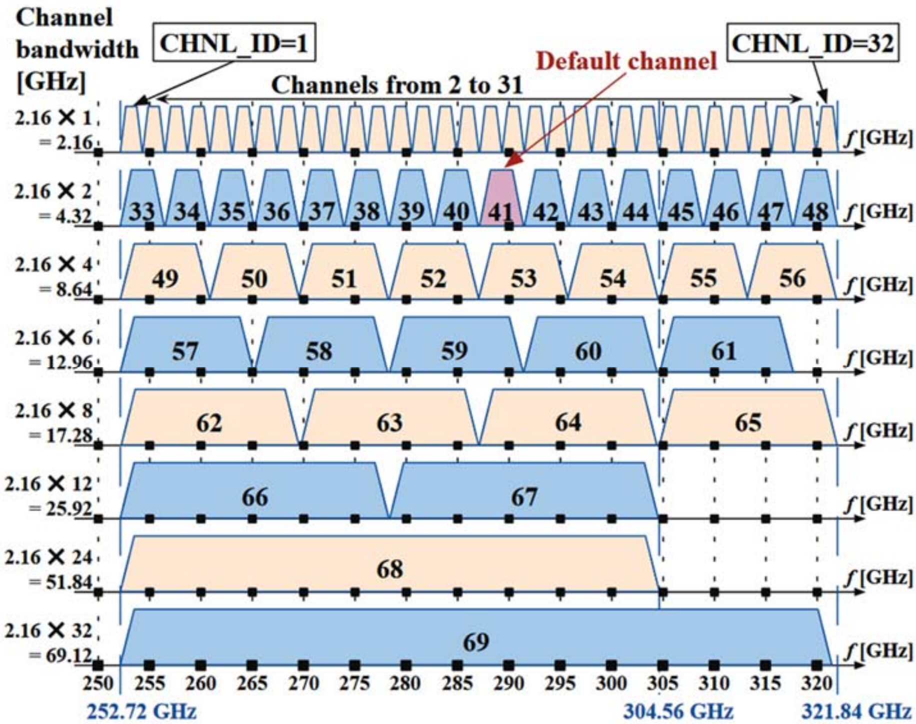

Figure 14: Channel plan of IEEE Std 802.15.3d [8]. (© 2020 IEEE, reproduced with permission)

Therefore, a multicarrier system was implemented in SiMoNe that allows for the simulation of parallel bit streams with a fully independent configuration of e.g. bitrate, MCS and transmit power.

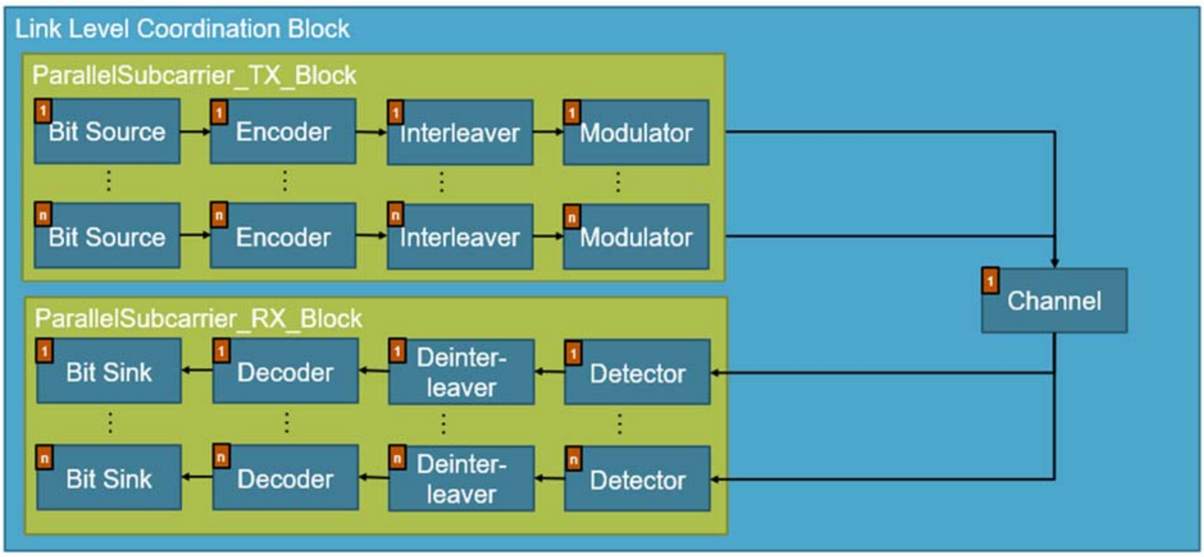

Figure 15: Block scheme of the multi-carrier transmission.

Based on the block concept of SiMoNe, multiple bit generation blocks, encoders and modulators are created and sequentially executed as shown in Figure 15. The subbands are converted to the respective intermediate frequency (IF) by a local oscillator (LO) and superposed to a single transmit signal.

At the receiver the signal is down converted for each subband and filtered by a filter bank of low pass filters. The parallel processing in the receiver is performed by independent receiver chains that consist of a matched filtering, resampling, synchronization, scaling, detection, demodulation and decoding. Figure 16 shows a schematic block diagram of the whole link level architecture.

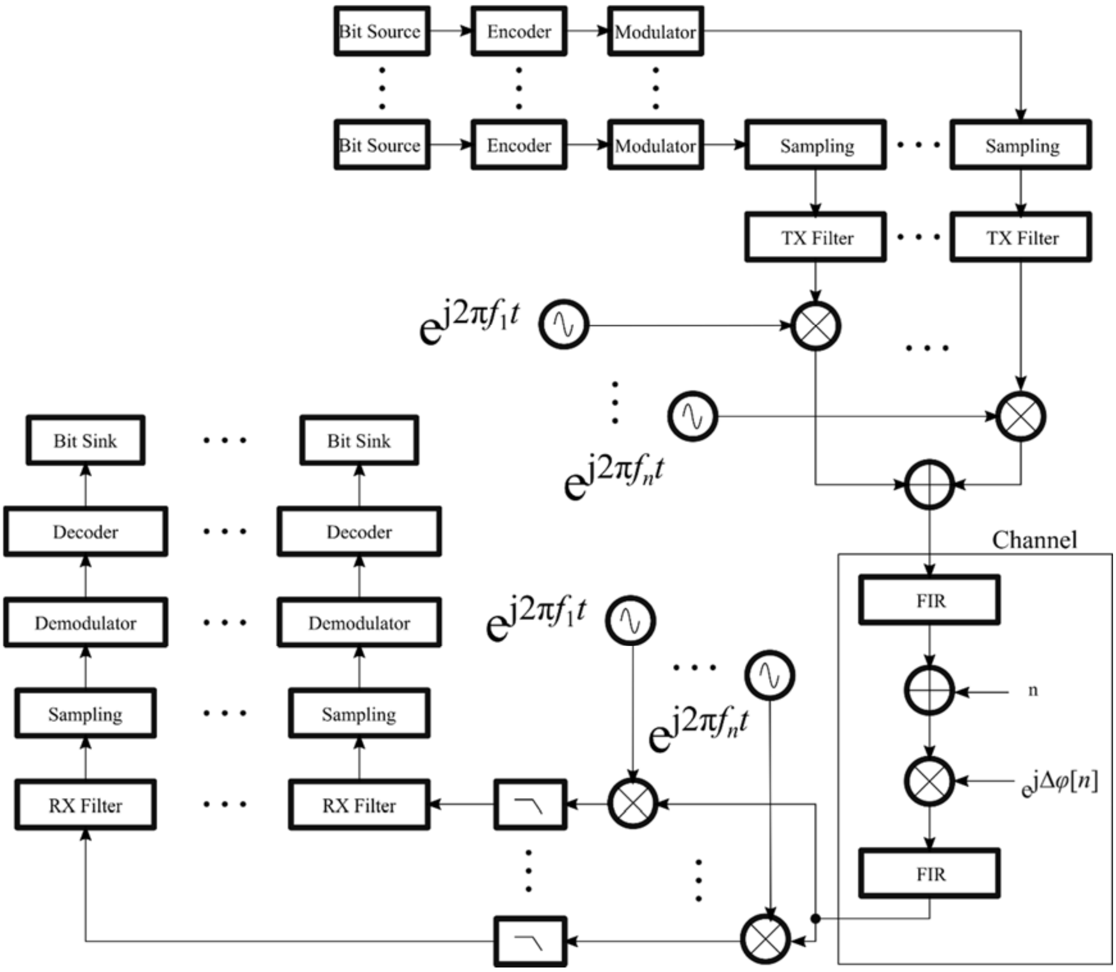

Figure 16: Block diagram of the link level simulation architecture.

To examine the dependency of the subcarrier bandwidth on the BER in the relay scenario, several LLSs are performed with varying subcarrier bandwidth and MCS. According to IEEE 802.15.3d the channels 1-24, 33-44, 49-54, 62-64 and 68 are used with an overall channel bandwidth of 51.84 GHz. Table 5 summarizes the simulation parameters of the multicarrier scalability simulations.

Table 5 Parameters for the Relay Simulations for Multicarrier Scalability.

Parameter	Value
Modulation scheme	BPSK, QPSK, 16-QAM, 64-QAM
Coding scheme	No Coding, Hamming, Reed-Solomon, LDPC14/15, LDPC11/15
Subcarrier symbol rate	1.76 GBd, 3.52 GBd, 7.04 GBd, 14.08 GBd, 42.24 GBd
TX Pulse	RRC with roll-off factor 0,3
TX Power	0 dBm
Noise	Thermal noise $N = kBTF$
Noise figure	10 dB

The simulations confirm a constant bit energy per noise power spectral density E_b/N_0 for different subcarrier bandwidths as shown in Figure 17 and Figure 18.

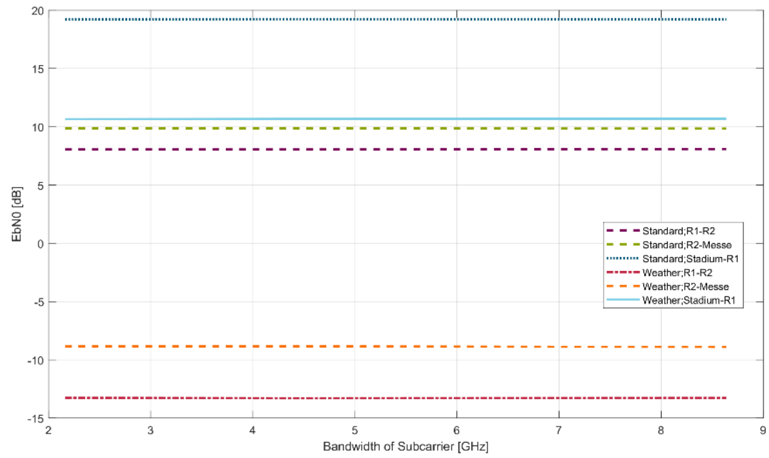

Figure 17: Bit energy per noise power spectral density for a system bandwidth of 8.64 GHz.

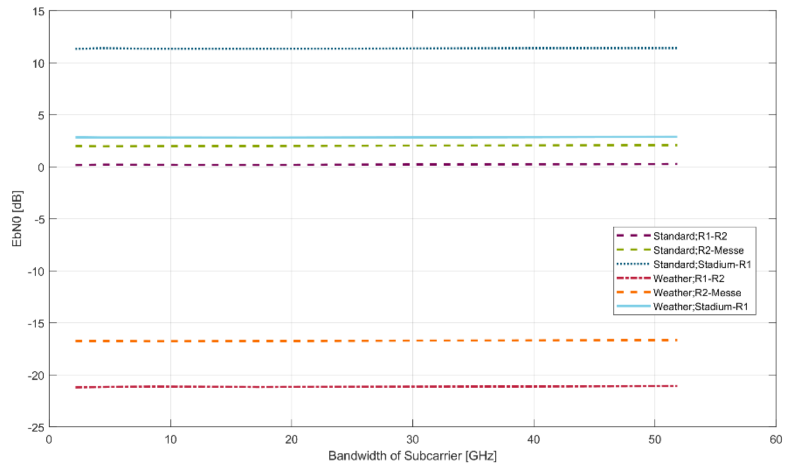

Figure 18: Bit energy per noise power spectral density for a system bandwidth of 51.84 GHz.

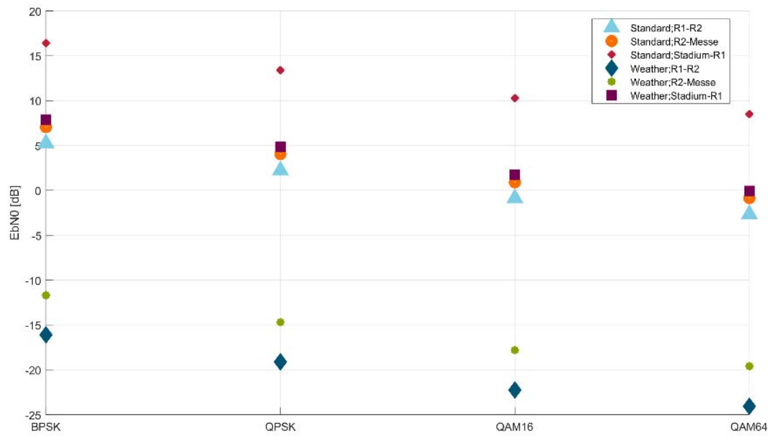

Figure 19: Bit energy per noise power spectral density for $B_{\mathrm{SC}} = 2.16\ \mathrm{GHz}$ and various modulation schemes.

Figure 19 shows that the E_b/N_0 decreases as expected with increasing modulation order.

Since the SNR is very low for the links relay 1 – relay 2 and relay 2 – messe, a transmission is not possible for extreme weather conditions. All other links provide a BER lower than 10^{-7} for a BPSK transmission with LDPC11/15 and a system bandwidth of 8.64 GHz. Only the link Stadium – relay 1 can be operated with 64-QAM and LDPC11/15 at a system bandwidth of 8.64 GHz. Depending on the requirements on the BER, a suitable MCS has to be chose for proper operation. Figure 20 and Figure

21 illustrate some selected results of the BER for 16-QAM, LDPC11/15 and a system bandwidth of 8.64 GHz and 51.84 GHz, respectively. Data points with an error-free simulation (e.g. Standard; Stadium-R1) are not plotted and can be assumed to be lower than 10^{-7}. We notice that the BER is in general independent of the subcarrier bandwidth. Only for a low BER and a small subcarrier bandwidth some inter-channel interference (ICI) seems to occur that increases the BER. However, this ICI does not limit the BER in general but makes low BER values fluctuating for small subcarrier bandwidth.

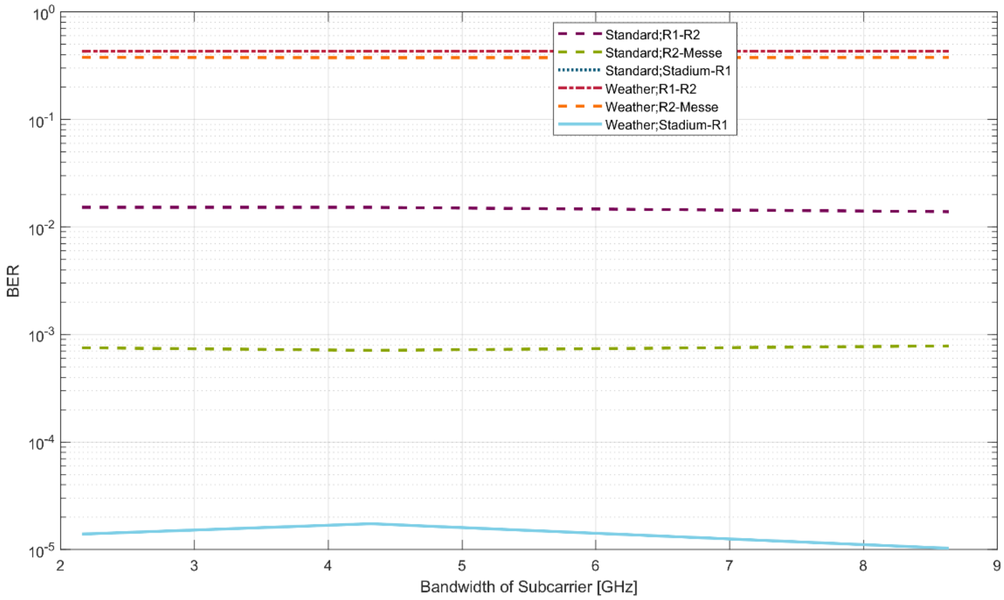

Figure 20: BER of relay transmissions with system bandwidth of 8.64 GHz, LDPC11/15 and 16QAM.

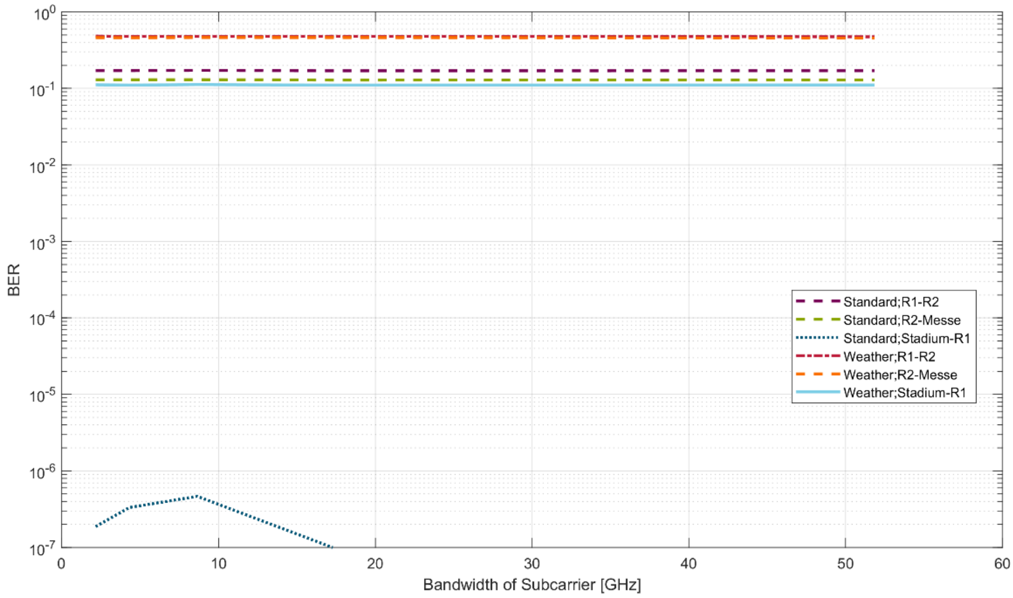

Figure 21: BER of relay transmissions with system bandwidth of 51.84 GHz, LDPC11/15 and 16QAM.

The influence of impairments of the RF devices on a single carrier transmission has been examined in [1] and is currently adopted for multicarrier systems.

8. Conclusion

The deliverable presents the results from the joint system level simulations and link level simulations. Two scenarios have been examined: A backhaul network scenario and a relay scenario both located in Berlin. Based on ray-optical channel predictions the signal and interference powers are determined in the system level simulation. In the network scenario, link level simulations are performed based on a fixed mapping of signal-to-interference-plus-noise ratios to modulation and coding schemes. The overall network performance is analysed for a channel bandwidth of 4.32 GHz and 51.84 GHz as well as for normal and extreme weather conditions. The relay scenario focuses on the examination of the scalability of a multi-carrier concept that is also used for the ThoR hardware demo. Up to 24 subcarriers are transmitted in parallel over the THz backhaul channel showing only a minor influence of the subcarrier bandwidth on the global performance.

9. References

[1] 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

[2] Hirata, A. et al. Deliverable D5.5 Final Report on Antenna, Propagation and Channel Models, EU H2020 ThoR Deliveralbe, May 2021

[3] IEEE Standard for High Data Rate Wireless Multi-Media Networks Amendment 2: 100 Gbps Wireless Switched Point-to-Point Physical Layer, IEEE Std 802.15.3d-2017, September 2017.

[4] International Telecommunication Union, Attenuation by atmospheric gases and related effects, Recommendation ITU-R P.676-12, August 2019

[5] B. K. Jung, N. Dreyer, J. M. Eckhardt and T. Kürner, "Simulation and Automatic Planning of 300 GHz Backhaul Links," 2019 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), 2019, pp. 1-3, doi: 10.1109/IRMMW-THz.2019.8873734.

[6] Jung, B.K. et al. Deliverable D2.4 Definition of Scenarios for Demonstration and Simulation, EU H2020 ThoR Deliveralbe, June 2019

[7] Jung, B.K. et al. Deliverable D5.4 Planning Rules of THz Backhaul/Fronthaul Links, EU H2020 ThoR Deliveralbe, July 2021

[8] V. Petrov, T. Kurner and I. Hosako, "IEEE 802.15.3d: First Standardization Efforts for Sub-Terahertz Band Communications toward 6G," in IEEE Communications Magazine, vol. 58, no. 11, pp. 28-33, November 2020, doi: 10.1109/MCOM.001.2000273.