**Horizon 2020 Grant Agreement no: 814523**

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

# ThoR

# Deliverable D6.2

# Concept for Software Simulation

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## Contents



## Change register

| Version | Date | Author | Organisation | Changes |
|---|---|---|---|---|
| A | 20-06-2019 | Thomas Kürner | TUBS | TOC |
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# 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.


| | | |
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# 2. Abbreviations

| | |
|---|---|
| BER | Bit Error Rate |
| FIR | Finite Impulse Response |
| FFT | Fast Fourier Transform |
| ISI | Inter-Symbol Interference |
| LOS | Line Of Sight |
| MCS | Macro-Cell Site |
| ML | Maximum Likelihood |
| MLSE | Maximum Likelihood Sequence Estimation |
| MPC | Multi-Path Components |
| OOK | On-Off Keying |
| PSK | Phase Shift Keying |
| QAM | Quadrature Amplitude Modulation |
| QPSK | Quadrature Phase Shift Keying |
| RAN | Radio Access Network |
| RRC | Root Raised Cosine |
| RF | Radio Frequency |
| SCS | Small-Cell Site |
| SINR | Signal to Interference plus Noise Ratio |
| SiMoNe | Simulator for Mobile Network |
| SON | Self-Organizing Network |
| SUMO | Simulator for Urban MObility |

# 3. Executive summary

This deliverable provides the concept of the software simulations on both the system level as well as the link level that will be used in the ThoR project in order to analyse the performance of the resulted wireless backhaul links at the 300 GHz frequency spectrum range.

Within this document the software simulator (SiMoNe) is described and the principle of the prototypical software simulation flow for the ThoR project is explained. Also the provisional results of the system-/link level simulation are provided which was done with the ThoR scenario defined in [1].

With the system level simulation two points are predicted: received power and signal to interference plus noise ratio (SINR). This predicted value will be compared with the system requiring values defined in [2]. Through the link level simulation, bit-error-rate (BER) and the data rate of every planned wireless backhaul links are calculated. Accordingly, the achievable data rate of each link is specified. With the results of the system / link level simulation, the planning methods of the wireless backhaul links will be evaluated, as well as the planning guidelines will be derived.

# 4. Purpose of Software Simulations in ThoR

In Work Packages 5 and 6 TUBS is performing detailed software simulations both on the system (e.g. network) level and link level:

- The purpose of the *system level simulations carried out in WP 5* is to assess the high-level performance of each radio link in order to derive the actual achieved *Signal-to- Interference plus Noise Ratio (SINR)* for a concrete configuration of the deployment taking into account the path loss of the link and the interference from other links. Based on these results, methods and guidelines for the planning of backhaul/fronthaul links will be derived. The simulator available at partner TUBS will be based on and integrated into the Simulator for Mobile Networks (SiMoNe) [3] and [4].
- The purpose of the *link level simulations carried out in WP6* is to derive the Bit Error Rate (BER) and the achievable data rate of a single link taking into account the simulated channel impulse response, the modulation and coding schemes, the signal processing at the receiver and the measured characteristics of the components used in the actual ThoR hardware demonstrator including the RF impairments. These simulations will be used to show that an implementation of IEEE 802.15.3d can provide >200 Gbps. The simulator will be based on the IEEE 802.15.3d Physical Layer Simulator, which is currently implemented by TUBS within the parallel running H2020 TERAPOD project [5]. The Physical Layer Simulator is also part of the SiMoNe platform and will be extended by models to take into account the above mentioned hardware characteristics models. As part of the corresponding modelling and validation activity, simulations using hardware-in-the-loop and post-processing, *e.g.* using the Digital Oscilloscope and AWG available at partner USTUTT, will be applied.

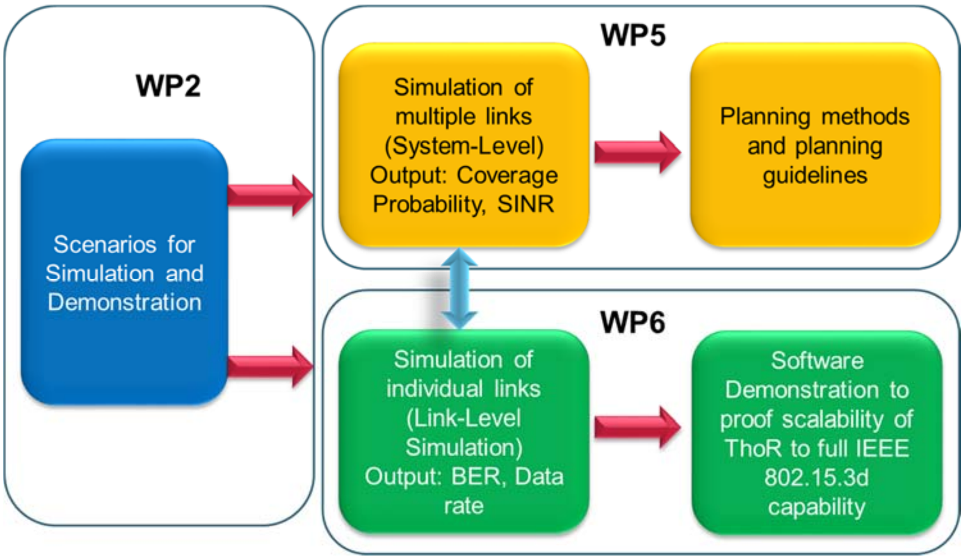


**Figure 1 Tasks and relations between WPs 2, 5 and 6 dealing with simulation**

Both the link level and the system level simulations will make use of the deployment scenarios defined in WP2 [1]. Both simulators will be mutually coupled. The system level simulator provides channel impulse responses and interference levels from other links, which are used to model the communication channel in the link level simulation. Vice-versa the link level simulator will return BER values, which will be used as look-up tables in the system level simulation in order to provide input for the calculation of link budgets and coverage probabilities. Figure 1 shows the relations between the three mentioned work packages and tasks.

 

This deliverable is highly interrelated with two deliverables, which are due around the same time, namely deliverable *D2.4 Scenarios for Simulation and Demonstration* [1] and upcoming *D5.2 Preliminary Antennas, Propagation and Channel Models* [6], see Figure 2. The simulation scenarios are described in D2.4 and the antennas, propagation and channel models used in the simulation are described in D5.2 [6].

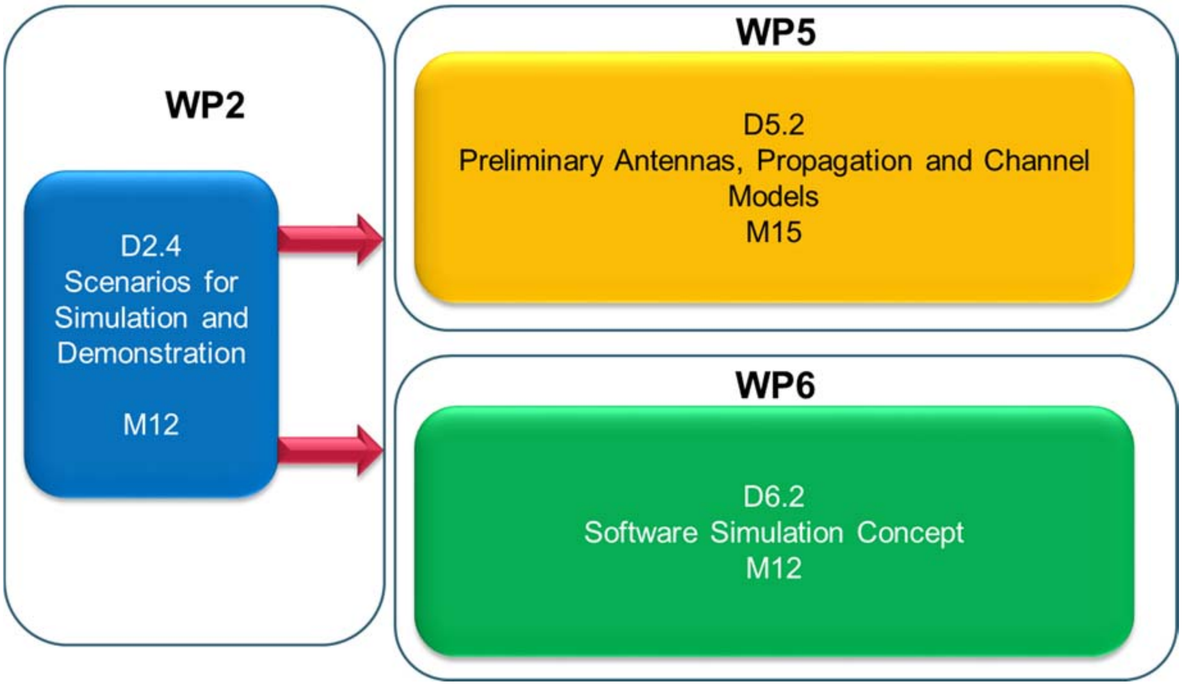


**Figure 2 Relevant simulation concept of the deliverables of the end of project year 1**

The remaining document is structured as follows: The following chapter 5 provides a short description of the simulation framework followed by a brief description of the concepts for link level and system level simulations in chapters 6 and 7. The concept for the coupling of the link and system level simulation is described in chapter 8. Conclusions are provided in chapter 9.

Although this document provides only the concept for simulations, exemplary simulation results will be provided in the following chapters wherever possible using functionalities, which are available in SiMoNe from previous work, the H2020 TERAPOD project, and have been already implemented within the ThoR project.

# 5. Software Simulation Framework

A simulation framework is one of the needed key elements for predicting and analyzing system performance. Within simulations, problems can be inspected before the system is deployed in the actual field. Therefore, the 'Simulator for Mobile Networks' (SiMoNe) [3] was developed at TUBS in order to predict the performance of a mobile network within a given scenario. We will first give a general introduction into the SiMoNe framework (Section **Fehler! Verweisquelle konnte nicht gefunden werden.**) and follow with a detailed description about the channel prediction (Section 5.2).

## 5.1. Simulator for Mobile Networks

The 'Simulator for Mobile Networks' (SiMoNe) is a mobile network simulator developed at the Institute for Communications Technology at Technische Universität Braunschweig [3]. SiMoNe targets the simulation of realistic mobile networks including hundreds of mobile radio cells and thousands of mobile subscribers. Up to now, diverse cellular radio technologies such as GSM, 4G and 5G, as well as WiFi networks like 802.11ac and 802.11p, are supported. Subscriber movements are emulated using realistic mobility models. Therefore, the Simulator for Urban Mobility (SUMO) is used to model vehicular traffic [7] whereas self-developed mobility models do exist for pedestrian-, train-, tram- or drone-traffic. Moreover, data traffic models e.g. for video- or audio-streams as well as HTTP or Email-traffic are included for realistic data traffic emulation.

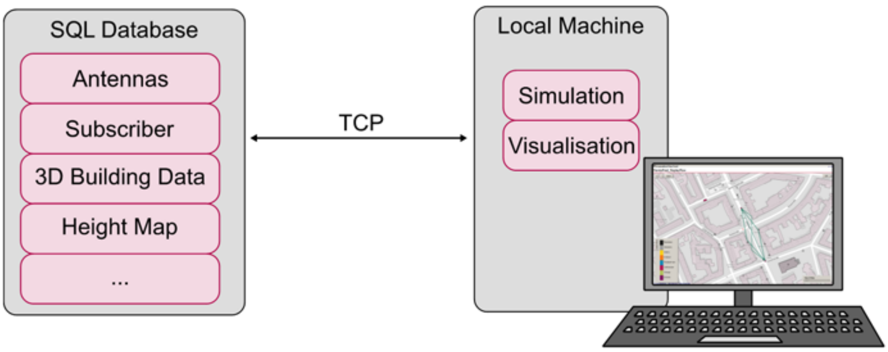


**Figure 3: SQL Database Connection**

SiMoNe is linked to an SQL database to serve every simulation with the data needed (see Figure 1). Next to network and subscriber information mentioned before, this database holds e.g. 3D building data, height maps and clutter maps needed for (ray optical) path loss predictions as described in Section 5.2.

SiMoNe makes use of a modular design principle that allows an easy modification or extension of the simulation framework: Each simulation is set up by functional blocks as shown in Figure 3 with each encapsulating a specific logical function.

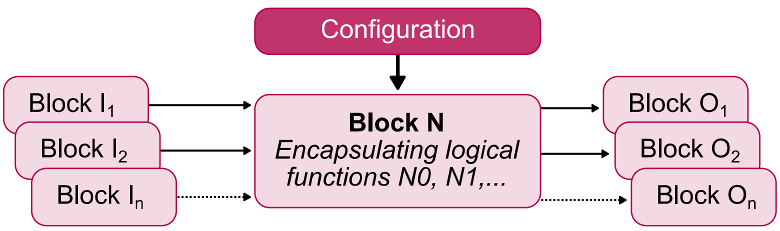


**Figure 4: A modularized block with inputs and states**

A Block processes states (results) of input blocks $I_1$ to $I_n$ and computes output states that are used by other blocks ($O_1$ to $O_n$). Moreover, algorithms can be controlled by block specific configuration parameters. A simulation is then defined by multiple linked blocks while the blocks are executed one by one in logical order. A set of linked blocks is called 'Simulation Flow'. A Simulation Flow is executed on a given time resolution for a defined period of time.

The SiMoNe simulation framework was already applied in various studies. In [8] the capabilities of self-organizing networks (SON) for automatic network-planning and –optimization was evaluated to be capable of ultra-dense networks requested by 5G technology. In [9] the performance of traffic steering algorithms using 802.11p and LTE technology to handle vehicular data traffic (V2X) was investigated. Moreover, within the scope of SiMoNe a lot of research was done in improving and accelerating ray optical path loss predictions [10] [11].

### 5.2. Channel Prediction

SiMoNe supports different propagation models that can be used for channel prediction. For large scale, map based scenarios, the Free-Space path loss model as well as the Okumura-Hata channel model can be applied. For small scale scenarios three ray optical path loss predictors are currently available: The femto predictor (FemtoPred) is a ray tracer developed for general outdoor and indoor scenarios. It can handle 3D building data as well as antenna diagrams. The FemtoPred is able to consider higher order reflections, roof diffraction and obstacle interaction (reflection and diffraction). A specialized version of the FemtoPred is the mobility predictor (MobPred) developed for scenarios with a large number of mobile receive and/or transmit antennas. The MobPred handles 2.5D building data with constant height above antenna level as applied in device-to-device communication, e.g. vehicular communication. It supports mostly the same features as the FemtoPred but offers a significant less computation time. Lastly, a ray launcher was developed that can offer highly detailed predictions for big scenarios as city environments.

However, the currently available ray optical path loss predictors are not suitable for the scenarios required inside the ThoR project. This is because of neglecting weather conditions (temperature, air pressure, humidity and rain rate) that have a considerable impact on the channel characteristics at the target frequency band from 280 GHz to 320 GHz as applied in the ThoR project. Three major factors affect the attenuation of a wireless channel: gaseous attenuation [12], attenuation due to rain [13] and attenuation due to cloud and fog [14]. Therefore, a path loss model accounting ITU-R should be integrated into the FemtoPred to calculate a suitable path loss prediction of the propagation channel at 300 GHz.

Ray optical path loss predictions inside the FemtoPred can be split in three steps: First, rays are searched geometrically based on the image source method. Second, every ray is described by its electromagnetic effect with respect to its interaction from the transmitter to the receiver. This includes a computation of the complex power as well as the angle of transmission and angle of reception. Third, the 3D antenna gain based on the azimuth and elevation is multiplied with the complex power to consider the antenna pattern.

An exemplary 3D plot of a propagation path is shown in Figure 5 and in Figure 6. It accounts the direct ray (LOS) shown in blue colour and the first order reflection (green colour). Transmit and receive antennas are shown in red colour. Further information about this scenarios can be found in Section **Fehler! Verweisquelle konnte nicht gefunden werden.**. A general description of the scenarios defined in the ThoR project can be found in [1].

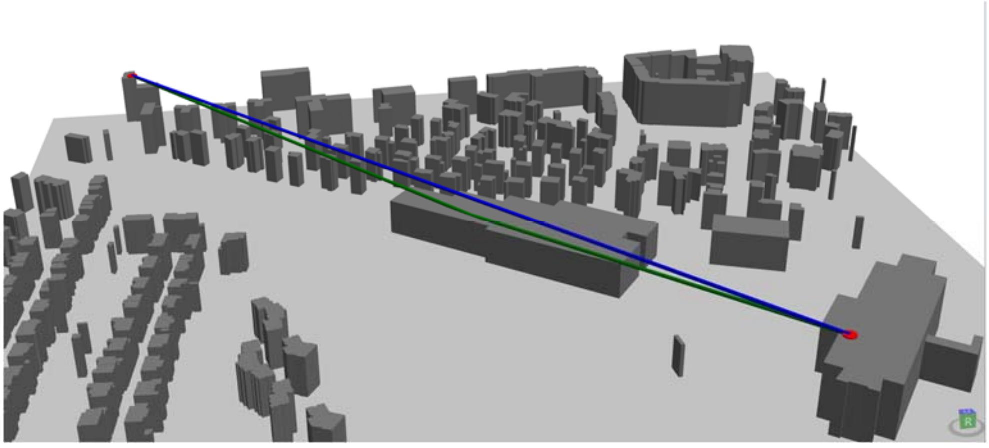

**Figure 5: 3D map of a link of the Berlin scenario 4**

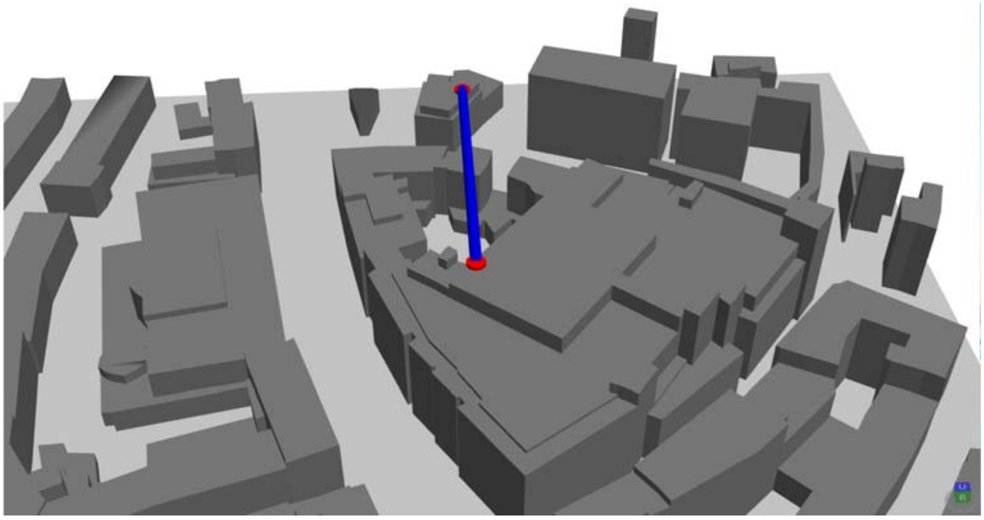

**Figure 6: 3D map of a part of the Hannover scenario**

The 3D map of a link of the Hannover scenario defined in [1] is shown in Figure 6. This link is exemplary chosen as the wireless backhaul link resulted by the planning algorithm described in [15], which will be published in September 2019 at the IRMMW-THz 2019. In this case only direct ray visualized as the blue line exists by taking into account for the first reflection.

### 5.3. ThoR's Scenarios for Simulation

In regards to the ThoR project, totally six realistic scenarios are provided for the simulation and the experimental demonstration in [1]. Every scenario is generated depending on the population and typical density of Macro-cell sites (MCS) and Small-cell sites (SCS). Five of them are designed for typical radio-access-network (RAN) with SCS deployed case and one of them is special relay use-case.

In this deliverable, two partial scenarios are shown, which are the simulation environments for the system level simulation (see Figure 7) as well as for the link level simulation (see Figure 8). The first scenario shown in Figure 7 is a Hannover scenario, which is an ultra-dense deployed case of SCS containing the high throughput demanded area defined in [1].

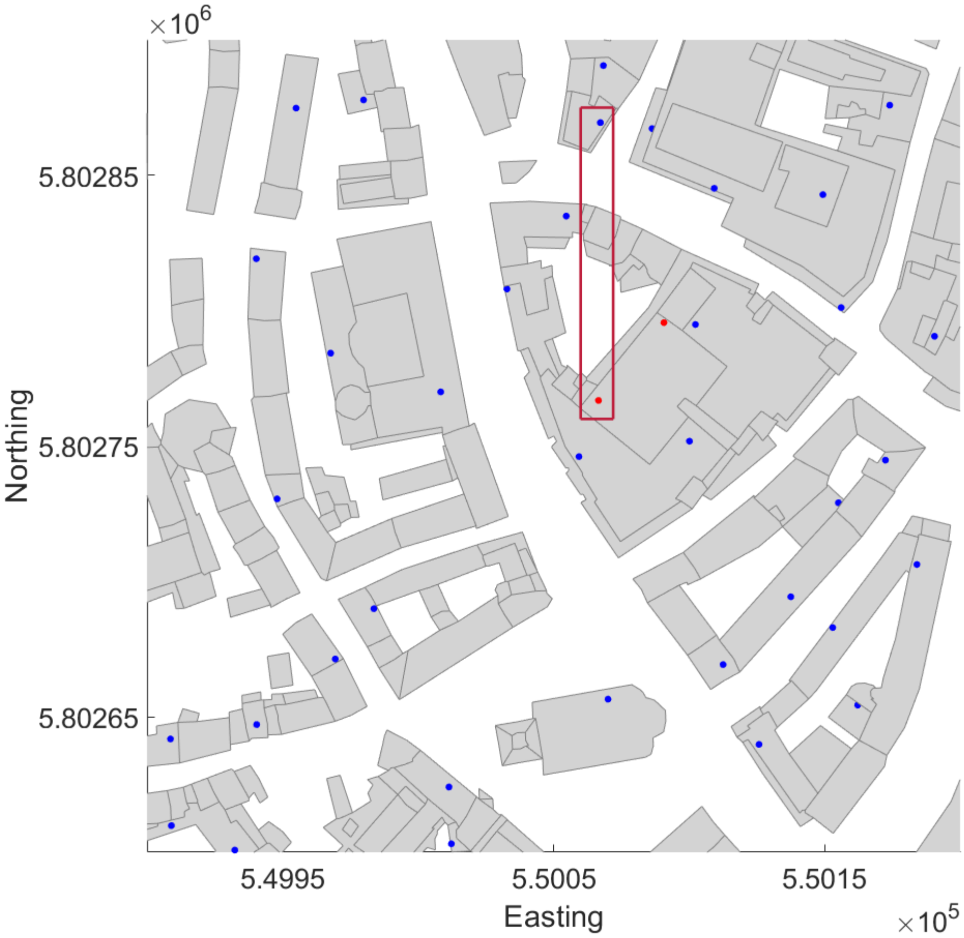


**Figure 7: 2D map of a part of the Hannover scenario**

In the Figure 7, the 2D map of the partial Hannover scenario is shown, where red points represent the fibre linked MCS, blue points represent SCS and red box represents the link that is chosen as a wireless backhaul link after the running of the automatic planning algorithm of 300 GHz backhaul links described in [15]. The results of the system level simulation of the chosen link will be provided in the chapter 7.

The second scenario is Berlin scenario 4 defined in [1]. This scenario is special relay-case of the high data transportation (e.g. Football match, Olympic games). The 2D map of the partial Berlin scenario 4 is shown in Figure 8, where red points represent the relay cell sites and the red box represents a wireless relay link The link level simulation is done using this scenario and the exemplary results of the simulation will be shown in chapter 6.

 

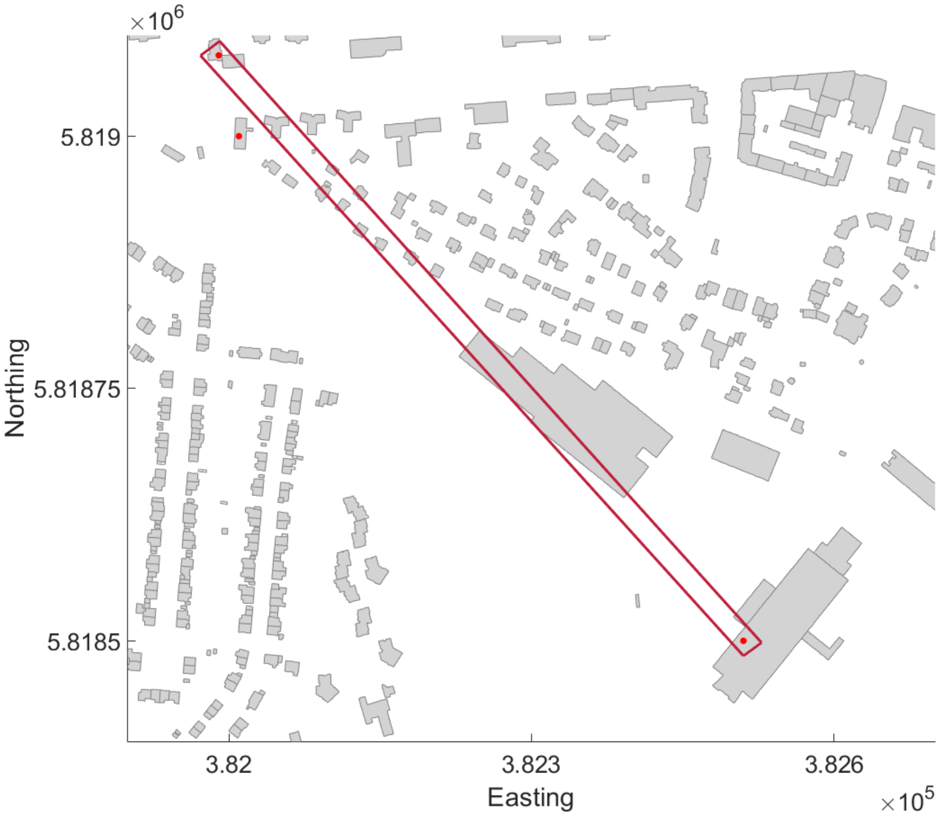


**Figure 8: 2D map of a part of the Berlin scenario 4**

# 6. Link Level Simulator

The link level simulator that is currently developed at TUBS is part of the SiMoNe simulator [3]. It is based on the same block structure which is described in section **Fehler! Verweisquelle konnte nicht gefunden werden.** and is able to simulate the transmission of single bits from a transmitter to a receiver via a modifiable channel. The main structure and functionalities were developed in the H2020 TERAPOD project [5]. Figure 9 shows a flow diagram that presents the block structure with the individual components and illustrates which project contributes to the link level simulator.

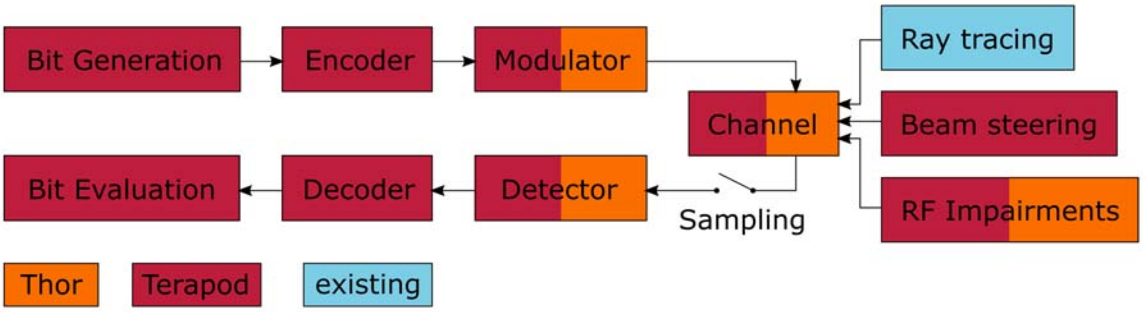


**Figure 9: Basic structure of the Link Level Simulator**

The Bit Generation Block creates the bits that are transmitted through the channel. A pseudo-random test sequence is implemented but specific protocols can be implemented as well. The Encoder realizes the channel coding that adds redundancy bits as a forward error correction. A Hamming-Code, Reed-Solomon-Code and an LDPC-Code will be implemented within the TERPAOD project. The Modulator maps the bits to symbols and implements the impulse forming. On-Off-Keying (OOK), Phase-Shift-Keying (PSK) and Quadrature-Amplitude-Modulation (QAM) are provided as modulation schemes. The user can freely select the bandwidth and the transmit pulse among a root-raised-cosine (RRC) impulse with adjustable role-off factor, a rectangular impulse or a sinc-shaped impulse.

The channel is implemented as a finite-impulse-response filter (FIR) using a fast-correlation algorithm via a Fast Fourier Transform (FFT). The impulse response can be entered manually providing the multipath components (MPC) with their amplitude and their delay. The other option consists of linking the link level simulator with the ray-tracing algorithm developed in SiMoNe. The ray-tracer provides the corresponding information of a dedicated link in a specific setup and enables the simulation of individual links within a complex and realistic scenario taking into account different antenna and propagation effects. For high frequency applications as treated in ThoR, the characteristics of the electronic devices have a high influence on the transmission performance. Therefore, the time discrete channel allows for the consideration of radio frequency (RF) hardware characteristics like phase noise or power density spectra of the transmitter.

The Detector interpolates the received signal and samples at each symbol clock. The symbols is detected via a maximum likelihood (ML) algorithm or a maximum likelihood sequence estimation (MLSE) algorithm. The Bit Evaluation Block compares the transmitted bits with the received bits, counts the bit errors and calculates the bit error rate (BER).

The ThoR project will contribute to the development of the link level simulator in such a way that the modulation and detection will be adapted to adequate protocols for backhaul applications. In addition, the channel will take into account backhaul related specifications like weather conditions. Especially the parallelization concept of the link level simulation and the system level simulation will be adjusted considering the implementation of IEEE 802.15.3d standard.

An exemplarily simulation for the relay scenario in Berlin visualized in Figure 5 shows the influence of the multipath propagation. The first order reflection on the roof top causes a strong inter-symbol interference (ISI). The simulation was run with a Quadrature Phase-Shift Keying (QPSK) modulation, a bandwidth of 5 GHz and RRC-pulses with a roll-off factor of $\alpha = 0.7$. The eye diagram of the received signal for a signal-to-noise ratio $SNR = 30\,\mathrm{dB}$ is plotted in Figure 10 showing the amplitude of the in-phase signal as a function of time normalized to the symbol duration $T_S$. It can clearly be seen that the impact of the ISI impedes a clear reception of the information. The destructive interference creates a third state where no signal is received. In contrast, the transmission with the direct path only shows a clear received signal without ISI. Here, the symbols can be easily detected in a correct way.

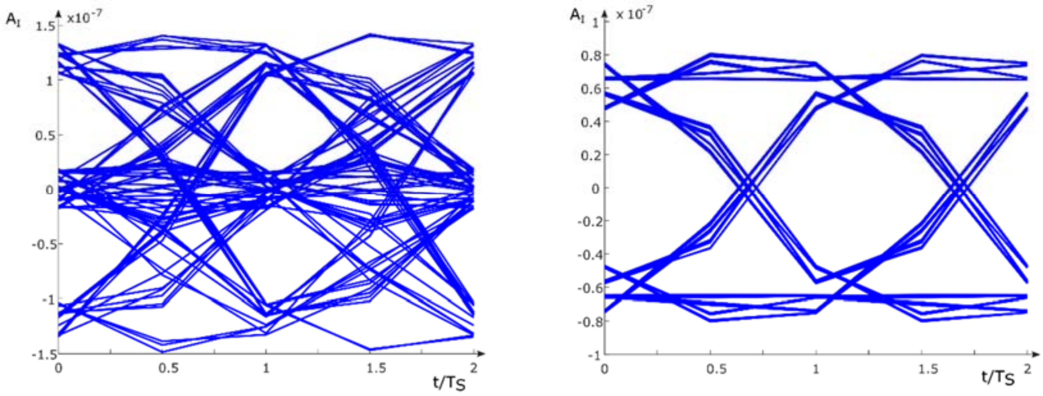


**Figure 10: Eye diagram with MPC (left); eye diagram without MPC (right)**

The high ISI is furthermore verified in a series of simulations where the SNR was increased from 0 dB to 50 dB in steps of 10 dB. Figure 11**Fehler! Verweisquelle konnte nicht gefunden werden.** shows the resulting BER as a function of the SNR. Since the transmission in the scenario under test is dominated by the ISI, the increased SNR does not change the high BER (blue curve). The comparison to the channel without the first order reflexion that only contains the direct path shows a stronger dependence on the SNR (orange curve). With increasing SNR the BER drops quickly to a level where communication is possible. Since very low BERs cause a high simulation effort, the BER calculation was limited to a value of $10^{-8}$. Further scenarios and analysis will be performed and additional functionalities implemented in the link level simulator within the course of the project.

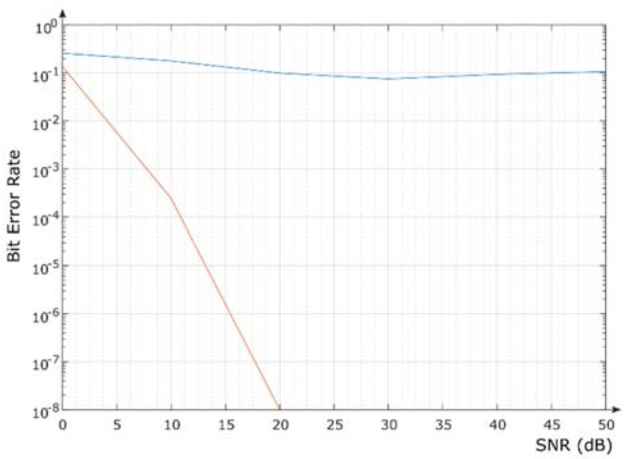


**Figure 11: BER as a function of SNR; blue: channel with first order reflection, orange: channel with direct path only**

 

# 7. System Level Simulator

A system level simulation in terms of this deliverable is to carry out the possible wireless backhaul links within the set of the designated cell sites considering realistic network environments and to evaluate the received power of the signal for the coverage prediction as well as the SINR for the modulation and coding scheme.

First of all, the wireless backhaul links are chosen by selecting as few as possible fiber backhaul requiring cell sites through the automatic planning algorithm of 300 GHz backhaul links explained in [15]. Once the algorithm is done, the received power and the SINR of each antenna of the cell sites are provided in order to evaluate the performance of the configured system.

Our system level simulator predicts the existing rays between the existing cell sites considering the weather condition as it is described in chapter 5.2. Based on the predicted values of the received power, the SINR at every antenna is derived taking into account additionally the theoretical thermal noise.

Three various gain antennas are used in the simulation: 50 dBi, 40 dBi and 30 dBi antennas. The 50dBi antenna is designed simply in order to cover the measured value of the 300 GHz parabolic reflector antenna described in [16] and [17]. The 40 dBi and 30 dBi antennas are derived from the mathematical model in [18]. The transmit power of the 50 dBi antenna is assumed as 0 dBm. The transmit power of the other gain antennas (30 dBi and 40 dBi) are regulated so as to maintain the same level of the received power by increasing the transmit power. Therefore, the transmit power of the 40 dBi antenna is supposed as 20 dBm. Likewise the transmit power of the 30 dBi antenna is assumed to be 40 dBm.

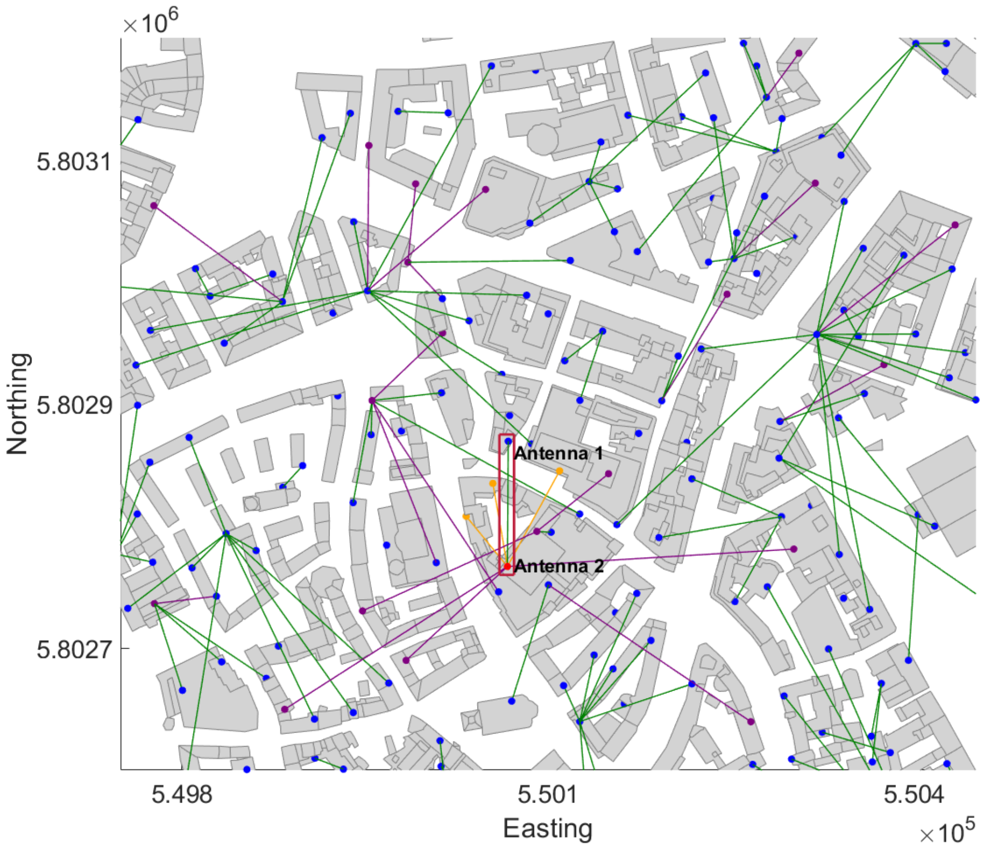


**Figure 12: 2D map of the exemplary planned wireless backhaul links with considerable interference to the Antenna 2 in Hannover scenario**

Figure 12 shows a part of the planned wireless backhaul links with considerable interference in the Hannover scenario. Herein a single link is exemplary selected in order to show the system performance which is shown in the red box in Figure 12.

In this Figure, the considerable interference to the Antenna 2 according to the various antenna gain can be seen. The considerable interference is assumed to be above -77 dBm which is the mathematical thermal noise of the 5 GHz bandwidth. Herewith the green lines are the automatic planned wireless links. The violet points show the locations of antennas, which make interference to the Antenna 2 when using the 30 dBi antenna. Besides, the violet lines show the links whose electromagnetic wave exceed the -77 dBm at the Antenna 2. Likewise, orange points are the locations of the antennas which make interference to the Antenna 2 in the case of using 40 dBi and 30 dBi antennas. The orange links are the links whose signal exceed -77 dBm at the Antenna 2.

In the perspective of the system requirements, the received power of the signal should be above -44 dBm and SINR of 22 dB, which is the requisite for supporting the highest modulation and coding scheme defined in [2].

In Figure 12, Antenna 1 and 2 are denoted in the red box, and are wirelessly linked. In [2] the required receive power is defined as -44 dBm and 22 dB for SINR in order to support the highest modulation and coding scheme. The power level of the received signal at the Antenna 1 and 2 are predicted as a value of -22.8 dBm. This exceeds the required value of -44 dBm and, therefore, the power level of the received power is enough for using the highest modulation and coding scheme.

 

Now we will look at the SINR values. The SINR of the Antenna 1 and 2, using a 50 dBi antenna, is predicted to be above 49.1 dB. Likewise in the case of a 40 dBi antenna, the SINR is predicted to be above 26.3 dB and with a 30 dBi antenna above 11 dB. Thus, in the case of using a 30 dBi antenna, the SINR cannot reach the required value of 22 dB. Furthermore, the resulted SINR value strongly depends on the used radiation patter of the antenna and the SINR value is steadily decreasing using lower gain antenna. This is a result of the aggregated interference of the other antennas, which are positioned on the same site (fibred backhauled base station having multiple antennas). Therefore, this interference should be avoided in advance and accounted for at the planning stage by isolating each antenna at the same cell site and considering enough angular spacing between the antennas.

# 8. Concept for Coupling of Link Level and System Level Simulation

The link level simulation and system level simulation cannot be separated in order to achieve a flawless performance of the designed system since they are mutually coupled. Therefore, each simulator of both simulations is considering the results of the other simulation. The idea of the coupling of both simulation is written in the following sub chapter.

## 8.1. Input from the System level Simulator to the Link Level Simulator

The system level simulator is aware of the whole scenario and has knowledge of all cells and users. Therefore only a ray tracing simulation within this system level context is able to predict a precise channel impulse response and the interference from other cells or users. The information on the channel and the interference is made available to the link level simulator in such a way that it can properly simulate the behaviour of the link under test.

## 8.2. Input from the link Level Simulator to the System Level Simulator

The link level simulator calculates different key performance indicators and general quantities of interest of a single link under test like the data rate, the bit error rate or the link delay. One possible configuration is that the system level simulator triggers the link level simulator in case that it needs detailed information on a special link (see Figure 13). The link level simulator will perform the simulation on the fly and provide the requested information. The other operating mode is that the link level simulator pre-calculates all link characteristics that are needed for the system level simulation a priori and stores the results in a look-up table. This enables a faster and more spontaneous simulation for the system level simulator.

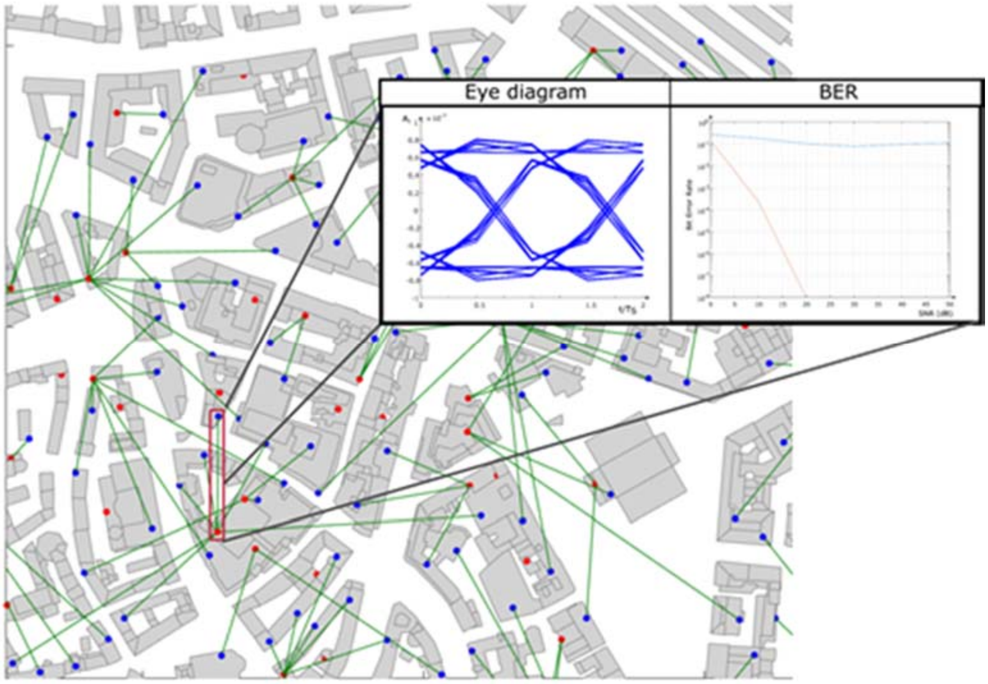


**Figure 13: An exemplary visualized result of the link level simulation belonging to the selected link**

 

# 9. Conclusion

In this deliverable D6.2, the concept of the software simulation including system level simulation and link level simulation is provided. The provisional results of both the system and link level simulations are exemplary shown. For both simulation, the realistic scenarios defined in the ThoR document D2.4 [1] are used. The simulation results provide system requirements in terms of antenna gain and isolation, for example, and will be used to regulate the guidelines for the planning of the 300 GHz wireless links. In order to prove the possibility of wireless data rates above 200 Gbps for backhauling and the fronthauling, we will develop a simulator which takes into a account the PHY layer of IEEE Std. 802.15.3d - 2017.

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