User Manual of the Meta Wireless System Level Simulator

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The Vienna 5G System Level Simulator is part of the Vienna Cellular Communications Simulators (VCCS) software suite. The simulator is currently available under a non-commercial, academic use license. For download and license information of the simulator, please refer to our **license agreement**.

Contents

Acronyms

3GPP	3rd Generation Partnership Project
3D	3-dimensional
5G	the 5th generation of mobile networks
AWGN	Additive White Gaussian Noise
BLER	Block Error Ratio
BS	Base Station
CLSM	Closed Loop Spatial Multiplexing
CQI	Channel Quality Indicator
CRC	Cyclic Redundancy Check
ecdf	empirical cumulative distribution function
LOS	Line-Of-Sight
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
MCS	Modulation and Coding Scheme
MIESM	Mutual Information Effective Signal to Interference and Noise Ratio Mapping
MIMO	Multiple-Input Multiple-Output
NLOS	Non Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OLSM	Open Loop Spatial Multiplexing
PDP	Power Delay Profile
PMI	Precoding Matrix Indicator
PPP	Poisson Point Process
PSD	Power Spectral Density
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RF	Radio Frequency
RI	Rank Indicator
RIS	Reconfigurable Intelligent Surface
ROI	Region Of Interest
SF	Shadow Fading
SFV	Shadow Fading Value
SFM	Shadow Fading Map
SINR	Signal to Interference and Noise Ratio
SISO	Single-Input Single-Output
SLS	System Level Simulator
SNR	Signal to Noise Ratio
TXRU	Transceiver Unit
VCCS	Vienna Cellular Communications Simulators

1 Introduction

In cellular communications, simulations are an inevitable tool for understanding the mutual interactions of all involved players in the network. Especially for gaining insight in the performance of a large-scale scenario, a real-world measurement approach becomes too costly and laborious. Therefore, system-level simulators are developed along with the standardization process of the current mobile communications standard.

With the addition of the the 5th generation of mobile networks (5G) System Level Simulator to the family of the Vienna Cellular Communications Simulators (VCCS), we tackle the need for simulating large-scale networks, capturing the change in network layouts and physical transmission. System-level simulations aim to evaluate the performance of a large network comprising a substantial number of BSs, RISs, and users. In this regard, the simulator simulates the communication between users and BSs, with or without the assistance of RISs. Due to its modular structure, the simulator allows the coexistence of different BS, RIS, and user types, including mobile users. This, on the one hand, allows the simulation of multi-tier networks, and on the other hand, by also supporting different user types, more diverse and realistic scenarios are supported. Additionally to various propagation models that can be used, there is the option to distribute blockage objects and use the geometry to calculate different propagation parameters. Regarding the network geometry, not only 3D blockages but also resembling walls and buildings can be placed. Consequently, randomly generated cities can be created, such as a Manhattan grid layout or randomly placed buildings with arbitrary orientation, but also building data from real cities can be chosen as a network environment.

The current version of our System-Level Simulator supports downlink transmission in heterogeneous networks with an arbitrary number of network nodes. It performs Monte Carlo simulations in order to achieve an average network performance. Therefore, we average over many spatial constellations and channel realizations and thus obtain average results of the user throughput and macroscopic Signal to Interference and Noise Ratio (SINR) obtained from the large-scale fading values, as well as the Block Error Ratio (BLER) for each individual user. To save time and quickly get simulation results, the *lite* simulation mode offers a *lite* SINR as a result that includes the effects of the distance-dependent path loss, shadowing, and a small-scale channel realization, but no precoder or receive filter. A full simulation takes into account all effects and gives more results, but it also takes longer simulation time compared to the *lite* simulation.

2 Overview of the Simulator

This section gives an overview of the simulator, staring from the installation and then the interface of it. It should be noted that this simulator is generated and tested in Windows and has not been tested in other systems. Therefore, it is not ganranted that this simulator would also work with other systems without errors. In case of any simulation errors, you can contact us through the Vienna simulator forum `https://vccsforum.nt.tuwien.ac.at/`. Another full version of the Vienna system-level simulator that includes more functions and features can be accessed through the link `https://www.tuwien.at/etit/tc/en/vienna-simulators/vienna-5g-simulators/`, and a user manual for the full simulator can be found in `https://owncloud.tuwien.ac.at/index.php/s/izVNiuNNwnw1VS8`.

2.1 Software installation

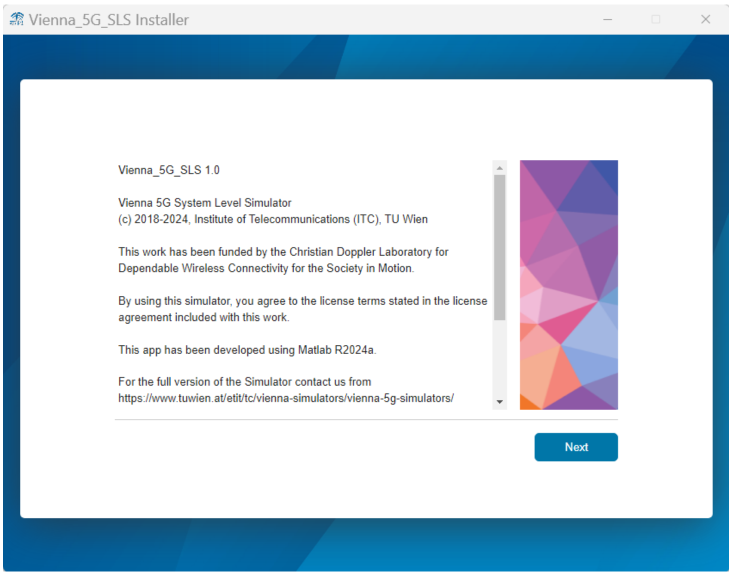
The following steps are required to successfully install the simulator:

1. Unzip the package and extract the installer and user manual, with the name of “MetaWirelessSLS.exe” and “UserManual.pdf”.
2. **Run** the application file “MetaWirelessSLS.exe” **as administrator** and follow the instructions for the next steps.
3. Click “Next” on the next two windows (e.g., Fig. 1), and click the “Begin Install” on the next page (Fig. 2). The installation process will be finished.

2.2 Interface of the simulator

After the successful installation of the software, when running this simulator, it should show an interface as in Fig. 3, which includes four main parts:

1. **Files**: this part controls the simulation scenario selection, loading, and saving. It also checks and resets simulation parameters as well as shows the simulation process and errors as output information.
2. **Edit**: this part sets all necessary parameters for running a simulation, such as the configuration of BS, User, RIS, city, etc.
3. **Simulate**: this part controls the simulation action, such as running a simulation and plotting the simulation results.



Vienna_5G_SLS 1.0

Vienna 5G System Level Simulator
(c) 2018-2024, Institute of Telecommunications (ITC), TU Wien

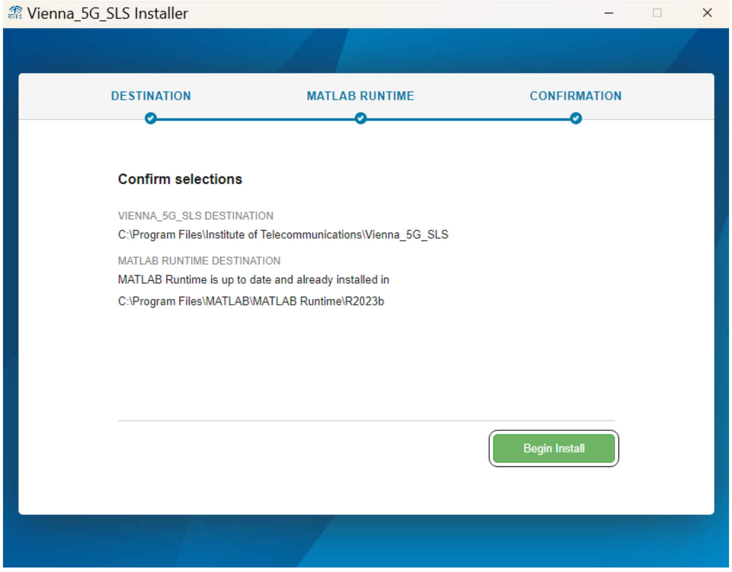
This work has been funded by the Christian Doppler Laboratory for Dependable Wireless Connectivity for the Society in Motion.

By using this simulator, you agree to the license terms stated in the license agreement included with this work.

This app has been developed using Matlab R2024a.

For the full version of the Simulator contact us from
https://www.tuwien.at/etit/tc/vienna-simulators/vienna-5g-simulators/

Figure 1: Step of the installation.



Confirm selections

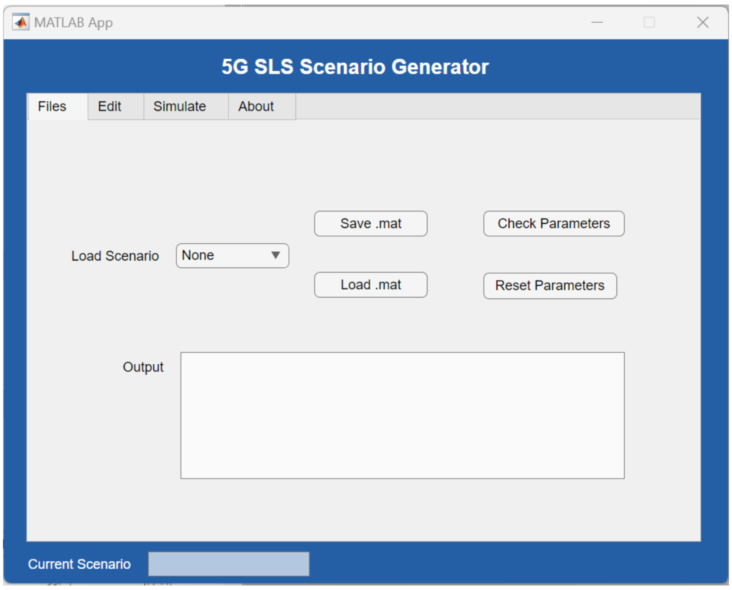
VIENNA_5G_SLS DESTINATION
C:\Program Files\Institute of Telecommunications\Vienna_5G_SLS

MATLAB RUNTIME DESTINATION
MATLAB Runtime is up to date and already installed in
C:\Program Files\MATLAB\MATLAB Runtime\R2023b

Figure 2: Step of the installation.

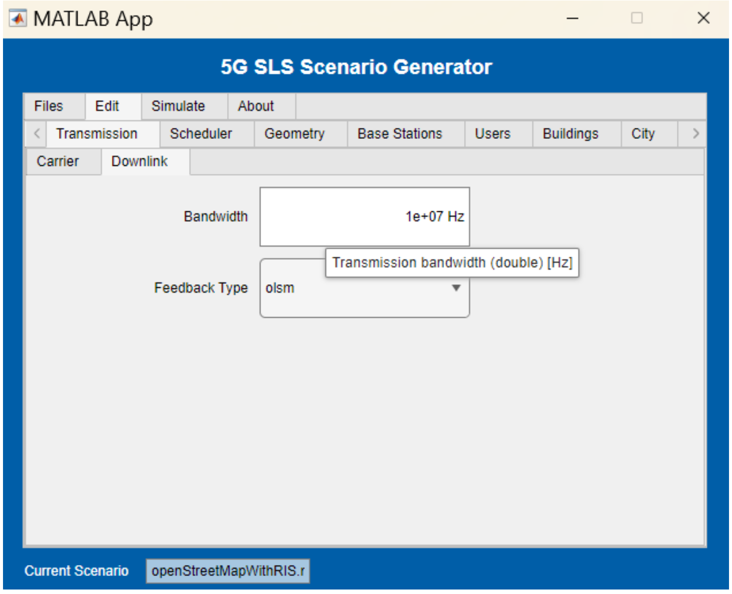
4. **About**: this part gives some extra information on the simulation development group, the license, funding sources, and links to a full version of the Vienna system-level simulator as well as the forum.

The details of each part will be introduced in the following sections. When hovering the mouse over any parameter box, it will show the explanation of



Load Scenario: None

Figure 3: Interface of the simulator.



Bandwidth: 1e+07 Hz

Transmission bandwidth (double) [Hz]

Feedback Type: olsm

Current Scenario: openStreetMapWithRIS.r

Figure 4: Mouse hover over parameters to see the explanation.

the parameter as shown in Fig. 4.

3 Files

From this panel, the users can load predefined scenarios as listed in “Load Scenario”, and can choose to save or load the scenario as “.mat” file. The predefined scenarios include “openStreetMap”, “openStreetMapWithRIS”, “RISonBuldingWalls”, “ManhattanWithRIS”, “basicLiteScenario”, and “basicScenario”. The scenarios that include “RIS” in the name simulate RIS-assisted networks. Otherwise when the scenario name does not include “RIS”, it means the simulation only includes Base Station (BS) and users, and no RIS is involved. For setting a simulation scenario, we recommend starting from an existing scenario that is most similar to the intended simulation and modifying the parameters. The purpose of the predefined scenarios is to show how to set up simulations with specific configurations. In general, the predefined scenarios only run a few random realizations. Thus, the results should not be interpreted as general truths, but only as single observations, often of only a small part of a network. To obtain reliable Monte Carlo simulation results, more repetitions with more random realizations have to be performed.

After selecting the scenario, all necessary parameters are filled with default values. Users can change any of the prefilled parameters according to their needs. When the “Check Parameters” button is clicked, the simulator will check if all the parameters are set correctly and inform any incorrect settings. If the default parameters have been changed and the users wish to restore the default setting, then the “Reset Parameters” button should be clicked. The Output box gives any information on the simulation progress, warnings, errors, etc.

4 Edit

If a predefined scenario has been loaded, most parameters will filled with their default values. In general, the default values are set to create the most generic scenario that does not use any additional features. If no predefined scenario is loaded, the users have to set each parameter on their own. In order to simulate network elements like base stations, RISs, and users, a group of network elements has to be added with their corresponding parameters. The minimum setup for a valid simulation is to add base stations and users, for example, base stations positioned in rings of a hexagonal grid and users distributed through a Poisson Point Process (PPP).

4.1 Time Config

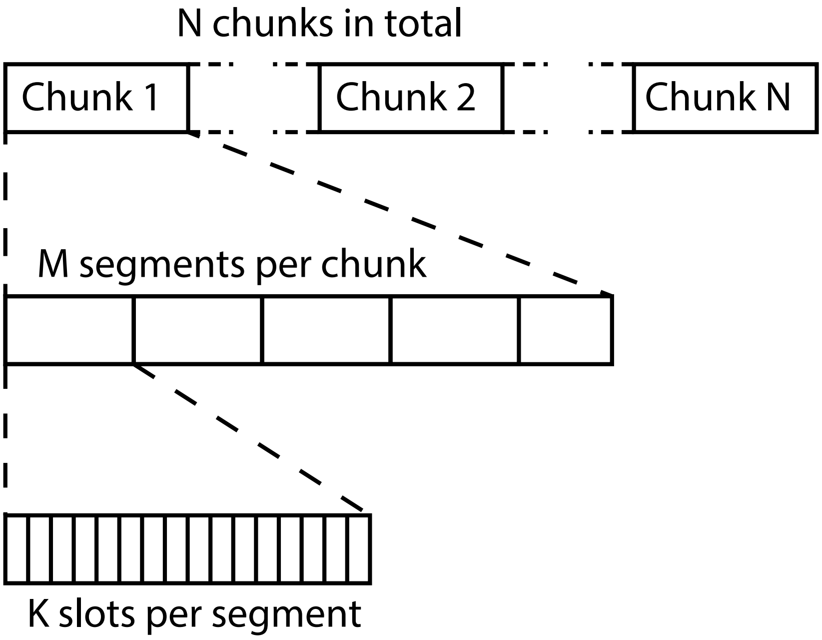


Figure 5: The different time units utilized in the simulator.

The timeline of the simulator is divided into three different units, namely time *slots*, *segments*, and *chunks*. In Fig. 5, the simulation timeline is sketched. It shows that the simulation is separated into chunks, in which some time passes that is not simulated. These chunks then consist of segments that can have varying lengths and are determined by the coherence time of the macroscopic fading. Each segment is then divided into slots during which the small-scale fading is constant.

The **slot** is the shortest unit and also corresponds to the scheduling granularity. Thus it corresponds to one iteration of the inner simulation loop. It has a constant length, e.g., 1 ms to represent an Long Term Evolution-Advanced (LTE-A) subframe, but can otherwise be specified freely.

A **segment** consists of a number of time slots and corresponds to the time (and distance) in which the macroscopic fading is assumed to be constant (e.g., the cell association and large-scale path loss values are constant, but the small-scale channel realization varies within the segment). Thus, the macroscopic fading values are only updated at the beginning of a segment, including the cell association. The length of a segment depends on the user speed and trajectory, as well as the correlation distance of the macroscopic fading values. This means that for a stationary scenario, only a single segment is created.

The **feedback delay** indicates the number of slots it takes the feedback to reach the base station. A larger feedback delay leads to more outdated feedback values and, thus, suboptimal transmission with lower throughput.

4.2 Transmission

In this section, one can set the carrier frequency and bandwidth for a simulation, as well as feedback type. This simulator supports only downlink transmission, “Closed Loop Spatial Multiplexing (CLSM)” and “minimum” feedback types for simulations. The feedback types “Open Loop Spatial Multiplexing (OLSM)” and “muMIMO” are used in the full version of the Vienna system-level simulator and are not available in this version.

4.2.1 Feedback

The feedback is used to provide the scheduler with estimates of the channel conditions. In particular, finite and discrete indicators, which quantify the quality of the channel, are reported after a fixed delay. The scheduler then utilizes those indicators to optimize the Modulation and Coding Scheme (MCS), layer-to-codeword mapping, and precoding w.r.t. maximal throughput. Minimal feedback can be used if the choice of the precoder is of little importance.

If “CLSM” feedback is chosen as the feedback type; then the feedback reports the Rank Indicator (RI), the Channel Quality Indicator (CQI), and the Precoding Matrix Indicator (PMI) to the scheduler according to [1]. The CLSM is only compatible with precoders that use a codebook since the precoder is chosen through the PMI.

4.3 Scheduler

The scheduling allocates physical resources available at a base station to the users that are associated with this base station. Physical resources here refer to the resource grid in time and frequency, which is divided into resource blocks that combine several Orthogonal Frequency Division Multiplexing (OFDM) symbols. For each resource block, the scheduler decides which user is served on these resources and then sets the transmission characteristic accordingly. The transmission characteristics include the used precoder, transmit power, CQI, and number of codewords transmitted. This information is collected in the scheduler signaling. Since the scheduling distributes physical resources that are attributed to a base station, the scheduling is performed individually per base station, which can be seen as a cell with physical resources, i.e., a spectrum to use for data transmission to serve the users in the cell.

Two scheduling methods are available in this simulator: the round-robin scheduler, and the best CQI scheduler. The Quality of Service (QoS) aware scheduler and multi-user schedulers are available in the full simulator version. The round-robin scheduler schedules the users one after the other in a row. When all users have been assigned resources, the first user is scheduled again, and so on. In the case of the best CQI scheduler, the user with the highest CQI value calculated by the feedback is allocated to each resource block.

4.3.1 The Resource Grid

In each slot in a simulation, each cell (base station with attached users) has the same **resource grid** available for data transmission. This resource grid is illustrated in Fig. 6. The resource grid occupies the bandwidth set in the simulation scenario and has a duration of one slot long in time. The macroscopic fading is constant over the whole resource grid.

The resource grid in each cell is identical, with identical resource block sizes. This allows a simple evaluation of the **interference** experienced by a receiver. The alignment of all resource grids in all cells implies the assumption that the network is perfectly synchronized.

The resource grid is composed of **resource blocks**, which are the scheduling units in the simulation. This means that each resource block can be assigned to the transmission to a user. After this assignment to a user, a precoder is chosen for the resource block. The number of resource blocks in frequency depends on the chosen simulated bandwidth. The small-scale fading is constant in time and frequency for each resource block but can vary in frequency from one resource block to another.

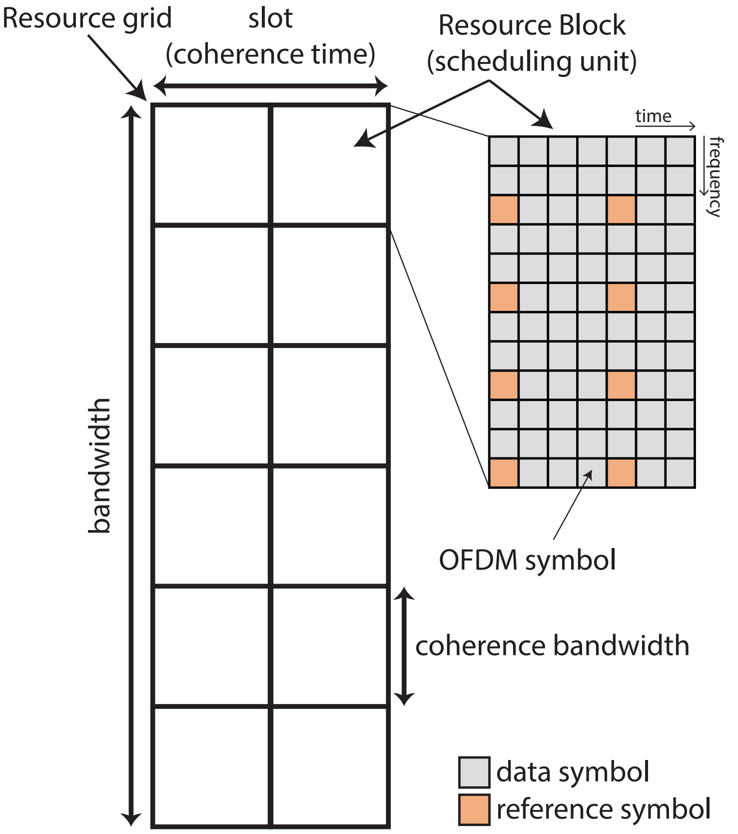


Figure 6: Resources for transmission in each slot in each cell.

4.3.2 Spectrum Scheduling

The spectrum scheduler is a special type of scheduler, which is always linked up to a composite base station and used for distributing resources between the several base stations inside the composite base station. This is accomplished according to some allocation rule, which is defined by the used spectrum scheduler type. The information of the spectrum scheduling is then forwarded to the schedulers of the sub base stations building up the composite base stations.

Up until now, two spectrum scheduler types have been implemented: "static" and "dynamicUser". In each of them, a different allocation rule is implemented. The `static` spectrum scheduler type allocates resources evenly between all available technologies. The `dynamicUser` spectrum scheduler type allocates based on the number of attached users in each technology. Table 1 summarizes the previously described behavior.

Scheduler	**Technology**	**User count**	**Buffer size**	**Resource balance**
dynamicUser	LTE	20	10 MBit	4/5
	5G	5	20 MBit	1/5
static	LTE	20	10 MBit	1/2
	5G	5	20 MBit	1/2

Table 1: Spectrum scheduling strategies

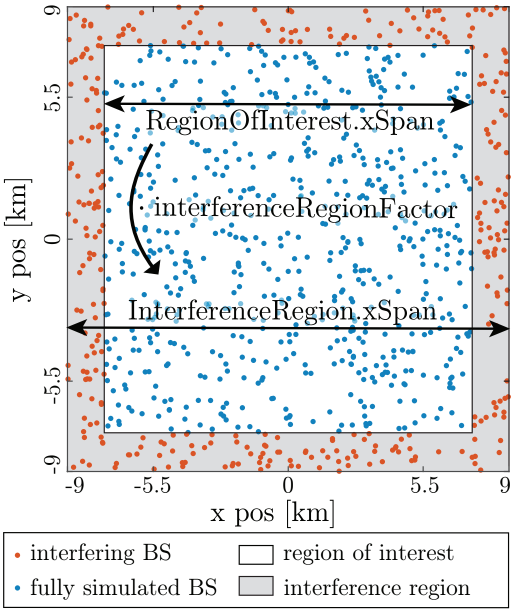


Figure 7: ROI (in white) with an additional interference region (in gray) with BSs creating additional interference for users at the border of the ROI.

4.4 Geometry

A simulation region needs to be defined in order to perform simulations. The simulation region contains a Region Of Interest (ROI) and optionally an interference region. The interference region is on the outskirts of the ROI and contains interfering transmitters that emulate regular transmitters, which is depicted in figure 7. The purpose of this additional interference region is to assure that users close to the border of the ROI experience network conditions comparable to the users at the center of the region of interest. Without the interference region, users close to the border would experience little to no interference, which would distort the simulation results.

The base station placement in the interference region is an extension of the base station placement in the ROI with the exception of BSs with predefined positions. Therefore, if there are only BS with predefined positions in the ROI, additional BS can be placed manually in the interference region with a given density. For the user placement in the interference region, two placement options are available. The users can be placed, like the base stations, in an extension of the user placement in the ROI, or the users can be placed randomly in the interference region, independently from the user placement in the ROI. The placement of users in the interference region creates additional interference for uplink transmissions and is thus not necessary if only the downlink transmission results are of interest.

The size of the interference region with respect to the ROI is set with the parameter `Interference Region Factor`. It indicates by which factor the total simulation region is bigger than the ROI, i.e., the diameter of the ROI is multiplied by this factor to get the diameter of the interference region.

To save computational complexity the BSs in the interference region are not fully simulated unless a user of the ROI is attached to them. Instead, simplified random scheduling and feedback are used to simulate the interference region BSs.

4.5 Base Stations

The simulator distinguishes between the entity *BS* and *antenna*, the two objects are depicted in Fig. 8. Each BS can have one or more antennas attached, which can be seen as physical entities with a position $\{x, y, z\}$ in the 3-dimensional (3D) space. The antenna object represents an antenna or an antenna array with N_{Tx} transmit and N_{Rx} receive antennas. BSs do not have physical locations but instead, the physical positions are specified on the assigned antenna objects.

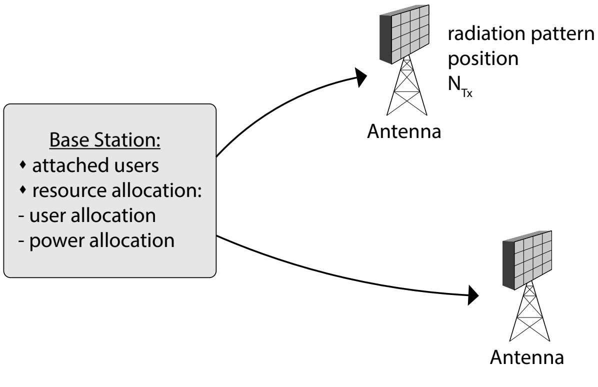


Figure 8: Abstract BS with two attached antennas with physical positions in the simulation region.

4.5.1 Base Station

The BS handles the physical resources available for transmission. It holds a list of all antennas that belong to this BS as well as a list of users currently attached to this BS. Each BS has a scheduler that allocates the available resources to the users attached to the BS.

Different placement methods can be used to define the placement of BSs, such as Poisson distribution, predefined locations, Hexgrid, Hexring, placed on buildings, and placed in interference regions. Each BS type, e.g. macro or femto BS, is indicated with an enumeration. If a new BS type is to be added in the simulator, then it has also to be indicated with a corresponding enumeration. Additionally, default transmit power and path loss models should be specified for new BS types.

Sectorized Base Stations The number of base station sectors is 1 by default, it is possible to specify up to 6 sectors. To simulate more than one sector, the number of BS sectors has to be specified with the BS parameter `nSectors`. The horizontal direction of the antenna, or the horizontal direction of the first sector antenna if there is more than one sector, can be specified with the antenna `azimuth` parameter.

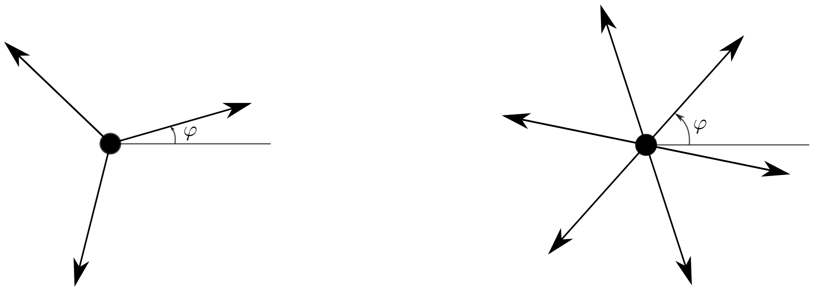


Figure 9: Base stations with multiple sectors and rotation φ

4.5.2 Antenna

The *antenna* collects all parameters necessary to calculate the antenna gain for their antenna type. The scheduling information provided by the BS is stored at and accessible through the antenna object. Various antenna types can be chosen. Two important parameters for antenna gain calculation are the antenna azimuth φ and antenna elevation θ. Fig. 10 clarifies the definition of both, where the origin would be the position of the antenna and the direction of the arrow where the antenna would have its maximum gain. The elevation is only used in the antenna gain calculation of antenna arrays. Note that $\theta = 0°$ would mean that the antenna would have its maximum gain in the direction of the zenith. The default values are $\phi = 0°$ and $\theta = 90°$.

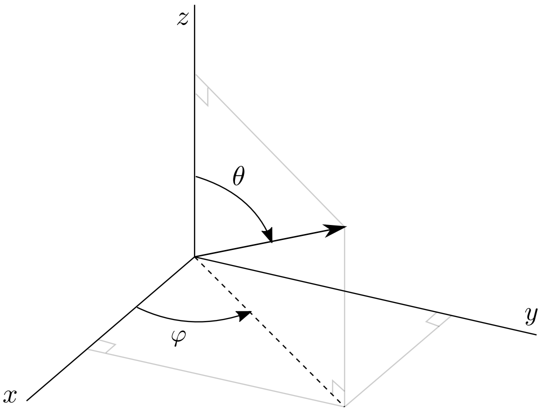


Figure 10: Illustration of antenna azimuth and elevation

4.6 Technologies and Numerologies

Users and antennas can have different technologies, such as “LTE” and “5G”. The term “technology” refers to a more abstract concept of network elements in which direct interaction is only possible between elements of the same technology. The term “numerology” is equivalent to the 5G numerology parameter, and is an integer indicator from 0 ... 5.

4.6.1 Precoding

The precoders perform a mapping from the different layers to Radio Frequency (RF) chains and from RF chains to antenna elements, as is depicted in Fig. 16. The precoders are used in the feedback, and the scheduler. In the Long Term Evolution (LTE) feedback, each baseband precoder codebook is considered to calculate the expected SINR, and then the feedback sets the PMI to maximize the SINR. In the scheduler, this PMI is finally used to set a baseband precoder individually for each resource block.

Baseband Precoding The baseband precoder is chosen individually for each resource block and maps the different layers to transmit RF chains. The layers are also often referred to as user streams. Baseband precoding is also referred to as digital precoding. The baseband precoder can utilize feedback to choose a precoding matrix from a codebook. The documentation of each

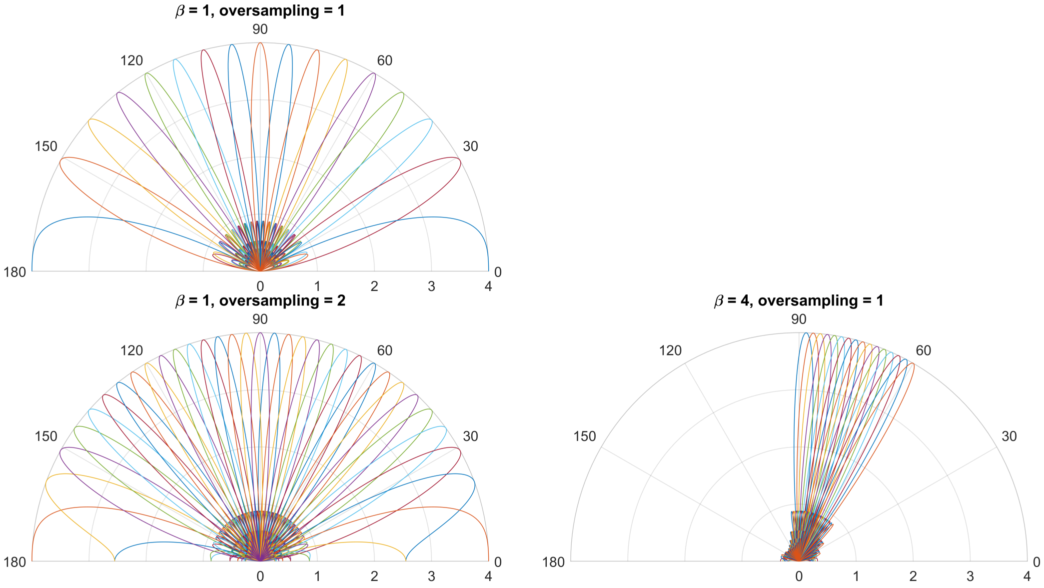


Figure 11: 2D Kronecker precoder beams with different oversampling factor and downtilt factor β for digital precoding.

precoder refers to the feedback types that may be selected among several precoding matrices using PMI.

Each base station can have its own downlink and uplink precoder assigned. Some important implemented precoders are listed below including their compatibility with the different feedback types.

- `PrecoderLTEDL`: LTE precoder for downlink according to [2] for up to 4 transmit chains and four layers `ClsmFeedback`.

- `Precoder5G`: 5G precoder for downlink according to [3] for single panel antenna arrays with `codebookMode=1`. This precoder is suited for digital precoding without an analog precoder. Supports up to 6 transmit chains and 4 layers. The standard specifies the precoders for dual-polarized antenna arrays. Since the simulator uses single polarized antennas some modifications were made to fit them in the simulator. For a more flexible and configurable precoder, use the Kronecker product-based precoder.

- `PrecoderKronecker`: Kronecker product based precoder according to [4]. This precoder is designed for uniform planar arrays. Like the 5G precoder it is suited for digital precoding without an analog precoder. The codewords are created by taking the Kronecker product of two DFT codewords. It is based on the same principles as the 5G precoder but allows for greater flexibility since it is possible to adjust the oversampling factors of the DFT codewords and thus the codebooks size. Figure 11 shows the beams resulting from the precoders of the codebook in the 2D case. Increasing the oversampling factor increases the number of beams (and precoders). Also, they begin to overlap. By increasing the down-tilt factor β, the beams get restricted to a smaller area. For more details please refer to paper [4].

Analog Precoding The analog precoder maps the RF chains to antenna elements. This allows to perform beamforming by adding a phase shift for each antenna element. In case no beamforming is performed, the analog precoder uses a one-to-one mapping from the RF chains to the antenna elements.

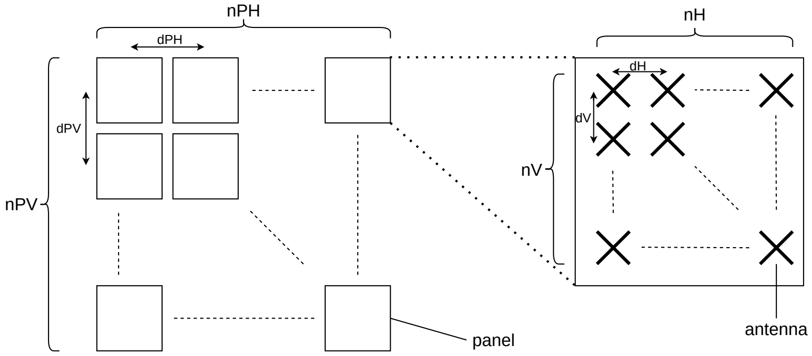


Figure 12: Antenna array consisting of panels with antenna elements placed on them.

The Multiple-Input Multiple-Output (MIMO) analog precoder performs beamforming for antenna arrays. The antenna array consists of several panels with antenna elements placed on them as depicted in Fig. 12. The RF chains are mapped to a column of antenna elements as specified in [5]. This mapping is repeated for antenna columns as depicted in Fig. 13. The mapping is repeated on each panel.

4.7 Users

The user object acts as the other endpoint of the communication link. The user class, like the antenna, has a position in the ROI and collects parameters to define the channel between user and antenna, which include the channel model and the number of RF transmit and receive chains.

Different placement methods can be used to define the placement of users, such as Poisson distribution, predefined locations, Gaussian cluster, uniform clusters, and located in interference regions. The user's position will be

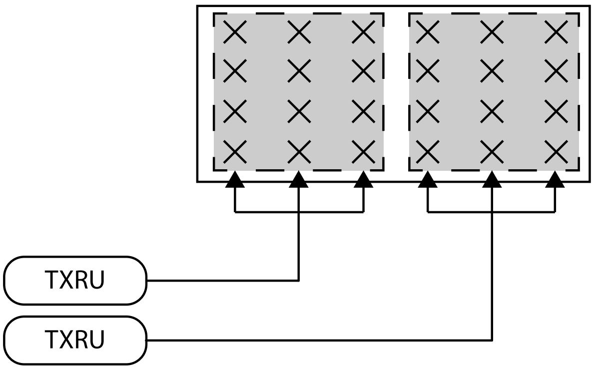


Figure 13: Mapping of RF chains to antenna columns. The mapping of the first column is repeated to the following columns if there are more antenna columns than RF chains.

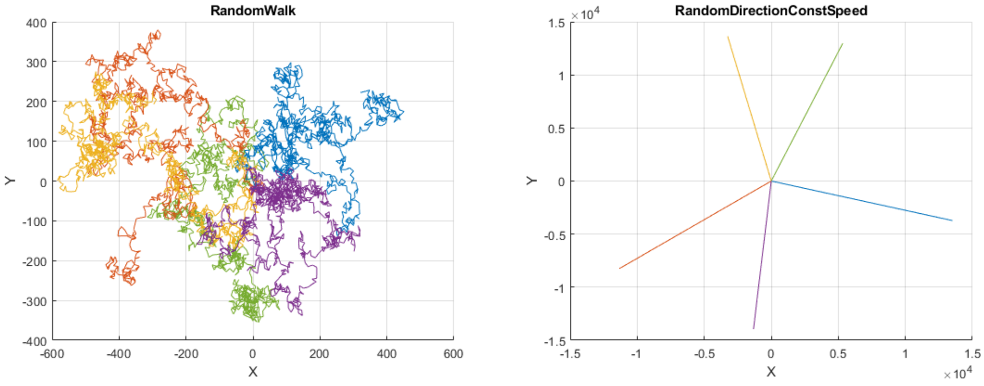
updated with its movement during the different time slots. There are 4 types of movement functions for the user and Fig. 12 shows three examples of different movement type:

1. RandomWalk: the user walks around randomly, changing directions.
2. RandomDirectionConstSpeed: The user walks in one unique radomly chosen direction at a constant speed.
3. Predefined: this function overwrites the initial user position with predefined positions.
4. StaticPosition: the user stays at one constant position during the whole simulation.

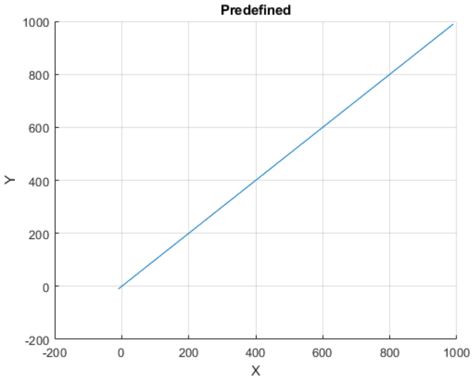
4.7.1 Channel Models

Each user and RIS needs a valid channel model. The channel models available for RISs are Rayleigh and Additive White Gaussian Noise (AWGN) models, while more channel models are available for users, such as “PedA”, “PedB”, “VehA”, “VehB”, etc. More channel models are implemented in the full simulator. They are defined through a Power Delay Profile (PDP) and are from 3GPP standards [6–10]. The 3rd Generation Partnership Project (3GPP) TR 38.901 3D channel model is an implementation of the model described in the corresponding 3GPP standard [5].

For the PDP channel models, channel traces are generated with all possible combinations of the number of receive antennas, the number of transmit



(a) RandomWalk (b) RandomDirectionConstSpeed



(c) Predefined

Figure 14: The different movement types

antennas, carrier frequency, and channel model that can occur during the simulation. For each channel model, the length of the channel traces has to be set. Then, the needed channel traces are loaded into memory, and a random part of the trace is selected to get a channel realization for one time slot. The channel traces should be much longer than the total simulation time to ensure that the samples taken from the trace are independent of each other, but the trace should be as short as possible since they need to be loaded into memory.

In general, the channel is assumed to be constant in time for a time slot, and a single value is calculated for the channel in the time domain. In the frequency domain the channel is assumed constant for a resource block. When the option “correlated fading” is chosen, the channel model is created according to [11] and a user speed has to be set to generate a channel trace. This user speed is set to the fastest user speed and used to calculate the

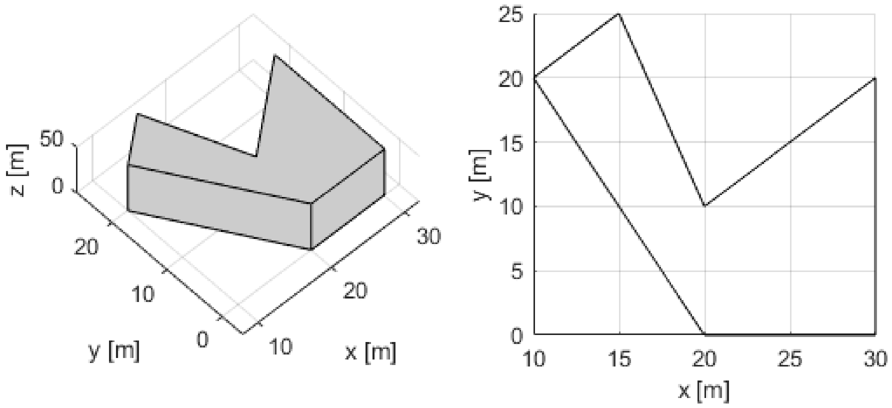


Figure 15: Building and floor plan.

Doppler frequency for the channel.

4.8 Buildings

On top of the network element generation, this simulator supports the generation of *blockages*. The basic building block to represent signal-blocking objects is a wall with arbitrary dimensions and orientation in 3D. Buildings are then created by combining multiple walls. With these, city layouts can be generated, such as a Manhattan grid with streets and building blocks.

When creating walls, buildings, and cities, the option exists to configure the wall penetration loss (by default it is 10 dB). It should be noted that when ray tracing path loss model is chosen, the wall loss parameter should be set as zero since the ray tracing simulation already includes the loss from walls. The buildings in the scenario are not restricted to a rectangular layout. An example of such an arbitrary building and its `floorPlan` is given in figure 15

4.9 City

There is the option to generate buildings together with streets, which is implemented in the `City` class. This abstraction provides two mechanisms for the reproducibility of simulation results, which can be configured by the following parameters:

- `Height Random Seed` - `shuffle`
- `Save File` - JSON file where the city should be stored
- `Load File` - JSON file to load the city from

Using “shuffle” for the `Height Random Seed` will lead to different heights on every run. If a city is stored in a JSON file, the building heights and many other parameters of buildings and streets can be adjusted manually by editing the file and then loading it again on subsequent simulation runs.

There are two types of cities, one is `Manhattan`, where buildings and streets are generated according to a Manhattan grid layout. The other option is `OpenStreetMap`, where streets and buildings are generated based on real-world data from OpenStreetMap [12]. Here the buildings and streets that are located in a certain area specified by coordinates are fetched via GET-request from [12]. This data is then processed, and a `floorPlan` is derived for the buildings, and a street layout is created.

Wall Loss Calculation Depending on the chosen wall loss model, the loss value is either specified directly or calculated from specified material parameters and the carrier center frequency of the scenario. The loss calculation is performed during the evaluation and assignment of dependent parameters in the simulation setup. The calculation is based on [5].

The frequency-selective wall loss L_W in dB is calculated as follows:

$$L_\mathrm{W} = L_\mathrm{W,npi} - 10\log_{10}\left(\sum_{i=1}^{N}\left(p_\mathrm{i} 10^{\frac{-L_{\mathrm{material_i}}(f)}{10}}\right)\right) \tag{4.1}$$

$L_\mathrm{W,npi}$ accords for the additional loss caused by non-perpendicular incidence. $L_{\mathrm{material_i}}(f)$ is the penetration loss of material i of the wall and p_i is the proportion of material i.

$$\sum_{i=1}^{N} p_\mathrm{i} = 1 \tag{4.2}$$

$L_{\mathrm{material_i}}(f)$ is a linear function of the frequency. The parameters $a_{\mathrm{material_i}}$ and $b_{\mathrm{material_i}}$ for common materials (e.g. concrete or glass) can be found in [5].

$$L_{\mathrm{material}_i} = a_{\mathrm{material_i}} + b_{\mathrm{material_i}} \cdot f \tag{4.3}$$

The four different wall loss models available are:

- `staticLoss`: loss value in dB is directly assigned without any calculation
- `lowLoss`: loss value is calculated according to equation 4.1 (material proportions: 70% concrete, 30% glass)

- `highLoss`: same as `lowLoss` but with other material proportions (30% concrete, 70% IRR glass)
- `userDefined`: same as `lowLoss` but with user defined material proportions (an arbitrary number of materials can be used)

4.10 RIS

Reconfigurable Intelligent Surfaces (RISs) are extra network nodes in addition to BSs and users. A RIS is a planar surface with a number of elements that are defined by the parameter “nTXelements”. It should be noted that either the “nTXelements” or (“nRow” and “nColumn”) should be set; when both parameters are set, the (nRow × nColumn) will be used in default as the RIS element number. If the “dx” and “dy” are set, they will be directly used, and the “Element Spacing factor” will not be used. Otherwise, if the “dx” and “dy” are not set, the “Element Spacing factor” will be used to calculate them. The amplitude of each element is set as one, which is the ideal case that RIS does not introduce any losses. By setting the parameter “Phase Optimization” as true or false, the phase shifts of RISs will be optimized or be random variables. Currently, the RIS phase shift optimization only supports Single-Input Single-Output (SISO) scenarios where each BS and user have only one single antenna. More detailed RIS modeling and phase shift optimization method can be found in [13]. The abovementioned parameters are all for the “RIS CM” path loss model. The parameters “Geometrical Area”, “Theta r”, “Theta i”, and “Efficiency” are used for the “RIS EM” path loss model. More details about the two models can be found in [14, 15].

Different deployment strategies can be used to define placement of RISs, such as predefined position, Poisson distribution, and locating on building walls. Only one deployment method can be set for RIS within one scenario. Since RISs are mainly used to improve the communication quality for blocked users, they should be placed where there are Line-Of-Sight (LOS) connections between base stations and RISs, as well as LOS connections between users and RISs. Therefore, the System Level Simulator (SLS) filters these purely blocked RISs out, so that the remaining RISs all have LOS connections with some base stations and with some users.

4.11 Pathloss Model

The path loss model used for a link is chosen depending on the type of link considered. The link properties that play into the path loss model decision are LOS/Non Line of Sight (NLOS) property, indoor/outdoor property, and base station type (such as macro, pico, or femto). A different path loss model for each link type can be defined in the simulation setup.

The link properties are dependent on the network geometry or can be decided by a model. For example, the LOS-state of a link can be modeled by a LOS-probability. The properties can also be fixed in the simulation setup. For example, a user can be defined as an indoor user for the whole simulation. Some models may require additional parameters to be set. A good example of that function is the `FreeSpace` model. The model defines a power damping factor, which is, in our case, called α. This factor has a default value of two but can be changed by the needs of the user.

The path loss is calculated for each of the BS-user, or BS-RIS-user links, specified as "No RIS" or "With RIS" cases. For "No RIS" case, six path loss models are implemented in this simulator: "FreeSpace", "Fixed", "Indoor", "RayTracing", "Rural", and "Urban". More path loss models can be found in the full version of the Vienna system-level simulator. Four path loss models are available for RIS-assisted links, such as "Fixed", "RIS CM", "RIS EM", and "RayTracing" models. More details about these models are explained in [16] and [14]. The path loss is calculated without wall loss and antenna gain because those are already calculated in their respective calculation functions.

It is worth noting that the RayTracing model is different from other path loss models. The MATLAB ray tracer supports various scenarios, propagation models, and effects of buildings and materials. Since the MATLAB ray tracer can simulate the building loss, material loss and reflection loss, when these parameters are considered in the ray tracing model, the wall loss and shadow fading should not be calculated after the path loss again and should be set as zero in the scenario file. If the ray tracing path loss model is chosen, ray tracing will be performed for all links and the traced path loss values will be used for simulation.

5 Simulate

Once all parameters are set, the simulation can be started in this part. The performance evaluation is done through Monte Carlo simulations with a large number of randomly sampled realizations of a scenario that is generated according to the parameters specified prior to the simulation. In order to obtain reliable results, care has to be taken to simulate a sufficient amount of random realizations. The random sampling occurs through the network realization at the start of the simulation and through the small-scale fading realizations used to determine the channel in each slot.

If the network elements in simulations are randomly positioned, a sufficient number of realizations can be obtained by simulating large networks, or by simulating several realizations of smaller networks and aggregating the results. If the result empirical cumulative distribution functions (ecdfs) changes for each simulation run, the number of simulated realizations is too small, and the network behavior described by the results depends on the specific random realization. For example, an especially unfortunate network realization could position all users in the same cell and an interfering base station very close to the serving cell, which would lead to very low user throughput. The results would then not be representative of the general network setup considered for simulations but would only reflect the properties of the specific network setup.

If the "Lite Simulation" box is clicked, only geometric and depending macroscopic parameters are considered, as well as an instantaneous channel realization. Scheduling, precoding, feedback, and equalizing processes are skipped, leaving only the calculation of the macroscopic parameters (path loss, antenna gain, shadowing, wall loss) and the generation of the small-scale fading channel in the simulation. The results of *lite* SINR and wideband SINR can be obtained from a lite simulation.

Lite SINR It should be noted that the *lite* SINR is calculated for all users in each time slot, which implies that all users are transmitting in each slot, which cannot be the case when more than one user is placed in a cell. Thus, the *lite* SINR has to be seen as a theoretical SINR, that is the SINR that could be achieved if the user was scheduled on all resources.

Wideband SINR The wideband SINR only depends on macroscopic fading parameters and is thus calculated per segment. The wideband SINR is defined as

$$\mathrm{SINR}_{wideband} = \frac{P_{\mathrm{rx},d}}{\sum_{i=1}^{N_{\mathrm{int}}} P_{\mathrm{rx},i} + N}. \tag{5.1}$$

where N_{int} is the number of cells creating interference. The indices d and i represent the desired and interfering cells and N represents the noise power experienced by the user aggregated over the whole transmission bandwidth. The receive power P_{rx} consists of the transmit power P_{tx}, the antenna gain G, the path loss L_{path}, the shadowing L_{shadow}, and the wall loss L_{wall}:

$$P_{\mathrm{rx}} = P_{\mathrm{tx}} \cdot G \cdot L_{\mathrm{path}} \cdot L_{\mathrm{shadow}} \cdot L_{\mathrm{wall}}. \tag{5.2}$$

The modeling of the Shadow Fading (SF) is based on Shadow Fading Maps (SFMs). Those SFMs are arrays of so-called Shadow Fading Values (SFVs) which are spatially correlated random variables. Such an array of random variables can be generated by means of the following steps:

1. Generate an array of uncorrelated Gaussian random variables
2. Apply the FFT to the array
3. Multiply the transformed array with the Power Spectral Density (PSD) of the intended spatial correlation
4. Apply the inverse FFT

The advantage of this method is, that correlated shadow fading values for positions with minimal granularity can be generated without the need to resolve the whole ROI with the same precision. A more precise explanation on this topic can be found in [17].

When running a full simulation, all the abovementioned processes are involved. We first do a link abstraction to get post-equalization SINR results. The details are explained in the following steps.

Link Abstraction Fig. 16 shows the processing chain with an abstraction of a link between a BS and a user in the simulator. Each step in the processing chain is represented by a matrix of the dimensions indicated in squared brackets. The implementation assumes that a Zero Forcing receive filter is used and that the small-scale fading is constant for the duration of a time slot. It is also assumed that if no user is scheduled at an interfering BS, this BS does not generate any interference unless the `alwaysOn` feature is activated at the BS antenna. Further assumptions are that one receiver operates on a

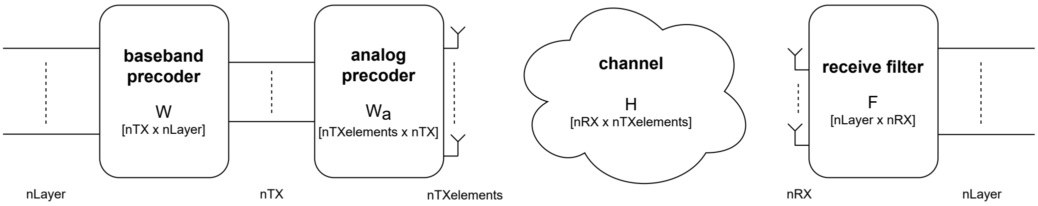


Figure 16: Abstraction of a link between a BS and a user. Each step is represented by a matrix in the simulation. The dimension of the matrix is indicated in squared brackets. `nLayer` represents the number of layers, `nTX` the number of transmit RF chains, `nTXelements` the number of antenna elements at the transmitter and `nRX` the number of receive antennas.

constant number of layers within a time slot and that the allocated transmit power is evenly distributed between those layers. The output result from this processing chain for one time slot is post-equalization SINR.

Terminology In the following, the terms used in Fig. 16 are related to commonly used terms and terms used in 3GPP standards. The layers that are input for the baseband precoder are also often referred to as streams or user streams. The `nTX` transmit RF chains are referred to as Transceiver Unit (TXRU) in 3GPP standards related to analog precoding, where analog precoding is referred to as TXRU virtualization. The concept of antenna ports and antenna port mapping is from LTE-A standardization and is not implemented in the simulator - equivalently it can be seen as a one-to-one mapping - and the number of transmit RF chains `nTX` is always equal to the number of antenna ports `nAtPort`. The number of transmit antenna elements `nTXelements` refers to the number of antenna elements, i.e. the antennas represented by crosses in Figs. 12 and 13. On the receiver side, `nRX` represents the number of receive antennas.

Post-equalization SINR The post-equalization SINR takes into account the utilized receive filter and precoders and the inter-layer interference, as well as the transmit power allocation. It is calculated for each layer of each resource block as depicted in Fig. 17.

The post-equalization SINR values and the Channel Quality Indicator (CQI) values are used to determine the throughput of a given user in terms of the number of successfully transmitted data bits. This is done in three steps as it is depicted in Fig. 18.

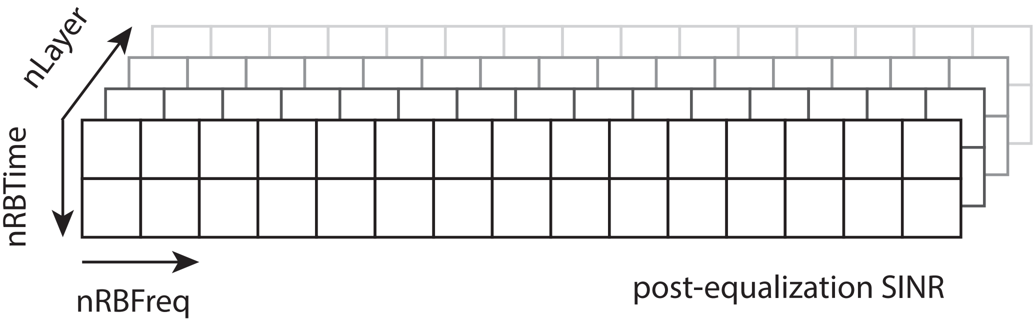


Figure 17: The post-equalization SINR is calculated for each resource block and each layer for each slot.

Effective SINR Mapping The first step maps the time-frequency selective post-equalization SINR values of a given user to an average Signal to Noise Ratio (SNR) with equivalent performance in an AWGN channel for a modulation and coding scheme selected by the feedback. This is based on a method called Mutual Information Effective Signal to Interference and Noise Ratio Mapping (MIESM) described in [18] which uses calibrated [19] capacity curves for the averaging process. The output is termed effective SNR.

BLER Mapping The next step is to obtain a Block Error Ratio (BLER) from the given effective SINR value. Here we utilize BLER-curves which are a mapping from an SINR to a BLER over an AWGN channel. These curves exist for every CQI value specified in the standard and are stored in the simulator. As each CQI value corresponds to a modulation and coding scheme, we can take our computed effective SINR for a specified CQI and perform a table lookup to get the BLER, which is quite performant.

Throughput Calculation The last step is to calculate the number of transmitted bits based on the number of available data symbols and the chosen MCS. The evaluation of the number of available data symbols is shown with the exemplary resource block shown in Fig. 19. The figure shows a resource block consisting of 12 subcarriers and 7 OFDM symbols. Of these 84 symbols, 8 are used for the transmission of cell-specific reference symbols and 7 are used for the transmission of synchronization symbols. These OFDM symbols cannot be used for data transmission, leaving 69 data symbols available for transmission in this resource block. This process is repeated for all resource blocks scheduled to the user transmission that is evaluated.

The MCS is defined through the CQI choice. To continue the example

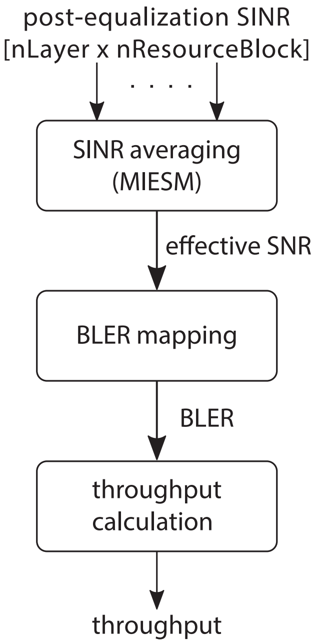


Figure 18: Schematic of the simulation results.

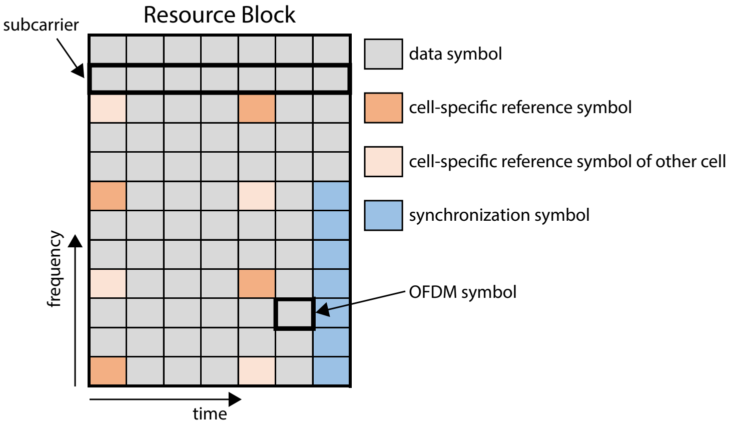


Figure 19: Exemplary resource block.

calculation, we will assume that a CQI of 15 from CQI table 1 is used for transmission and that only our exemplary resource block has been scheduled to this user. A CQI of 15 results in 64-Quadrature Amplitude Modulation (QAM) modulation and a coding rate of $\frac{948}{1024}$. With 64-QAM modulation order, 6 bits can be transmitted per symbol. Additionally, 24 Cyclic Redundancy Check (CRC) bits are transmitted. To calculate the number of bits N, we use the number of data symbols $N_{\text{data}} = 69$, the modulation order $M = 6$

and the coding rate $R = \frac{948}{1024}$, as well as the number of CRC bits $N_{\text{CRC}} = 24$

$$\begin{aligned} N &= 8 \cdot \left\lfloor \frac{N_{\text{data}} \cdot M \cdot R}{8} \right\rceil - N_{\text{CRC}} && (5.3) \\ &= 8 \cdot \left\lfloor \frac{69 \cdot 6 \cdot \frac{948}{1024}}{8} \right\rceil - 24 && (5.4) \\ &= 360 && (5.5) \end{aligned}$$

where $\lfloor \cdot \rceil$ represents the rounding operation. The rounding operation, in combination with the division and multiplication by 8, represents the transmission of data in bytes instead of individual bits.

Best CQI Throughput An upper bound throughput is calculated with the bestCQI option. This upper bound is the throughput that would result if the scheduler decides for the highest CQI that still results in a successful transmission.

Once the simulation is finished, “Show All Plots” will plot the final results, such as the network layout, BLER, SINR, and throughput. In addition to those results, there is the option to plot the LOS connections in the network layout. For example, the LOS connections between BS and user for scenarios without RIS can be plotted when the box “LOS Connections for no RIS scenario” is clicked. The option “LOS Connections for RIS scenario” plots the LOS connections for RIS-assisted scenarios, i.e., the LOS paths for BS-user, BS-RIS, and RIS-user links.

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