GIGAYASA

Broadband Wireless Simulator for 5G/B5G

A System Level Simulator

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Broadband Wireless Simulator for 5G: A System Level Simulator

Vikram Singh, Sabarinathan R. and Vijay Mareedu

ABSTRACT—Wireless Communication has been one of the most transformative technologies of this century. The first release of 5th Generation (5G) of wireless networks was released in 2018 as release-15 of 3GPP standards. This release laid down the basic framework to enable the use-cases targeted by 5G networks. Currently, 3GPP is in the process of defining the release-18, 4th release of 5G networks standards also called as 5G-Advanced. Every fresh release of 3GPP standards enables new use-cases and aims to enhance the efficiency and performance of wireless networks based on new methods, improved signaling and optimized procedures. These research ideas require state of the art tools, simulators based on latest release of 3GPP standards for performance evaluation. Such simulations are often called system level simulations and the tools used to carry out these simulations are called System Level Simulators (SLS). The SLSs mimics the devices and networks in non-real-time fashion and uses realistic models for physical phenomena such as radio channels, hardware impairments etc. This article discusses a similar tool named Broadband Wireless Simulator for 5G also called BWSim5G (R23.a)* where 23a denotes the year and release of the tool. This tool implements the scheduler and physical layer of 5G networks and supports a wide variety of features. We will elaborate the feature list and use-cases of BWSim5G (R23.a) for research, academia and industries.

Index Terms—**5G, 5G-Advanced, System level simulations, Physical layer, 3GPP, ITU, wireless standards, mobility, AAS, Beamforming, advanced antenna systems, Massive MIMO, millimeter wave, OFDM, Type-I codebooks, Type-II codebooks, Link adaptation, rank channel mModels, Uadaptation, power control, scheduler, a, UMi, RMa, InH, InF, IOO, IMO, InF-DH, InF-SL, InF-DL, InF-SH, InF-HH.**

I. INTRODUCTION

5G new radio aims to provide enhanced mobile broadband (eMBB), ultra-reliable low latency communication (URLLC) and massive machine type communication (mMTC). These use cases stand to revolutionize the industries, transport, space, smart cities, vehicles, warehouses, homes, entertainment, remote and emergencies services through Industry 4.0, vehicle to everything (V2X), non-terrestrial networks (NTN), narrow-band IoT (NB-IoT), support for reduced capacity devices (RedCaps) and XR/AR/VR devices, Drone communication, and high precision positioning. Many of these applications demand large bandwidth which is not available at 450 MHz – 6 GHz bands (FR1), hence support has been extended for millimeter wave band (FR2) as well. The air interface has been designed to leverage the benefits offered by massive MIMO and OFDM technology.

The first version of 5G standards was released in 2018 which laid the basic framework to support all the use-cases aimed by 5G-NR. From there onwards, every release of standards has enabled new applications and improved the performance of pre-existing ones. Currently, 3GPP is working on release-18 standards which, along-side many other work-items, is working on integrating artificial intelligence and machine learning in 5G networks. The 3GPP is a consortium of 7 national standards development organizations and many other market representatives who collaborate to develop standards for wireless communication networks. The national SDOs and ITU identifies the requirements for their regions and associate member explores technologies and research out ideas, signaling and procedures to meet these requirements. In 3GPP meeting the delegate evaluates their ideas and critiques the submissions from other associate companies to refine the proposals. Finally, the mutually agreed proposals are accepted as standards.

In this process the research on methods and evaluation of performance of these methods is crucial for designing very good standards. This is typically done using state of the art system level simulators (SLSs) which are based on the latest 3GPP standards. The associate members research new ideas and integrate these into the SLSs to evaluate their performance. The solutions which yield the desired performance are submitted to 3GPP meetings to request for signaling and procedure to enable these solutions. In 3GPP meetings, delegates from all the associate members discuss these ideas and finally the proposal after consensus becomes the standard. It is important to note that system level simulators play a very important role in designing and evaluating new standards. Broadband Wireless Simulator for 5G is one such simulator which supports a wide variety of use-cases and features which are elaborated in section II. The simulator is equipped with a graphical user interface for ease of use. The elements of GUI are discussed in section-III. The simulation is performed to analyze the performance of algorithms or procedures deployed in 5G networks. The performance of such methods is quantized using key performance parameters (KPIs) explained in section-IV. Finally, the paper is concluded with 10 case studies in section-V.

II. BWSIM5G FEATURES

BWSim is designed to support all the use-cases and features targeted by 3GPP. Some of those features are discussed in detail

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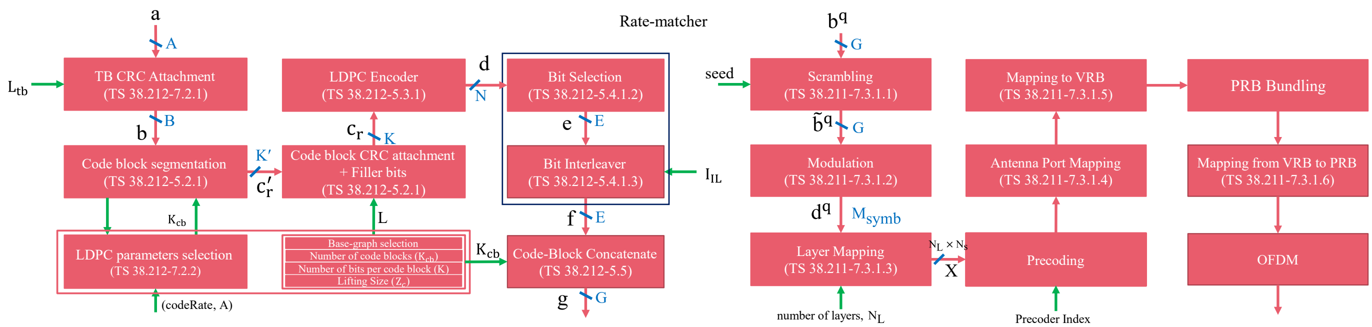


Figure 1: Physical layer processing for physical downlink shared channel (PDSCH) in 5G.

as follows.

A. Physical Channels

The physical layer accepts information from higher layers and processes it to successfully transmit it across the wireless channel. The information it receives is classified into broadcast information, control information and data information. Broadcast information, is common for all the users, is provided by the physical broadcast channel (PBCH). This information allows the UE to synchronize and connect with the base-station for communicating information. On the other hand, the uplink synchronization is carried out using the physical random channel (PRACH) The control information is provided to receivers via physical downlink/uplink control channel (PDCCH/PUSCH) to successfully decode the data information. It contains the modulation order, code rate, frequency and time resource over which data will arrive. This information is crucial for the receiver to decode the data information correctly. Finally, the data information is transmitted to the receiver using physical downlink/uplink shared channel (PDSCH/PUSCH) as shown in Figure 1. BWSim 5G implements these chains as per 3GPP standards but control channels, broadcast channel and random channels are abstracted to speed up the simulation. The overhead resulting from all the channels and procedure is considered for throughput and spectral efficiency computations.

B. Advanced Antenna Systems

Advanced antenna systems (AAS) allow the 5G radio access networks to exploit the beamforming gain and spatial multiplexing. AAS consists of AAS radio and AAS control unit which allows it to split the implement the beamforming and spatial multiplexing in both analog and digital domain. AAS allows the designer to interface large number of antennas, to exploit beam forming gain, with limited RF chain/transmit-receiver paths/transmitter, which enable spatial multiplexing, via the base-band unit to adapt the network to volatile wireless channel conditions. The architecture of AAS is shown in figure for a single panel dual polarized 8×8 uniform planner array. The 2D panner antenna array chip modules generally consist of hundreds of antennas. These antennas on the antenna arrays can be divided into sub-arrays where each sub-array is connected to an RF chain and the phase of the antennas on subarray can be controlled collectively. Each RF chain is directly connected to base-band unit antenna ports whose amplitude and phase can be controlled digitally. The [1,1,8,8,2] antenna array in Fig-[2] is split into 16 dual polarized subarrays with each subarray connected with 2 TxRU/RF, 1 for each polarization. This AAS architecture allows the baseband to steer the beam vertically by controlling the phase of subarrays using analog control unit and alter the direction of beam in horizontal direction changing the phase and amplitude of RF chains digitally. Hence, this provides the AAS the flexibility to beamform a signal in both vertical and horizontal direction. This implementation is suitable for SU-MIMO for transmitting multiple layers/streams of data to a user in a particular direction. The number of layers that can be transmitted from transmitter to receiver depends on the channel conditions and number of RF chains at transmitter and receiver. The inter-layers interference in SU-MIMO is managed by controlling the phase and amplitude of the RF

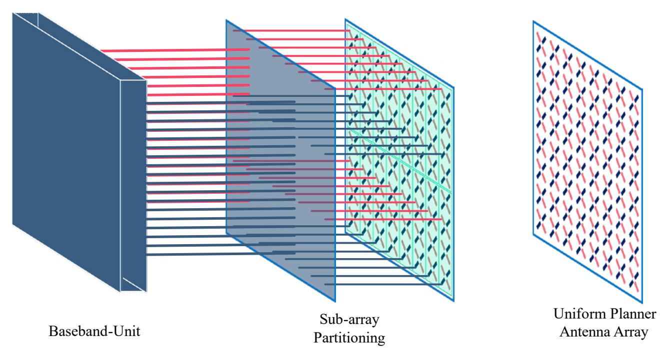
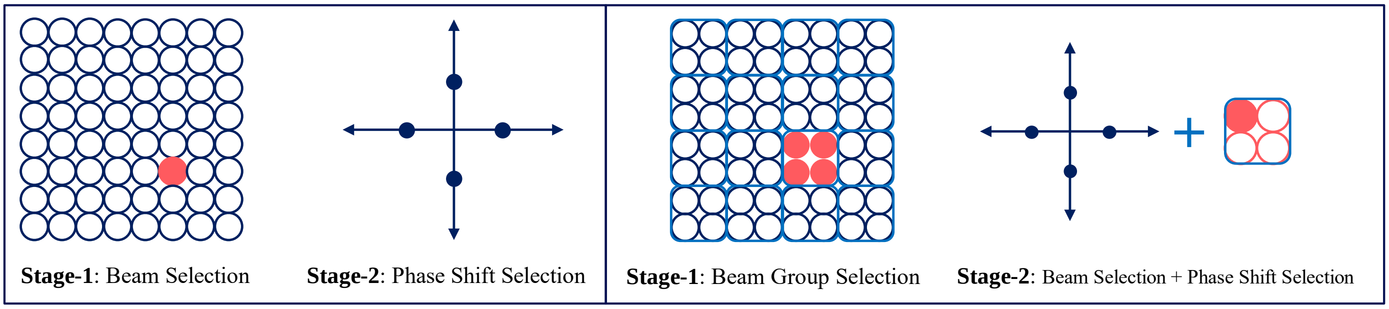


Figure 2: AAS Architecture for Antenna configurations [1,1,8,8,2] and RF chains (TxRUs) configurations [2, 8, 2].

chains. On the other hand, the multi-user interference is managed by computing null space/zero-forcing precoder using the CSI reported by each user. Its accuracy of null placement depends on the precision with which baseband controls the amplitude and phase.

C. Multiple Input Multiple Output (MIMO) Systems

5G networks, unlike 4G networks, can spatially multiplex multiple layers/streams by exploiting massive MIMO based hybrid precoding/beamforming architectures. 5G systems can be equipped with hundreds of antennas and up to 64 transceivers (32 RF chains for downlink and 32 RF chains for uplink). MIMO implementation requires the availability of CSI



(a) (b)

*Figure 3:*Type-I Codebook based Precoding process for (a) Mode-1 (b) Mode-2. Number of CSI-RS ports $(N_1, N_2) = (2,2)$ ➔ Oversampling factor $(O_1,O_2) = (4,4)$. Number of DFT beams in horizontal and vertical direction = (8, 8).

at the transmitter which can be acquired either based on reciprocity or based on feedback from the users. BWSim can be configured in both these modes for implementing the MIO. However, the reciprocity-based CSI acquisition may not work optimally for FDD systems and requires calibration of analog RF circuitry which is highly non-linear. Hence 3GPP decided to standardize the feedback-based CSI acquisition which can pose huge overhead if the SCI is reported in raw format. Hence, grid of beams (DFT codebooks based) precoder selection and reporting scheme was agreed to acquire the CSI at BS. Codebook based precoder schemes rely on UE estimating the CSI based CSI-RS and selecting a precoder matrix index (PMI) for the rank supported by the wireless channel and additional configurations provided by the BS. UE suggest the best PMI and rank indicator to BS for precoding in downlink. Currently 5G supports two types of codebooks which are discussed in the following sub-sections.

1. Codebook Type I

This codebook allows the UE to report orthogonal precoder indices from the grid of beams. This scheme supports reporting up to 8 precoders, one for each layer. The scheme is suitable for SU-MIMO as the resolution of precoders is low which might result in high inter user interference for MU-MIMO. The procedures of reporting PMI can be triggered in 2 modes. The mode-I reports a narrow beam PMI index in step-I and the phase shift for each beam in step-II. Mode-II reports the wide beam index in step-I and reports narrow beam index and phase-shift in second step. These precoders are defined for both single panel and multiple panel uniform planner arrays.

2. Codebook Type-II

To support MU-MIMO, the UE is required to report a high-resolution CSI so that adjacent UE can be segregated in spatial

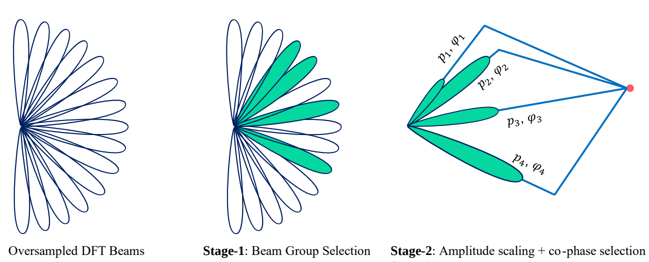


Figure 4: Type-II Codebook based precoding process

domain using orthogonal precoders. Unlike Type-I codebooks, type-II codebooks, reports multiple beam indices along with their scaling factors, amplitude, and phase values, for computing a fine resolution directional precoder for each layer and each user. Type-II codebooks can spatially multiplex up to 6 users with maximum 2 layers each. These codebooks support two modes, single panel Type-II codebooks and port selections Type-II codebooks.

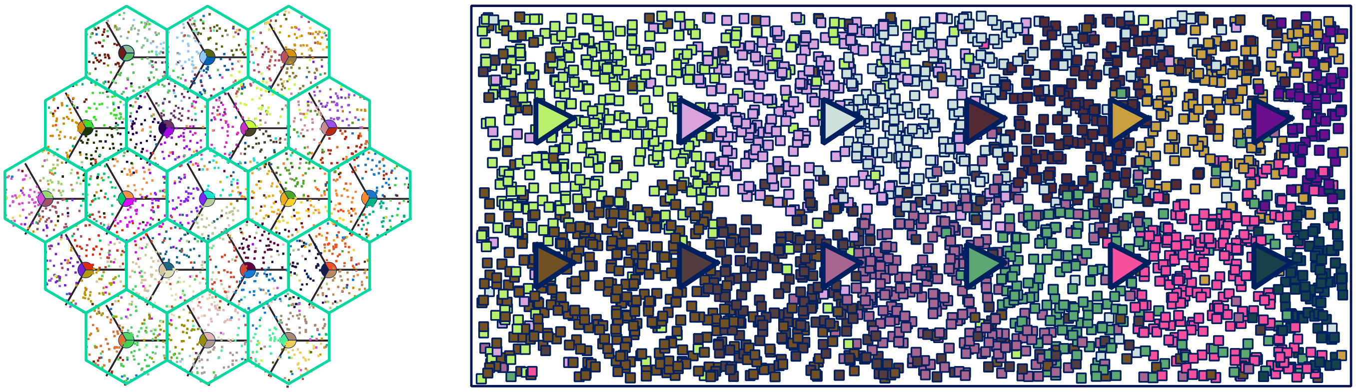
BWSim supports both these codebooks for downlink precoding. The precoder selection for MU-MIMO required the scheduler to select the suitable user pairs in spatial, time and frequency dimensions. Similarly, for SU-MIMO, the scheduler must multiplex the user across time and frequency such that the reported precoder results in efficient use of time and frequency resources.

D. System Terrains

3GPP has defined different indoor and outdoor terrains for study and evaluation. The channel models for these terrains are defined in [38.901]. The large scale and small-scale parameters for these terrains are computed using the real-world data collected by associate members in many channel-modelling campaigns. 3GPP has defined channel models for following terrains:

1) Rural Macro (RMa)
2) Urban Macro (UMa)
3) Urban Micro (UMi) canyon
4) Indoor Hotspot (InH)
   a) Indoor Open Office (IOO)
   b) Indoor Mixed Office (IMO)
5) Indoor Factory (Indoor Factory)
   a) InF-Sparse Clutter High BS (InF-SH)
   b) InF-Sparse Clutter Low BS (InF-SL)
   c) InF-Dense Clutter High BS (InF-DH)
   d) InF-Dense Clutter Low BS (InF-DL)
   e) InF-High Clutter High BS (InF-HH)

The BS can be placed in hexagonal or rectangular geometry as discussed in 38.901 based on the inter-site distance at a configured height. The UEs can be dropped randomly with uniform distribution in the network layout in wraparound fashion to simulate the symmetric intercell interference for the cells in outermost tier. BWSim supports all these terrain channel models and layouts. The 3, 7, 19 sites can be placed in



(a) (b)

Figure 5:(a) Hexagonal layout with 57 BS 3 sector deployment with ISD = 500 m and (b) Rectangular drop with 12 BS single sector with ISD = 20 m. 2000 UEs are dropped randomly in both the scenario.

a hexagonal layout with 3 sector or 6 sector coverage. Hexagonal layout is typically used for outdoor scenarios with 3 sector site deployment and rectangular layout is typically used for indoor scenarios with single sector sites. The typical values for inter-site distance, base-station heights, number of sites and UE distribution etc. are provided in [38.901].

E. Support for Frequency Range-I and Frequency Range-II

5G supports sub-6 GHz band, frequency range-I (FR1), and millimeter wave band, frequency range-2 (FR2), deployment. The FR1 is the legacy band aimed to provide coverage and capacity. It supports subcarrier spacings of 15 KHz, 30KHz and 60 KHz with bandwidth of operation up-to 100 MHz. On the other hand, FR2 is a new addition in 5G introduced primarily to support wider bandwidths for high data rate applications. FR2 supports subcarrier spacings of 60 KHz and 120 KHz to transmit data over up to 400 MHz of bandwidth. BWSim supports both FR1 and FR2 for the subcarrier spacing and bandwidth as shown in **Table 1**.

Frequency Range	Subcarrier spacing	Number of RBs	Bandwidth range
FR 1	15 kHz	25 - 270	5 MHz – 50 MHz
	30 kHz	11 – 273	5 MHz – 100 MHz
	60 kHz	11 - 135	5 MHz – 100 MHz
FR 2	60 kHz	66 – 264	50 MHz – 200 MHz
	120 kHz	32 - 264	50 MHz – 400 MHz

Table 1: Frequency ranges, subcarrier spacing, and bandwidth supported by BWSim.

F. Duplexing schemes

The 5G air-interface is designed based on OFDM waveform and OFDMA multiple access. 5G supports both frequency division duplexing (FDD) and time division duplexing (TDD). The TDD allows the network to dynamically switch between uplink and downlink. BWSim allows the users to pass TDD configurations at slot level and symbol level. The configurations passed are numerology specific as shown in Figure 6.

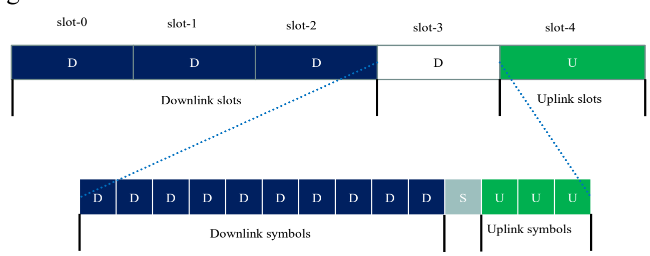


Figure 6: TDD configuration for 15 KHz subcarrier spacing with 2 slots and 10 symbols in DL and 1 slot and 3 symbols in UL.

G. Multiple Numerology Support

Generally, in system level simulations the subcarrier spacing for all the UEs is assumed to be same. However, practically different UEs can be configured with different numerologies. BWSim allows the user to pass numerology specific configurations for CSI estimation, CSI-RS transmission, periodicity, reporting delays and TDD configurations.

H. Adaptive Networks

Practical wireless channels are very dynamic and volatile which makes it difficult for the transmitter to convey the bits reliably to the receiver over the wireless channel. To counter this, 5G radios use forward error correction at the transmitter. Transmitter informs the receiver about the code rate and modulation order using DCI over PDCCH. However, using a fixed modulation order and code rate for data transmission may not be efficient. To achieve the optimal performance, these parameters need to be adapted according to channel conditions. The process of adapting the modulation order and code rate (MCS) as per channel conditions is called ***link adaptation***. BWSim implements the link adaptation using a standardized parameter termed channel quality index (CQI). This parameter is reported to BS by UE as a part of CSI measurements.

Another similar parameter is channel rank, which indicates the number of layers/streams that can be transmitted from BS

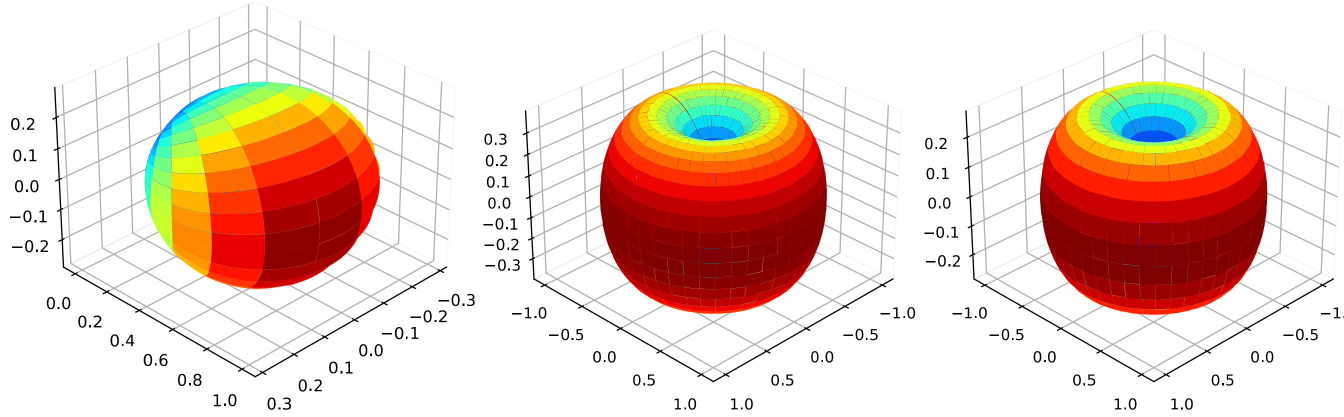


Figure 7: Radiation pattern for (a) Parabolic antenna [38.901] (b) Hertzian Dipole (Omni Directional) antenna (c) Linear Dipole

to UE. In practice, transmitting too many layers can degrade the network performance due to inter-layer interference specifically in ill-conditioned channels with very high condition number. BWSim ***rank adaptation*** feature allows the transmitter to select the suitable number of layers for SU-MIMO and MU-MIMO for affect transmission. Few other features of adaptive networks are covered in J. Scheduler.

I. Reference Signal Configurations

5G standards have defined many reference signals for handing channel and system impairments such as channel sounding, channel estimation, equalization, clock frequency and phase offset estimation. BWSim allows the user to configure the transmitter to transmit such reference signals with different periodicity, density, offset etc. and report the corresponding measurements considering the processing delay, reporting delay etc. based on the simulation requirements.

J. Scheduler

An important element of wireless networks is the *scheduler* which allocates resources to the UEs requesting network access for exchanging information. The scheduling is done based on many parameters such as link quality, network traffic, time frequency resources available for communicating information, volume of bits to be exchanged, arrival time of user request etc. BWSim implements a round robin and proportional fair scheduler which performs following tasks:

1) Appropriate resource blocks allocation to users
2) User-pairing over time and frequency resources for:
   a) SU-MIMO
   b) MU-MIMO
3) Link adaptation
4) Rank adaptation
5) Power control

K. Simulating Multiple Node Types

Typical system level simulation considers all the UE nodes of the same type and same capability. However, this might not be practically true as a BS might be serving a mobile phone, an internet of thing device or a drone etc. BWSim allows to simulate heterogenous node with different configurations and capabilities.

L. Mobility Models

BWSim simulates the UEs with arbitrary speed profiles to consider the effect of Doppler on the system performance. Users can create multiple nodes with different speed profiles to compare the performance against each other. The mobility models considered by the simulator is as per [38.901].

M. Antenna Models

Antenna radiation pattern plays a crucial role in Massive MIMO‘s ability to exploit spatial multiplexing and beamforming gain. Highly direction antennas often have low rank MIMO wireless channel but can allow high beamforming gain. On the contrary, the wide beam antennas have wider coverage, higher rank channels but have low beamforming gain. BWSim allows simulation using parabolic and omni directional antenna. However, custom antenna patterns can also be configured for evaluation using system level simulations.

N. Receiver Aspects

As 3GPP doesn’t lay down the standards for receivers, the implementation of receiver is proprietary and complements the transmitter. There are many complexity and performance tradeoffs that exist in receiver implementation.

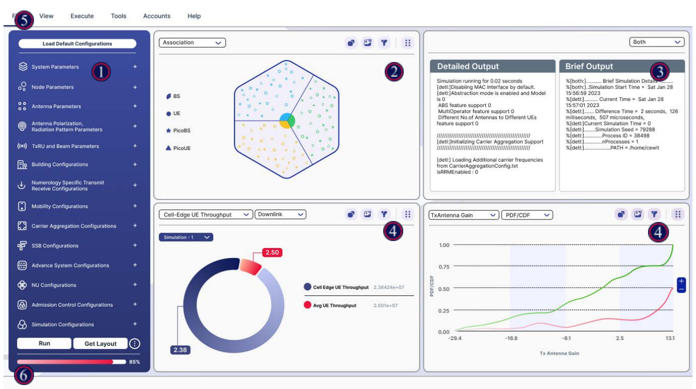
O. Type of Simulations

BWSim can be used for performing link level simulation using Jakes model. The *link level simulation* allows to plot the key performance parameters against the SNR. These simulations confirm the efficacy of algorithms for different SNR conditions.

On the other hand, the *system level simulations* assume the SNR to be a free parameter. The SNR of link depends on the propagation conditions and link state. These simulations evaluate the throughput, spectral efficiency, resource utilization, reliability of communication (BER) and coverage and cell edge throughput performance From UE and network perspective. The SLS are generally intense and might take a few hours. User can perform a quick low fidelity version of the SLS called multi-cell simulation. These simulations provide information about channel gain, antenna gain, link gain, received power (RSRP), received signal quality (RSRQ), signal to noise and interference ratio (SINR), signal to interference ratio (SIR), signal to noise ratio (SNR), path-loss and line of sight probability of each UE-BS link. The detailed about the simulations is provided in IV. Simulation Key Performance Parameters.

III. BWSIM GRAPHICAL USERS INTERFACE

5G networks are more flexible compared to 4G networks which results in more parameters which the users will have to configure to perform simulations. Many of these parameters are inter-related which make it further difficult to pass these input parameters. To handle this complexity, BWSim is integrated with a graphical user interface (GUI) which simplifies the process of configuring the parameters for the simulations. A few of the features of the BWSim GUI are defined in the following sub-section.



1. Configuration/Input Panel
2. Layout of UEs & BSs
3. Detailed & Brief Output Panel
4. Evaluation Panels
5. Menu Bar
6. Status Bar

Figure 9: BWSim-5G Graphical User Interface

A. Ease of Passing Configuration

BWSim-GUI provides a very simple interface for passing configurations for the simulation. The GUI captures the relations and dependencies between the parameters to assist users to set the configurations. For example: The TxRUs/RF-Chain parameters in AAS and number of ports in Type-I/II codebooks are related. The simulator captures such dependencies to aid users while interacting with BWSim. Furthermore, the GUI provides interaction with configurations to provide feedback to users to confirm whether they are entering the current inputs.

B. Multiple Simulation Setup

BWSim-GUI allows the users to run multiple simulations one after another and compare the evaluation results of these simulations.

C. Sequential Simulations

Many times users with to carry out many simulations in automatic mode. BWSim-GUI allows the users to place many configurations in a specific folder and run them sequentially without any involvement of the user. The results of all the simulations is stored in the respective folders/directories in the format user desires. The results can be saved as logs, images and/or raw format.

D. Importing and Exporting Simulation Logs

The simulation results can be exported to the desired location for further use in images format, log files or raw BWSim format. Similarly, these simulation result files can be imported for visualizations or further comparison with other results. The GUI allows import and export simulation configurations for future use.

E. Sharing the Simulation Results

The user can input their email-ID to GUI via setting and choose to receive the results of each simulation via email-ID.

F. Reporting Issues

BWSim-GUI provides an interface tousers to report any issues, provide suggestions and feature requests for future versions of the BWSim releases.

G. Interactive Evaluation Plots

BWSim-GUI provides interactive evaluation plots to users. Users can modify the properties of the evaluation plots such as line width of the plots, line colors, line markers, line marker colors and line marker size etc.

IV. SIMULATION KEY PERFORMANCE PARAMETERS

The performance of a method or procedure is evaluated based on performance metrics. The metrics used in BWSim for performance evaluation of different simulation types.

A. Link Level Simulation

In link level simulations, the users control the signal to noise ratio (SNR) of the linkand evaluate the performance of each SNR point.

1) Bit error rate (BER) vs SNR
2) Spectral Efficiency vs SNR
3) Block Error Rate (BLER) vs SNR
4) Throughput vs SNR
5) Pre-processed and Post-processed SINR vs SNR

B. System Level Simulation

System level simulations compute the following parameters to evaluate system performance.

1) CDF of Througput
2) CDF of Spectral Efficiency
3) CDF of BLER
4) Throughput vs UE-Index
5) Spectral Efficiency vs UE-Index
6) BLER vs UE-Index
7) Throughput vs BS-Index

8) Spectral Efficiency vs BS-Index
9) BLER vs BS Index

C. Multi-cell Simulation

Multi-cell simulation computes the parameters related to channel/link. These parameters includes:

1) CDF of Transmit Antenna Gain
2) CDF of Link Gain
3) CDF of Channel Gain
4) CDF of Signal to Interference and Noise Ratio (SINR)
5) CDF of Signal to Interference Ratio (SIR)
6) CDF of Reference Signal Received Power (RSRP)
7) CDF of Reference Signal Received Quality (RSRQ)

V. CASE STUDIES AND CONCLUSION

We have briefly listed customer case studies related to BWSim. In the subsequent paper, a detailed analysis of each case scenario with best practices learned during deployment will be examined.

A. Case Study-1: Effect of cell-size & terrain on the down tilt angle

The area spectral efficiency varies with the down tilt angle.This study shows variation in optimal down tilt angle. With size of the cell for Rural, Urban and Indoor terrains.

B. Case Study-2: Performance comparison of Type-I and Type-II Precoder

3GPP has standardized two precoding schemes,Type-I Precoder and Type-II Precoder, to support MIMO and beamforming for SU-MIMO and MU-MIMO systems. This study analyzes the performance of both these schemes for different antenna.

C. Case Study-3: Comparative Analysis of Different radio units

5G supports deployment of different radio units such as 2x2, 4x4, 8x8, 16x16 and 32x32 etc. This study analyzes the throughput and coverage of these radio Unit deployment in different terrains of different cell-size.

D. Case Study-4: Comparative analysis of different channel coding schemes

5G uses 4 different channel coding schemes. This study compare the link-level and system level throughput and reliability performance for different SNR and block lengths.

E. Case Study-5: Performance analysis of different antenna configurations

This study demonstrate the variation in network performance (link level and system level) with different antenna parameters such as beam-width, radiation patterns, sidelobe levels, number of antenna elements and geometry of antenna elements.

F. Case Study-6: Performance gain in Adaptive 5G networks

The network parameters such as transmission power, code rate, modulation order, scheduling, rank can be adapted based on the channel conditions. This study demonstrates the improvement in performance for adaptive networks.

G. Case Study-7: Interferences in 5G-NR Multicell Systems

This study analyzes ways to reduce Inter-user Interference caused by User Equipment (UE) devices and of Inter-cell Interference caused by ultra-dense 5G-NR networks, where a large number of cells are deployed in close proximity to one another.

H. Case Study-8: Indoor Terrains and their characteristics

This study analyzes the performance of Indoor Hotspot using Small Cells or Distributed Antenna Systems and Indoor Factory for real-time monitoring and control of machining centers and predictive maintenance of weld and paint robots.

I. Case Study-9: Line of sight models for Wireless Channel

This study estimated performance of Line of Sight Probability Models for indoor environment while considering building density in the surrounding area.

J. Case Study-10: Modulation schemes in 5G-NR

This study analysed effect of channel distortions and noise in Symbol Mapping and Symbol Decoding techniques.

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