WiSE: A System-Level Simulator for 5G Mobile Networks

Chin-Kuo Jao, Chun-Yen Wang, Ting-Yu Yeh, Chun-Chia Tsai, Li-Chung Lo, Jen-Hsien Chen, Wei-Chen Pao, and Wern-Ho Sheen
Industrial Technology Research Institute (ITRI)

Introduction

With an increasing demand for new generation mobile networks, ITU Radiocommunication Sector (ITU-R) has set forth key technical performance requirements for the development of the IMT-2020 system, also known as the fifth generation (5G) system [1], and has started to invite submissions of candidate radio interface technologies for IMT-2020 [2]. To ensure that IMT-2020's requirements can be met, the submitted candidate radio interface technologies will be evaluated by independent evaluation groups under the evaluation guidelines of Report ITU-R M.[IMT-2020.EVAL] [3], where system-level simulation is employed as the major tool for the performance evaluation of various application scenarios.

Unlike a link-level simulation, where only the link between a base station (BS) and a user equipment (UE) is evaluated, system-level simulation simulates a large number of BSs and UEs in a vast service area, where links between BSs and UEs may interfere with each other, as can be seen in Fig. 1. Hence, the network performance including system throughput, cell average packet throughput, UE average packet throughput, cell spectrum efficiency, cell edge user spectrum efficiency, packet retransmission number, packet loss rate, latency, handover rate, fairness, and so on can be evaluated in a comprehensive way. Nowadays, system-level simulations have been widely used in specification developments, equipment verification, network planning, and academic research.

System-Level Simulator for LTE and 5G NR

A powerful system-level simulator, Wireless Simulator Evolution (WiSE), has been released in [4] for performance evaluation of 4G/LTE and 5G mobile networks. WiSE was originally developed for the evaluation of 4G networks following the LTE specifications. Currently, it supports LTE Rel-14 including the key functions of enhancements on full-dimension multiple-input multiple-output (eFD-MIMO), with beamformed channel state information-reference signal (CSI-RS) transmission, Class A precoder for 32 antenna ports, and advanced CSI feedback. WiSE has been validated with the Third Generation Partnership Project (3GPP) calibration campaigns, and some of the calibration results are presented in the next section.

Very recently, WiSE has been extended to include key designs introduced in 5G New Radio (NR). Specifically, WiSE has the following salient features.

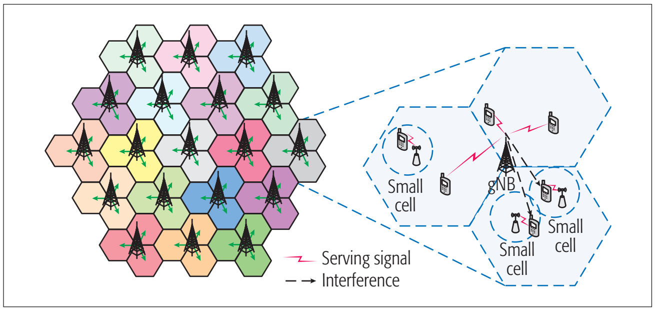

FIGURE 1. A typical network layout of system-level simulation.

New 5G Channel Model

WiSE implements all of the test environments defined in Report ITU-R M.[IMT-2020.EVAL] [3], namely Indoor Hotspot, Dense Urban, Rural, and Urban Macro test environments, with the corresponding 3D channel models. In the 5G channel model, new propagation characteristics are captured in order to support frequencies up to 100 GHz and 3D channel modeling, where both the horizontal and vertical spatial characteristics are considered. In addition, as shown in Fig. 2, WiSE implements the additional channel features specified in [5], which was modeled to support advanced simulations such as simulations with very large arrays and large bandwidth, simulations affected by oxygen absorption, simulations with spatial consistency, simulations of mobility, and simulations of blockage effects.

5G NR Radio Access Technologies

In order to fulfill the performance requirements of the IMT-2020 system, 3GPP is now working on the development of 5G NR technical specifications that enable flexible deployment of various services across different usage scenarios: enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine type communications (mMTC). In this respect, WiSE has been evolved following very closely the progress of 3GPP 5G NR specifications. So far, 5G new radio technologies such as scalable numerologies (subcarrier spacing, cyclic prefix), flexible duplex where DL and UL transmission directions can be dynamically changed on a per-slot basis, and code block group (CBG)-based transmission in which hybrid automatic repeat request (HARQ)-ACK feedback and retransmission can be done per CBG are already supported in WiSE. In addition, WiSE supports the simulation of NR-MIMO scenarios where beam sweeping and hybrid beamforming technologies are realized with planar antenna array and back-to-back panel structure.

Simulation Efficiency

As new technologies have been introduced into 5G, it becomes more challenging to carry out a 5G system-level simulation in an efficient manner. First, NR has designed a large

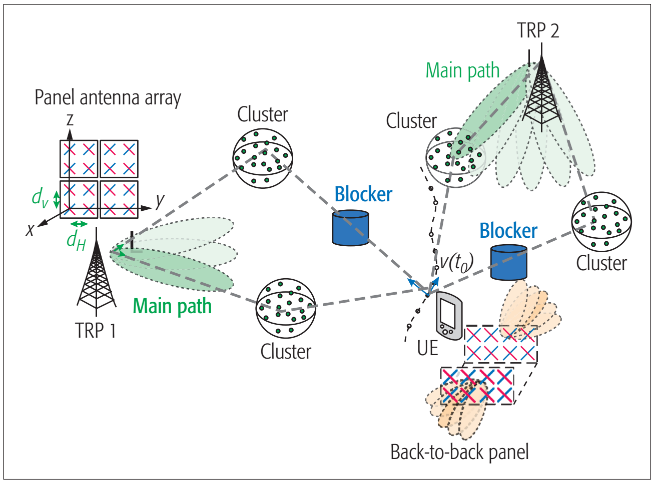

FIGURE 2. Illustration of 5G channel model and system-level simulation scenario.

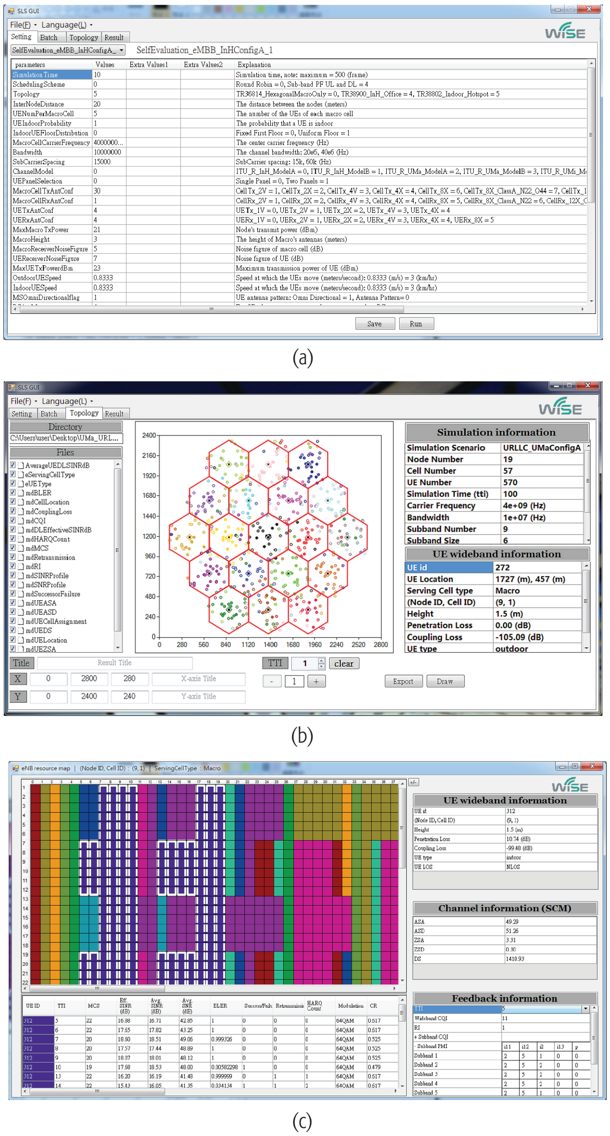

FIGURE 3. a) WiSE GUI for setting up simulation parameters; b) WiSE GUI depicts network layout and UE locations; c) time-frequency resource map in WiSE GUI.

Parameter	Value
Carrier frequency	Macro layer at 30 GHz
BS antenna height	25 m
Total transmit power per TRP	37 dBm for 40 MHz bandwidth
UE power class	23 dBm
Inter-site distance	200 m
TRP antenna elements	256Tx/Rx, $(M, N, P, M_g, N_g) = (4,8,2,2,2)$, $(d_H, d_V) = (0.5, 0.5)\lambda$. $(d_{g,H}, d_{g,V}) = (4.0, 2.0)\lambda$, +45°, -45° polarization
TRP TXRU configuration	8TXRU, $(M_p, N_p, P, M_g, N_g) = (1,1,2,2,2)$
UE antenna elements	32Tx/Rx, $(M, N, P, M_g, N_g) = (2,4,2,1,2)$, $(d_H, d_V) = (0.5, 0.5)\lambda$ $(d_{g,H}, d_{g,V}) = (0, 0)\lambda$. $\Theta_{mg,ng} = 90$; $\Omega_{0,1} = \Omega_{0,0} + 180$; 0°, 90° polarization
UE TXRU configuration	4TXRU, $(M_p, N_p, P, M_g, N_g) = (1,1,2,1,2)$
Antenna element gain	8 dBi for BS; 5 dBi for UE
UE speeds	Indoor users: 3 km/h; outdoor users (in-car): 30 km/h
Noise figure	7 dB for BS; 10 dB for UE
Traffic model	Full buffer
UE density	10 UEs per TRP
Channel model	UMa_A or UMa_B
TRP boresight	30/150/270 degrees
Beam set at TRP	Azimuth angle $\varphi_i = [-5*pi/16, -3*pi/16, -pi/16, pi/16, 3*pi/16, 5*pi/16]$ Zenith angle $\theta_j = [5*pi/8, 7*pi/8]$
Beam set at UE	Azimuth angle $\varphi_i = [-3*pi/8, -pi/8, pi/8, 3*pi/8]$; Zenith angle $\theta_j = [pi/4, 3*pi/4]$;
Criteria for analog beam selection for interfering TRP	Random selecting the random beams for non-serving TRP

TABLE 1. Simulation assumption for dense urban – eMBB.

number of MIMO precoding matrices, which results in a huge memory demand, especially for the NR Type II codebook. The precoding matrices are usually pre-generated and stored for speeding up the simulation time. However, according to our experiments, it is not realistic to store all precoding matrices of the NR Type II codebook. An efficient implementation is considered in WiSE by separating the precoding matrix $\mathbf{W}$ as a product of matrices $\mathbf{W_1}$ and $\mathbf{W_2}$. Only $\mathbf{W_1}$ and $\mathbf{W_2}$ are pre-stored in the WiSE simulator. $\mathbf{W}$ can be synthesized easily by applying $\mathbf{W} = \mathbf{W_1 W_2}$ operation that saves a great deal of computation memory.

Furthermore, the biggest challenge comes from the beam sweeping mechanisms, where multiple high-gain beams with narrow beam width are applied at both the transmit and receive point (TRP) and UE sides. Each TRP sweeps a Tx radio beam sequentially in time while the UE maintains a proper Rx beam to enable reception of the selected Tx beam. Consider a typical simulation of a dense urban scenario (e.g., in 3GPP TR 38.802 [6]) where a mobile network consists of 57 cells, each of which contains 10 UEs located within the geographic coverage. If each TRP (or cell) has 6H2V (6 horizontal and 2 vertical) Tx beams, and each UE has 4H2V (4 horizontal and 2 vertical) Rx beams; then there are 96 Tx-Rx beam pair links in total between a TRP and a UE. If the size of antenna elements is large, based on our experiments, 30-hour simulation time is needed only for cell assignment, not to mention the subsequent beam management procedure and beam-level mobility.

To speed up the simulations, WiSE adopts a smart mechanism that only takes significant links into consideration to handle the issue of the beam sweeping. With this mechanism, it turns out 60 percent of simulation time can be saved with negligible loss of precision. In addition, in order to further save simulation time, WiSE also utilizes the parallel processing methods, so it can be executed efficiently in a large-scale cloud server system. As a consequence, the WiSE simulator has been designed to greatly improve simulation efficiency.

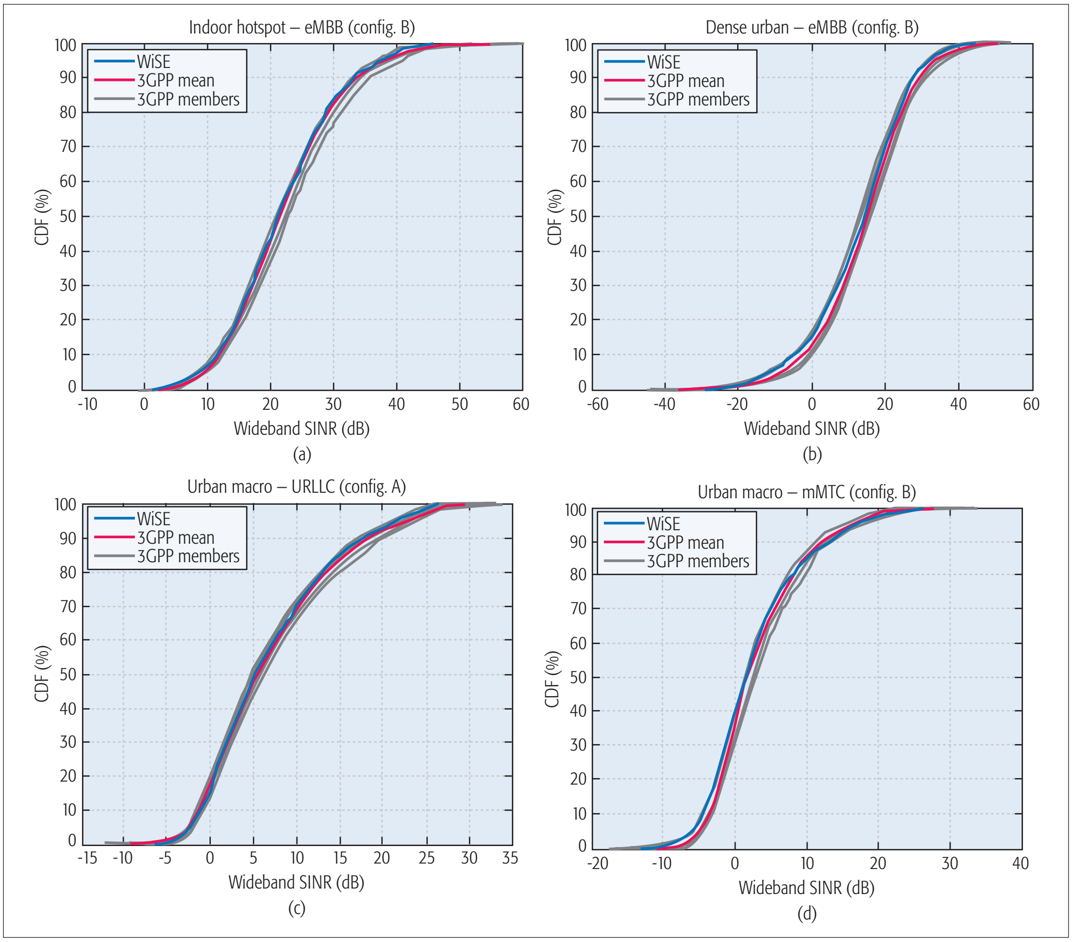

FIGURE 4. WiSE calibration results of the wideband SINR for: a) indoor hotspot — eMBB; b) dense urban — eMBB; c) urban macro — URLLC; d) urban macro — mMTC test environments.

Graphical User Interface

WiSE is equipped with a GUI tool by which we can observe the simulated system behaviors and debug the simulation codes in a visual way. As shown in Fig. 3a, the WiSE GUI tool provides a friendly interface for setting up the simulation parameters and triggering the execution of the WiSE simulator. Also, it can be seen from Fig. 3b that the WiSE GUI can depict the network layout and UE locations in the simulated environment, and summarize the simulation parameters and the UE wideband information on the right side. In addition, each UE is colored based on its serving cell; for example, a red UE means that the UE is served by the red cell. Therefore, Fig. 3b also demonstrates that UEs are not necessarily served by the nearest base station, but by the one with the best signal quality. Besides, it is worth mentioning that there is a transmission time interval (TTI) option at the bottom of the WiSE GUI. That can be used to observe UEs who are served at the selected TTI, and to observe the direction of beams formed at this TTI when the beam sweeping mechanism is applied.

Once we click a UE icon on the GUI tool in Fig. 3b, the WiSE GUI would pop up another window, as shown in Fig. 3c, to present the details of the scheduling information for the UE. First of all, the new window includes a time-frequency resource map, which specifies the allocated resource blocks (RBs) every TTI used for the UE. Besides, there is a table under the resource map recording the communication states of the UE for each transmission and reception, including the applied modulation and coding scheme (MCS) index, signal-to-interference-plus-noise ratio (SINR), block error rate (BLER), HARQ retransmission, and so on. At last, the UE's spatial channel information (including ASA, ASD, ZSA, ZSD, and DS) as well as the CSI feedback information (e.g., RI, wideband PMI, sub-band PMI, wideband CQI, and sub-band CQI) can also be found in the window as well. Consequently, supplementing the simulator, the WiSE GUI is a useful tool not only for analyzing the system behaviors, but also for figuring out the reasons behind the simulation results.

Calibrations

One of the most important performance metrics of a system-level simulator is the accuracy of simulation results. Because the system-level simulator is very complicated, the simulation results of different organizations involved in 3GPP standardization are not quite the same. In order to fairly compare the techniques proposed by companies, 3GPP usually holds calibration campaigns to align system-level simulation results of different companies. For example, the 3D channel model is calibrated [7] for the two-dimensional codebook designs of Rel-13 FD-MIMO, and the NR-MIMO calibration was used to check the high-frequency channel model [5], the basic 3D beamforming architecture, and the UE movement/rotation/blockage behaviors.

Recently, a new study item on self-evaluation toward IMT-2020 submission was approved by 3GPP [8]. The objective of this study item is to provide self-evaluation results of 3GPP NR specifications toward IMT-2020 submission against the technical performance requirements defined by Report ITU-R M.[IMT-2020.TECH PERF REQ] [1]. Before the discussion of self-evaluation, a calibration campaign for this study item was held to align the performance metrics among different companies' simulators. In addition, common understandings on baseline parameters and evaluation configurations for test environments can be reached during the calibration process. In this section we illustrate the calibration parameters and show the simulation results of WiSE.

The calibration procedure has five test environments for the three usage scenarios (eMBB, URLLC, and mMTC). The five test environments are indoor hotspot — eMBB, dense urban — eMBB, rural — eMBB, urban macro — mMTC, and urban macro — URLLC. Each test environment has multiple evaluation configurations as defined in [3]. Table 1 shows the baseline parameters for dense urban — eMBB config. B, and more detailed parameter settings can be found in [9]. The antenna elements of each panel map to one transceiver unit (TXRU) by applying 2D discrete Fourier transform (DFT) virtualization weights. Total 12 (6H2V) and 8 (4H2V) analog beams are considered at the TRP and UE sides, respectively. The best beam pair link is selected based on the maximum receiving power after beamforming. It should be noted that only one UE panel with maximum power is chosen (i.e., no combining is done between back-to-back panels).

The calibration metrics are coupling loss and downlink geometry (wideband SINR). The correctness of network deployment, antenna setting, penetration loss model, above 6 GHz channel model, UE distribution, and beamforming behavior can be diagnosed based on observing the cumulative distribution function (CDF) of coupling loss. On the other hand, the statistics of wideband SINR can be used to check coupling loss and interference calculation. Figure 4 shows the calibration results of the WiSE simulator for the four test environments. Compared to the 3GPP results, the WiSE curves are quite aligned with the curves contributed from other 3GPP companies. These calibration results verify the correctness of WiSE 5G functionality and the reliability of WiSE simulation results.

Conclusions

System-level simulation has become more and more essential for evaluating the performance of newly developed radio access technologies. From our viewpoint, WiSE is an efficient system-level simulator with simulation results validated by 3GPP calibration processes, and has been released for the use of the industrial and academic communities. The WiSE simulator is implemented by object-oriented programming in C++, and its source code is accessible, so it can easily be used to compare the performance gaps between a newly developed technique and the existing ones. As 3GPP standards continue evolving, WiSE simulator will be continuously upgraded in line with the functionalities of the newest mobile communication systems.

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