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5G is Real: Evaluating the Compliance of the 3GPP 5G New Radio System With the ITU IMT-2020 Requirements

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ABSTRACT The 3rd Generation Partnership Project (3GPP) submitted the 5G New Radio (NR) system specifications to International Telecommunication Union (ITU) as a candidate fifth generation (5G) mobile communication system (formally denoted as IMT-2020 systems). As part of the submission, 3GPP provided a self-evaluation for the compliance of 5G NR systems with the ITU defined IMT-2020 performance requirements. This paper considers the defined 5G use case families, Ultra Reliable Low-Latency Communication (URLLC), massive Machine Type Communication (mMTC) and enhanced Mobile Broadband (eMBB), and provides an independent evaluation of the compliance of the 3GPP 5G NR self-evaluation simulations with the IMT-2020 performance requirements for connection density, reliability, and spectral efficiency for future mobile broadband and emerging IoT applications. Independent evaluation indeed shows the compliance of the 3GPP 5G NR system with the ITU IMT-2020 performance requirements for all parameters evaluated by simulations.

INDEX TERMS mMTC, eMBB, URLLC, IoT, 5G, 5G NR, LPWA, connection density, simulation framework, spectral efficiency, evaluation, 3GPP, IMT-2020.

I. INTRODUCTION

Mobile communication applications have shifted from basic voice telephony to empowering a wide range of verticals across various industries, most notably via the rapidly expanding Internet of Things (IoT) applications, and are expected to continue to grow, occupy an integral part of our lives and ultimately transform societies as a whole [1], [12], [13]. While the fourth generation of mobile communication systems, formally referred to as International Mobile Telecommunications-Advance (IMT-Advanced) systems, provided a versatile platform for enabling a wide range of Mobile Broadband applications (and, to a certain extent, Low Power Wireless Internet of Things (IoT) applications [12]), the increasing potential for disruptive IoT applications with very high deployment densities (millions of devices in a relatively small areas) was one of the main motivators for the development of the next generation of mobile communication systems, the International Mobile Telecommunications-2020 (IMT-2020) commonly referred to as 5G – the fifth generation of mobile communication systems. The other motivators were increasing demand for enhanced mobile broadband services and the vast potential for mobile communications providing ultra-low latency and ultra-high reliability [1]–[3] for higher frequencies [24].

Candidate IMT-2020 systems are undergoing a rigorous evaluation process to ensure they fulfill the requirements set out by the International Telecommunication Union (ITU) for IMT-2020 systems, illustrated in Fig.1, to meet the performance requirements of emerging 5G applications, commonly grouped into enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC) and massive Machine Type Communications (mMTC) [1]–[5], [25]. The prime IMT-2020 candidate system, the 5G New Radio (NR) system developed by the 3rd Generation Partnership Project (3GPP) [6]–[10], promises to fulfill the IMT-2020 system requirements set out by the ITU [2]–[5] as detailed in the 3GPP self-evaluation submission [11]. Nevertheless, it is of utmost importance to independently verify the

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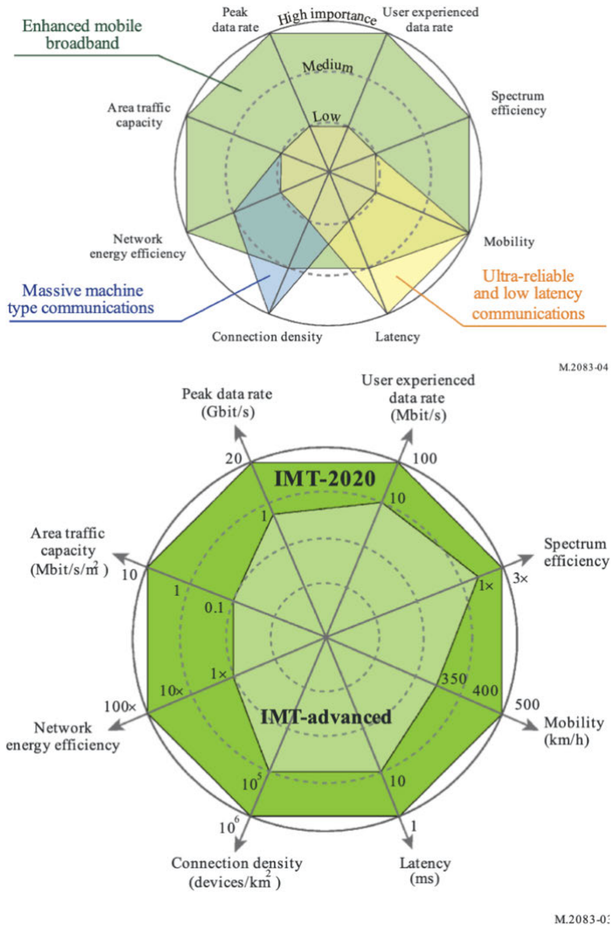

FIGURE 1. IMT-2020 use case scenarios (top) and performance requirements (bottom) (reproduced from [7]).

validity of the 3GPP submission prior to officially declaring the 5G NR system as an IMT-2020 compliant system.

This paper focuses on assessing the performance of the 3GPP 5G NR system for applications in the areas of massive Machine Type Communications (mMTC), Ultra-Reliable Low-Latency Communications (URLLC) and enhanced Mobile Broadband (eMBB), which are expected to play an integral role in future Internet of Things (IoT) applications, with focus on key parameters evaluated by system simulations to providing an independent evaluation to the compliance of the 3GPP submitted 5G NR self-evaluation simulations [11] via a custom simulator, which considered numerous academic and industrial simulations [14], [18]–[21] and compares the results of 3GPP developed simulations by companies such as Huawei, Ericsson, Intel and NTT Docomo among others. Some of these applications include, but are not limited to: smart wearables, health monitors, autonomous driving, and remote computing [25].

The contributions of this work are as follows: (i) a detailed system-level simulator for evaluating 5G candidate systems and (ii) an evaluation of the simulator performance in achieving 5G requirements for IMT-2020 in comparison with other

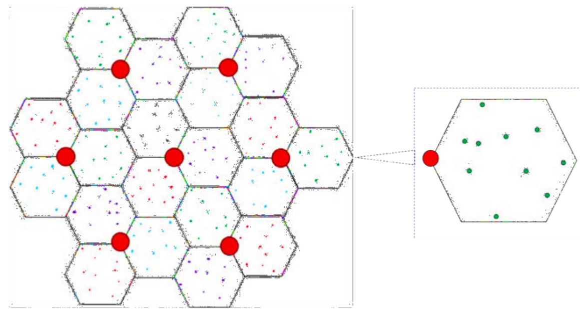

FIGURE 2. Urban Macro, Urban Micro, and Rural scenarios with UE distribution (UEs with the same color communicate with the same base station).

industrial simulators for multiple test environments. The rest of this paper is as follows. Overviews of IMT-2020 system requirements, evaluation processes and scenarios are in Section II. The system structure for performance evaluation and additional features are detailed in Section III. Section IV discusses the system setup and methodology for simulation and the simulation results are detailed in Section V. Section VI concludes the paper and the appendix details tables providing requirements and results for each assessment as well as the results.

II. SYSTEM REQUIREMENTS, EVALUATION PROCESS, AND SCENARIOS

A. EVALUATION GUIDELINES

The simulator acts as an evaluation tool for the submitted 3GPP proposal [7] as per the specified evaluation methodology and configurations in the 3GPP report. System-level and link-level simulations are performed using our simulation tool to provide an independent evaluation of the 3GPP self-evaluation, which provides a complete compliance documentation for several technologies with the minimum IMT-2020 performance requirements.

B. TEST ENVIRONMENTS

Five specific test environments are defined [22], [23] for evaluating compliance with the performance requirements of IMT-2020 systems: Indoor hotspot-eMBB, Dense Urban-eMBB, Rural-eMBB, Urban Macro-mMTC, and Urban Macro-URLLC. Simulation of all test environments (with the exception of Indoor Hotspot-eMBB) uses a wrap-around configuration of 19 sites as shown in figures 2 – 4, each of 3TRxPs (cells) creating a hexagonal layout.

Antenna element distribution, cell range, and inter-site distance (ISD) is considered for geometry. The indoor hotspot scenario models a 120m x 50 m building floor with 12 Base stations placed 20 meters apart as per Figure 3. The Dense urban area consists of a macro layer following a 3-TRxP hexagonal layout, and a micro layer with 3 micro-sites randomly dropped in each TRxP area a number of user equipment (UE) distributed in the area. The rural eMBB test environment follows the macro layer of the dense urban

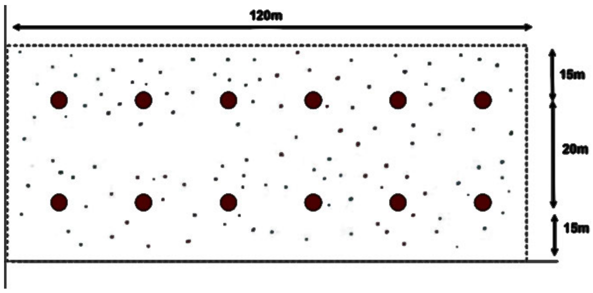

FIGURE 3. Indoor scenario with 12 access points (larger circles) and distributed users (smaller circles).

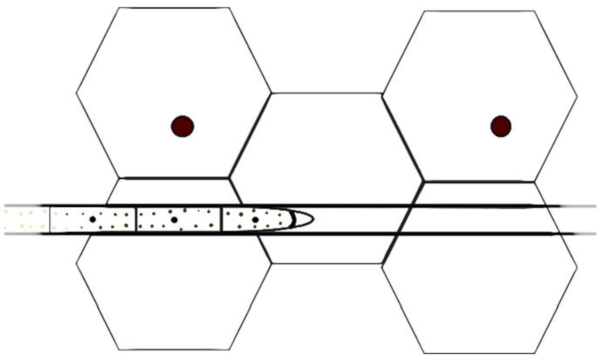

FIGURE 4. High speed mobility scenario (large circles are basestations, small circles are UEs).

area. A high-speed test environment is shown in figure 4 for mobility scenarios of UEs moving at 30 km/h, 120 km/h, and 500 km/h.

C. EVALUATION CRITERIA

For evaluating system performance using simulations, the following key parameters are taken into consideration:

1) SPECTRAL EFFICIENCY

The average spectral efficiency is obtained by running system-level simulations over a number of drops for each of the following three test environments: Indoor Hotspot-eMBB, Dense Urban-eMBB, and Rural-eMBB. Each drop is a sum of correctly received bits by all users over time as per the following equation [7]:

$$\widehat{SE}_{avg} = \frac{\sum_{j=1}^{N_{drops}} \sum_{i=1}^{N} R_i^{(j)}(T)}{N_{drops} T.W.M} \tag{1}$$

where $\widehat{SE}_{avg}$ is the estimated average spectral efficiency that approaches the average by increasing the number of N_{drops}, $R_i^{(j)}(T)$ is the correct number of received bits during time T for user i in drop j, W is the channel bandwidth, N is the number of users, M is the number of transmission/reception points between each transmit/receive antenna element pair. The 5th percentile user efficiency is the lowest 5th percentile point in the CDF of all users. The requirements for IMT2020 are detailed in Tables 1 and 2.

TABLE 1. 5th percentile user spectral efficiency requirements (reproduced from [7]).

Test environment	Downlink (bit/s/Hz)	Uplink (bit/s/Hz)
Indoor Hotspot – eMBB	0.3	0.21
Dense Urban – eMBB (NOTE 1)	0.225	0.15
Rural – eMBB	0.12	0.045

TABLE 2. Average spectral efficiency requirements (reproduced from [7]).

Test environment	Downlink (bit/s/Hz/TRxP)	Uplink (bit/s/Hz/TRxP)
Indoor Hotspot – eMBB	9	6.75
Dense Urban – eMBB	7.8	5.4
Rural – eMBB	3.3	1.6

2) CONNECTION DENSITY

The connection density is the total number of devices fulfilling a specific quality of service (QoS) per unit area (per km^2). The connection density is defined as [7]:

$$C = \frac{N_{mux}.W \big/ mean(B_i)}{ISD^2.\sqrt{3} \big/ 6} \tag{2}$$

where N_{mux} is the average number of multiplexed users for a given $SINR_i$, ISD is the Inter-site distance, and B_i is as follows [7]:

$$B_i = T \big/ (R_i / W_{user}) \tag{3}$$

The requirement is fulfilled if the 99th percentile of delay per user is less than or equal to 10 seconds and the system achieves a connection density of at least one million devices per square kilometer, evaluated for the Urban Macro scenario using simulations.

3) RELIABILITY

Reliability is defined as the success probability (1- P_e) in which P_e is the residual packet error ratio within maximum delay time as a function of SINR taking retransmission into account. The minimum requirement for the reliability is 1-10^{-5} success probability of transmitting a layer 2 PDU (protocol data unit) of 32 bytes within 1 ms in channel quality of coverage edge for the Urban Macro-URLLC test environment, assuming small application data (such as 20 bytes application data + protocol overhead). The requirement is fulfilled via downlink/uplink and LOS/NLOS as per Tables 3 and 4.

TABLE 3. URLLC Performance Metrics (reproduced from [6]).

URLLC Performance Metric	Minimal Value
User plane latency	1 ms (URLLC)
Control plane latency	(10 ms encouraged)
Reliability	99.999%
Mobility Interruption time	0 ms

TABLE 4. Assessment Methods for URLLC Performance Metrics (reproduced from [6]).

Characteristic for Evaluation	Assessment Method	Related Section of ITU-R Reports
User plane latency	Analytical	Report ITU-R M.[IMT-2020]. § 4.7.1
Control plane latency	Analytical	Report ITU-R M.[IMT-2020]. § 4.7.2
Reliability	Simulation	Report ITU-R M.[IMT-2020]. § 4.10
Mobility Interruption time	Analytical	Report ITU-R M.[IMT-2020]. § 4.12

TABLE 5. Mobility Classes (From [7]).

	Test environments for eMBB		
	Indoor Hotspot – eMBB	Dense Urban – eMBB	Rural – eMBB
Mobility classes supported	Stationary, Pedestrian	Stationary, Pedestrian, Vehicular (up to 30 km/h)	Pedestrian, Vehicular, High speed vehicular

4) MOBILITY

Mobility is the maximum mobile station speed at which a defined QoS can be achieved (in km/h). The successful evaluation of mobility is to fulfill the threshold values for the packet error ratio and spectral efficiency for a mobility of 120km/h and 500 km/h. Table 5 defines the mobility classes that are to be supported in the respective test environments. A mobility class is supported if the traffic channel link data rate on the uplink, normalized by bandwidth, meets the criteria specified in Tables 5 and 6.

TABLE 6. Traffic Channel Link Data Rate Requirements Normalized by Bandwidth (from [7]).

Test environment	Normalized traffic channel link data rate (bit/s/Hz)	Mobility (km/h)
Indoor Hotspot – eMBB	1.5	10
Dense Urban – eMBB	1.12	30
Rural – eMBB	0.8	120
	0.45	500

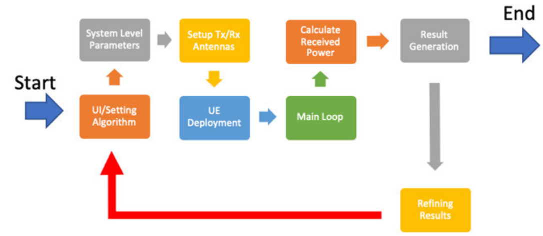

FIGURE 5. Modular Structure of the Simulator.

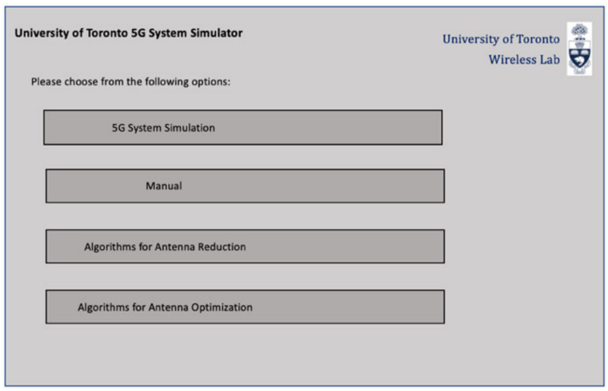

FIGURE 6. Simulator user Interface with mode options.

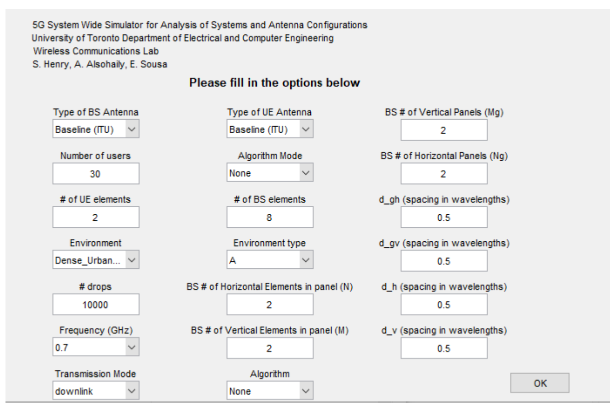

FIGURE 7. User-defined parameter menu.

5) USER-EXPERIENCED DATA RATE

User experienced data rate is the 5% point of the cumulative distribution function (CDF) of the user throughput. The target

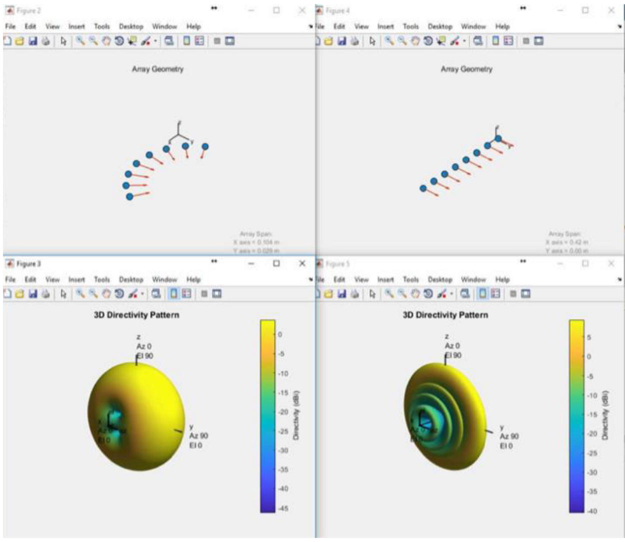

FIGURE 8. Antenna Gain and Directivity calculation via simulation.

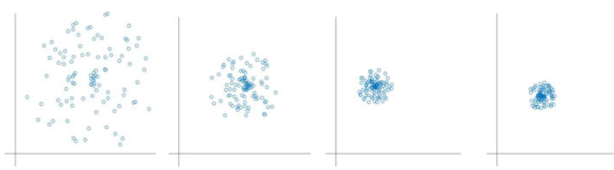

FIGURE 9. Convergence of SINR averages for URLLC calculations for 100 drops, 1000 drops, 5000 drops, and 10,000 drops (left to right).

TABLE 7. Requirements for mMTC Connection Density, 500 m, Non-Fullbuffer, Scenario A.

RIT	Antenna config & Tx scheme	Procedure	Numerology	Req.		Huawei	Ericsson	Univ of Toronto
FDD								
NB-IoT	1x2 SIMO, Single-tone	Early data transmission	15 kHz SCS	Connection density (/km2)	1000000	8,047,087		6,381,492
				Bandwidth (kHz)		180		180
NB-IoT	1x2 SIMO, (15-180 kHz)	RRC Resume, data after Msg5, RRC Connection Release	15 kHz SCS	Connection density (/km2)	1000000		1,233,000	1,190,895
				Bandwidth (kHz)			180	180
eMTC (LTE-M)	1x2 SIMO	RRC Resume, data after Msg5, RRC Connection Release	15 kHz SCS	Connection density (/km2)	1000000		1,893,000	1,489,022
				Bandwidth (kHz)			360	360.00

TABLE 8. Requirements for mMTC Connection Density, 1732 m, Non-Fullbuffer, Scenario A.

RIT	Antenna config & Tx scheme	Procedure	Numerology	Req.		Huawei	Ericsson	Univ of Toronto
FDD								
NB-IoT	1x2 SIMO, Single-tone	Early data transmission	15 kHz SCS	Connection density (/km2)	1000000	1,198,000		1,074,221
				Bandwidth (kHz)		360		360
NB-IoT	1x2 SIMO,(15-180 kHz)	RRC Resume, data after Msg5, RRC Connection Release	15 kHz SCS	Connection density (/km2)	1000000		1,018,000	1,004,539
				Bandwidth (kHz)			2700	2700
eMTC (LTE-M)	1x2 SIMO, DFT-S-OFDM	Early data transmission	15 kHz SCS	Connection density (/km2)	1000000	1,107,000		1,055,847
				Bandwidth (kHz)		540		540
eMTC (LTE-M)	1x2 SIMO, DFT-S-OFDM	RRC Resume, data after Msg5, RRC Connection Release	15 kHz SCS	Connection density (/km2)	1000000		1,026,000	1,009,807
				Bandwidth (kHz)			3240	3240

TABLE 9. Requirements for mMTC Connection Density, 1732 m, Non-Fullbuffer, Scenario A.

RIT	Antenna config & Tx scheme	Numerology	Req.		Huawei	Ericsson	Intel	Univ of Toronto
FDD								
NB-IoT	1x2 SIMO, Single-tone (16Rx@BS)	15 kHz SCS	Connection density (/km2)	1000000	41,325,000	46,058,578		35927461
			Bandwidth (kHz)		180	180		180
eMTC	1x2 SIMO, DFT-S-OFDM (16Rx@BS)	15 kHz SCS	Connection density (/km2)	1000000	39,995,000	25,674,701	40,036,848	32,850,912
			Bandwidth (kHz)		180	180	180	180
NR	1x2 SIMO, OFDMA (16Rx@BS)	15 kHz SCS	Connection density (/km2)	1000000	36,575,000	30,066,283	40,066,168	31,582,109
			Bandwidth (kHz)		180	180	180	180

TABLE 10. Requirements for mMTC Connection Density, 1732 m, Non-Fullbuffer, Scenario A.

RIT	Antenna config & Tx scheme	Numerology	Req.		Huawei	Ericsson	Intel	ZTE	Univ of Toronto
FDD									
NB-IoT	1x2 SIMO, Single-tone (16 Rx@BS)	15 kHz SCS	Connection density (/km2)	1000000	2,517,000	2,237,326		2,251,631	2,314,259
			Bandwidth (kHz)		180	180		180	180.00
eMTC	1x2 SIMO, DFT-S-OFDM (16 Rx@BS)	15 kHz SCS	Connection density (/km2)	1000000	1,344,000	1,231,947	1,062,780		1,214,735
			Bandwidth (kHz)		180	180	180		180.00
NR	1x2 SIMO, OFDMA (16 Rx@BS)	15 kHz SCS	Connection density (/km2)	1000000	1,138,000	1,269,767	1,237,402	1,424,456	1,267,312
			Bandwidth (kHz)		180	180	180	180	180.00

values for the UE data rate are 100MBits/s for downlink and 50MBits/s for the uplink user experienced data rate.

III. SIMULATION STRUCTURE AND FEATURES

In this section, a description of our system level simulator structure and methodology are introduced for evaluating the requirements. Simulations are performed to evaluate each requirement independently with the exception of the joint evaluation of 5th percentile user spectral efficiency and the average spectral efficiency as simulations are performed to simultaneously evaluate them.

The simulator structure is entirely modular as shown in Figure 5 and supports multi-link transmissions. A spatial geometry application is integrated for single and multiple antenna configurations to obtain results. A Graphical User Interface (GUI) allows users to choose whether to set variables manually, choose from a predetermined test scenario, or optimize the placement of antenna elements by choosing an algorithm as per figure 6.

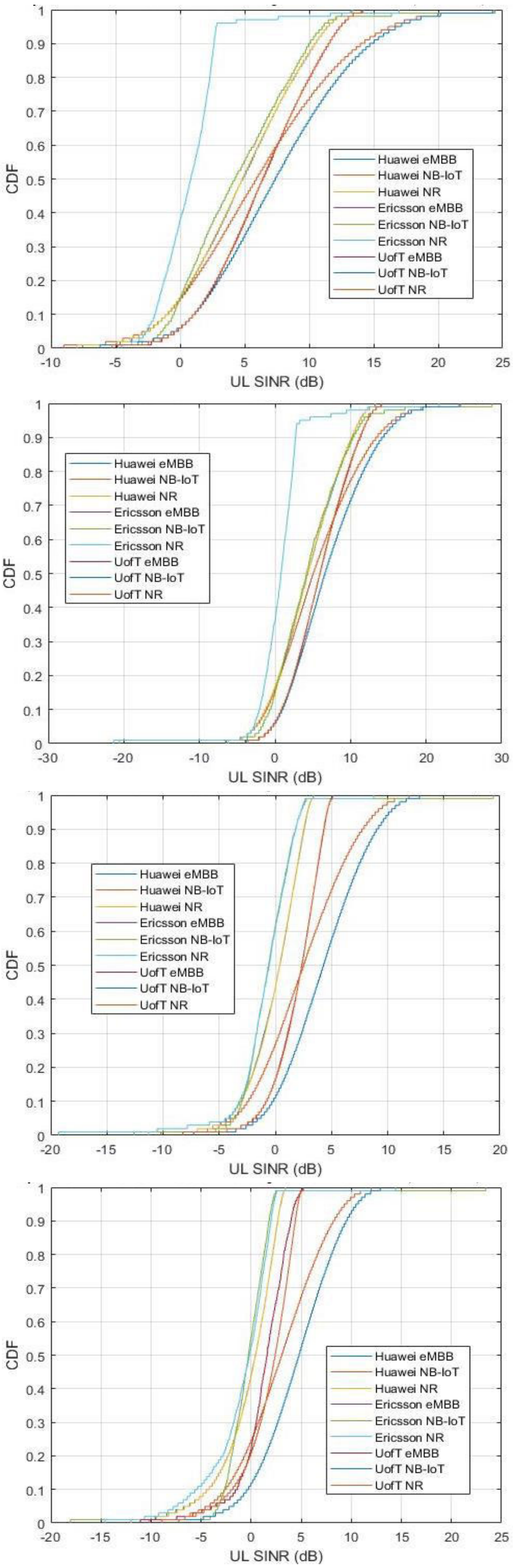

FIGURE 10. CDF of Uplink SINR, Connection Density, Dense Urban Test Scenario for Model A 500 m - Model B 1732 m - Model A 500 m - Model B 1732 m (top to bottom).

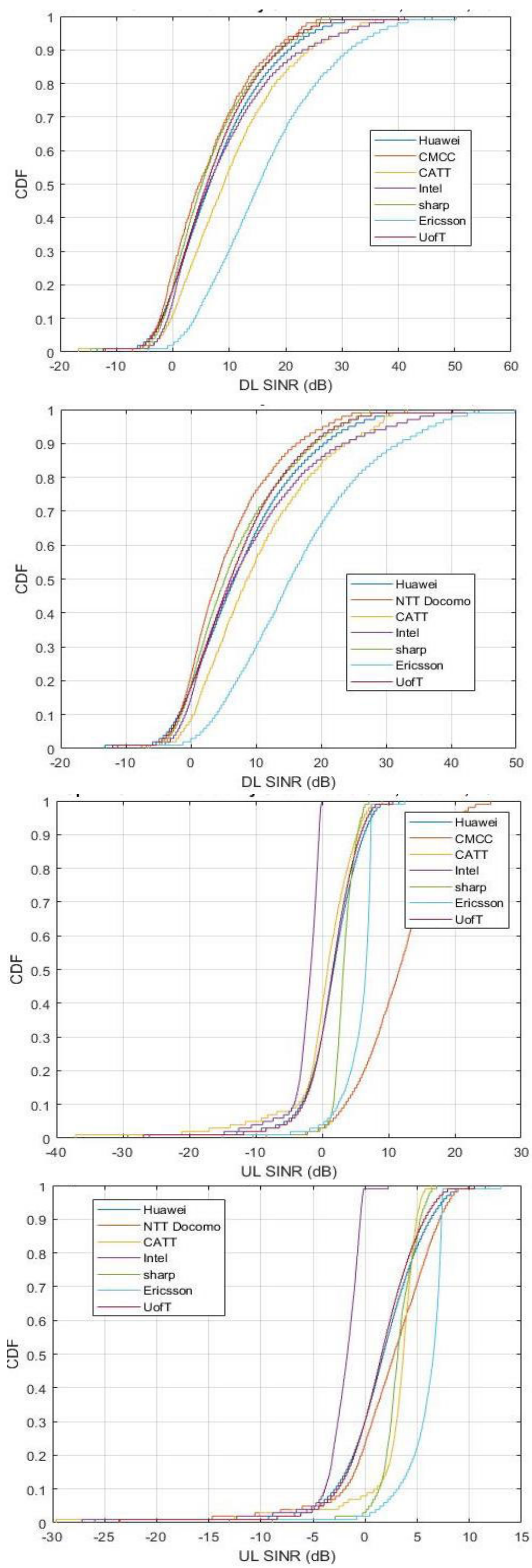

FIGURE 11. CDF of SINR, Reliability, Urban Macro Test Scenario at 4GHz for Downlink Model A - Downlink Model B - Uplink Model A - Uplink Model B (top to bottom).

TABLE 11. Comparing Reliability Results for URLLC Configuration.

f=700 MHz							
Channel Model A Downlink Reliability	Antenna Configuration	URLLC Requirement	Huawei	CATT	Nokia	Intel	Univ of Toronto
	2x2 SU-MIMO 14os one-shot (1 PDCCH+1 PDSCH)	99.999%	99.9998%				99.99969%
	2x2 SU-MIMO 7os one-shot (1 PDCCH+1 PDSCH)	99.999%	99.9998%	99.99904%		> 99.9999%	99.9997%
	2x2 SU-MIMO 4os slot aggregation = 2 (1 PDCCH + 2 PDSCH)	99.999%	99.9995%				99.999263%
	16x4 SU-MIMO 14os (1PDCCH + 1 PDSCH)	99.999%			99.999%		
Channel Model A Uplink Reliability	1x8 SIMO, OFDMA, 14os one-shot (1 PUSCH)	99.999%	99.9999%				99.9999%
	1x2 SIMO, OFDMA, 7os one-shot (2 PUSCH)	99.999%			9.9992%		
	1x8 SIMO 7os (1 PUSCH)	99.999%				> 99.9999%	
	1x8 SIMO, OFDMA, 14os one-shot (1 PUSCH, 8RB)	99.999%		99.9993%			
Channel Model B Downlink Reliability	2x2 SU-MIMO 14os one-shot (1 PDCCH+1 PDSCH)	99.999%	99.9998%	99.99904400%		99.99969%	
	2x2 SU-MIMO 7os one-shot (1 PDCCH+1 PDSCH)	99.999%	99.999%	99.9991%	> 99.9999%	99.9998%	
	2x2 SU-MIMO 4os slot aggregation = 2 (1 PDCCH + 2 PDSCH)	99.999%	99.9995%				
Channel Model B Uplink Reliability	1x8 SIMO, OFDMA, 14os one-shot (1 PUSCH)	99.999%	99.9999%			99.9999941%	
	1x2 SIMO, OFDMA, 7os one-shot (2 PUSCH)	99.999%					
	1x8 SIMO 7os (1 PUSCH)	99.999%			> 99.9999%		
	1x8 SIMO, OFDMA, 14os one-shot (1 PUSCH, 8RB)	99.999%		99.999%			
f= 4 GHz							
Channel Model A Downlink Reliability	Antenna Configuration	URLLC Requirement	Huawei	Nokia	Intel	Univ of Toronto	
	2x2 SU-MIMO 14os slot aggregation = 2 (1 PDCCH + 2 PDSCH)	99.999%	99.9998%			99.9999%	
	32x8 SU-MIMO 14os (1PDCCH + 1 PDSCH)	99.999%		99.999%			
	2x4 SU-MIMO 7os slot aggregation = 1 (1 PDCCH + 1 PDSCH)	99.999%			> 99.9999%		
Channel Model A Uplink Reliability	1x16 SIMO, OFDMA	99.999%	99.9998%			99.9997%	
	1x8 SIMO 7os (1 PUSCH)	99.999%			> 99.9999%		
	1x2 SIMO 4os (2 PUSCH)	99.999%		99.999%			
Channel Model B Downlink Reliability	2x2 SU-MIMO 14os slot aggregation = 2 (1 PDCCH + 2 PDSCH)	99.999%	99.99990561%		99.99969%		
	32x8 SU-MIMO 14os (1PDCCH + 1 PDSCH)	99.999%					
	2x4 SU-MIMO 7os slot aggregation = 1 (1 PDCCH + 1 PDSCH)	99.999%		> 99.9999%			
	2x2 SU-MIMO 4os (2 PDCCH + 2 PDSCH)	99.999%				99.99997%	
Channel Model B Uplink Reliability	1x16 SIMO, OFDMA,	99.999%	99.9999%		99.9999%	99.99993%	
	1x8 SIMO 14os (1 PUSCH, 12RB)	99.999%		> 99.9999%			

TABLE 12. Simulation Results for Downlink Spectral Efficiency, Indoor Hotspot, 12 TRxP, 4 GHz, Channel Model A.

RIT	Antenna and TXRU mapping	Antenna config & Tx scheme	Numerology	Req.		Huawei	Intel	Samsung	Univ of Toronto
FDD									
NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (4,4,2,1,1;4,4)	32x4 MU-MIMO Type II Codebook	15 kHz SCS	Average [bit/s/Hz/TRxP]	9	11.287	10.627	13.160	9.812
				5th percentile [bit/s/Hz]	0.3	0.356	0.398	0.330	0.359
TDD									
NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (4,4,2,1,1;4,4)	32x4 MU-MIMO, 4T SRS	30 kHz SCS	Average [bit/s/Hz/TRxP]	9	12.965			11.122
				5th percentile [bit/s/Hz]	0.3	0.377			0.324
NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (4,4,2,1,1;4,4)	32x4 MU-MIMO, 4T SRS	15 kHz SCS	Average [bit/s/Hz/TRxP]	9	12.773			10.109
				5th percentile [bit/s/Hz]	0.3	0.394			0.381

TABLE 13. Simulation Results for Downlink Spectral Efficiency, Indoor Hotspot, 36 TRxP, 4 GHz, Channel Model A.

RIT	Antenna and TXRU mapping	Antenna config & Tx scheme	Numerology	Frame structure	Req.		Huawei	Intel	Univ of Toronto
FDD									
NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (8,16,2,1,1;2,8)	32x4 MU-MIMO Type II Codebook (256Tx@gNB)	15 kHz SCS		Average [bit/s/Hz/TRxP]	9	13.340	12.586	12.84
					5th percentile [bit/s/Hz]	0.3	0.312	0.406	0.302
TDD									
NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (8,16,2,1,1;2,8)	32x4 MU-MIMO, 4T SRS (256Tx@gNB)	30 kHz SCS	DDDSU	Average [bit/s/Hz/TRxP]	9	14.218		12.507
					5th percentile [bit/s/Hz]	0.3	0.350		0.3286
NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (8,16,2,1,1;2,8)	32x4 MU-MIMO, 4T SRS (256Tx@gNB)	15 kHz SCS	DDDSU	Average [bit/s/Hz/TRxP]	9	14.563		11.86992
					5th percentile [bit/s/Hz]	0.3	0.385		0.3574

TABLE 14. Simulation Results for Downlink Spectral Efficiency, Indoor Hotspot, 12 TRxP, 30 GHz, Channel Model A/B.

RIT	Antenna and TXRU mapping	Antenna config & Tx scheme	Numerology	Req.		Huawei	Intel	Univ of Toronto
TDD								
NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (4,4,2,1,1;4,4); UE: (M,N,P,Mg,Ng; Mp,Np) = (2,4,2,1,2; 1,2)	32x8 MU-MIMO, 4T SRS (2 panel@UE)	60 kHz SCS	Average [bit/s/Hz/TRxP]	9	11.599		10.8511
				5th percentile [bit/s/Hz]	0.3	0.308		0.3241

Using the GUI, values are assigned to parameters as per the user choice in the previous stage. Once again, value assignment can be predetermined or set manually. The number of drops and time durations set the complexity level for the loop in the next stage. Each time iteration, and once all parameters are defined, transmitters and receivers are deployed in two-dimensional or three-dimensional modes depending on the desired degree of complexity. Finally, the transmit/receive antenna configurations and antenna element patterns are defined. Figure 7 shows an example of choice of parameters. Simulations are then performed for all drops in which the SINR and performance is computed. Once the parameters are initialized, the system then loops the desired configuration scenarios. The inner loop calculates the performance for each transmit/receive antenna element pair, adding the following into consideration: interference, path loss, antenna gain (shown in figure 8), and antenna beam-steering properties. This is enclosed within another loop that combines the received signals between antennas for the time duration indicated during the input stage as maximum ratio combining or proportional fair scheduling. The third outer loop is to repeat the inner two loops for each user normally distributed around the environment space (either two or three-dimensional). The fourth outer loop repeats the simulation for the indicated number of drops for the results in section V, with an average of 10,000 drops are used. The Result Generation stage provides performance assessments, tables, and cumulative distribution functions of the SINR for considered test environments. The process is repeated until the iteration results converge as shown in figure 9.

IV. SYSTEM SETUP AND SIMULATION METHODOLOGY

For the system-level simulation, user equipment (UE) are dropped independently over a predefined area of the network layout throughout the system and are modelled according to their respective traffic model. Each UE is randomly assigned LOS/NLOS channel conditions according to the

TABLE 15. Simulation Results for Downlink Spectral Efficiency, Dense Urban, eMBB, 4 GHz, Channel Model A.

Channel model A	RIT	Antenna and TXRU mapping	Antenna config & Tx scheme	Req.		Huawei	Univ of Toronto
DL	FDD		FDD				
	NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (8,4,2,1,1;1,4)	8x2 MU-MIMO Type II Codebook	Average [bit/s/Hz/TRxP]	3.3	7.040	6.594
				5th percentile [bit/s/Hz]	0.12	0.180	0.138
	TDD		TDD				
	NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (8,4,2,1,1;1,4)	8x2 MU-MIMO, 2T SRS	Average [bit/s/Hz/TRxP]	3.3	7.490	7.817
				5th percentile [bit/s/Hz]	0.12	0.159	0.193
UL	FDD		FDD				
	NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (8,4,2,1,1;1,4)	1x8 SU-MIMO, OFDMA	Average [bit/s/Hz/TRxP]	1.6	3.718	4.279
				5th percentile [bit/s/Hz]	0.045	0.127	0.138
	NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (8,4,2,1,1;1,4)	2x8 SU-MIMO, Codebook based, OFDMA	Average [bit/s/Hz/TRxP]	1.6	4.296	4.751
				5th percentile [bit/s/Hz]	0.045	0.093	0.104

	FDD								
	NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (8,8,2,1,1;2,8)	32x4 MU-MIMO Type II Codebook (128Tx@gNB)	15 kHz SCS	Average [bit/s/Hz/TRxP]	7.8	11.450		10.891
					5th percentile [bit/s/Hz]	0.225	0.376		0.358
	TDD								
	NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (8,8,2,1,1;2,8)	32x4 MU-MIMO, 4T SRS (128Tx@gNB)	30 kHz SCS	Average [bit/s/Hz/TRxP]	7.8	13.042		12.263
					5th percentile [bit/s/Hz]	0.225	0.382		0.361
	NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (8,8,2,1,1;2,8)	32x4 MU-MIMO, 4T SRS (128Tx@gNB)	15 kHz SCS	Average [bit/s/Hz/TRxP]	7.8	12.951		11.886
					5th percentile [bit/s/Hz]	0.225	0.388		0.314
	NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (12,8,2,1,1;4,8)	64x4 MU-MIMO, 4T SRS (192Tx@gNB)	30 kHz SCS	Average [bit/s/Hz/TRxP]	7.8	16.098		15.020
					5th percentile [bit/s/Hz]	0.225	0.494		0.462
	NR	gNB: (M,N,P,Mg,Ng; Mp,Np) = (12,8,2,1,1;4,8)	64x4 MU-MIMO, 4T SRS (192Tx@gNB)	15 kHz SCS	Average [bit/s/Hz/TRxP]	7.8	15.708		14.809
					5th percentile [bit/s/Hz]	0.225	0.484		0.454

channel model. Cell assignment to a UE is based on the cell selection scheme with applicable distances between UE and a base station depend on the proposed scenario. Signal fading and interference from each transmitter to each receiver is aggregated; interference over thermal parameter is taken into account as an uplink design constraint with an average interference of less than 10 dB. For full buffers, infinite queue depths are assumed. Channel quality, feedback delay, feedback errors, protocol data unit error which are inclusive of channel estimation error are modelled and packets are retransmitted according to the packet scheduler. For every drop, the simulation is run and repeated with UEs dropped at new random locations. 10,000 drops are performed for each simulation to ensure convergence in the system performance metrics of corresponding mean values. Finally, error modelling for channel estimation, phase noise, and control channels to decode the traffic channel is included.

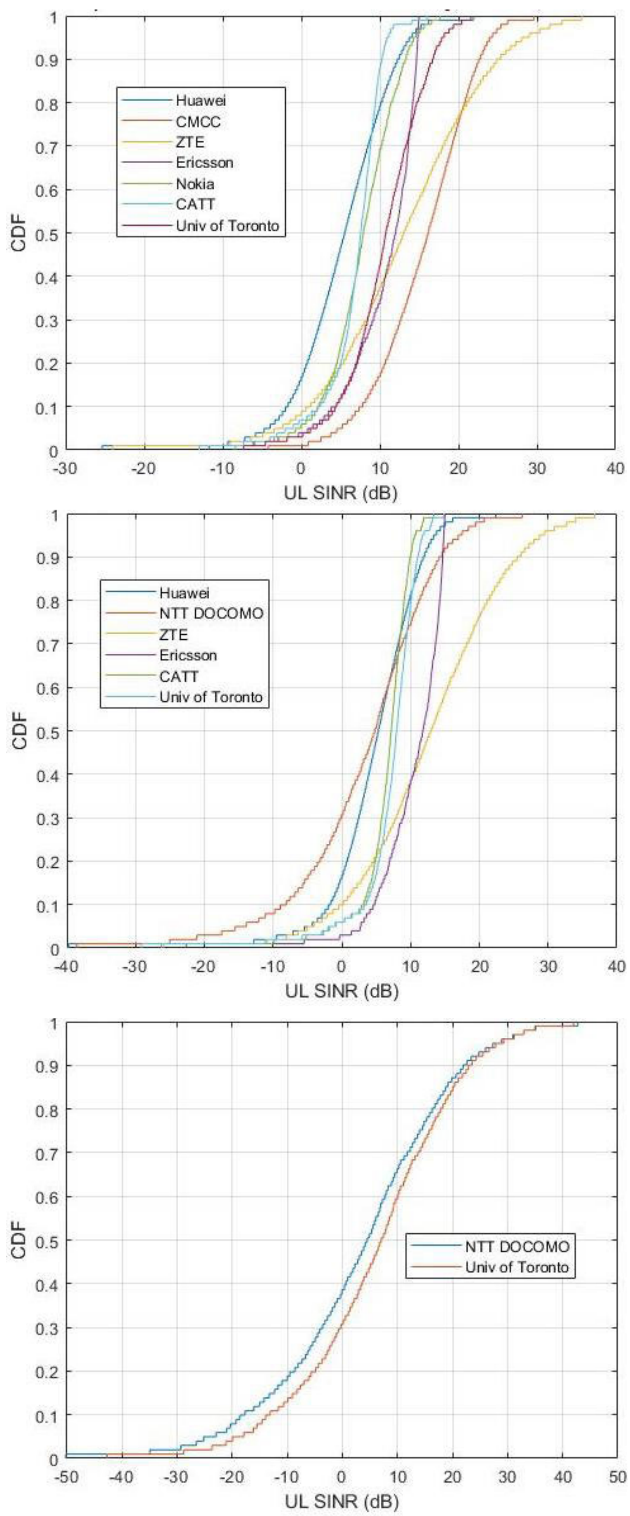

FIGURE 12. CDF of Uplink SINR, Mobility, Dense Urban Test Scenario at 4GHz for 4 GHz Model A – 4 Ghz Model B– 30 GHz Model A/B (top to bottom).

V. SIMULATION RESULTS

Based on the test environments and performance requirements outlined in Section II, simulations are performed using the simulator and methodology described

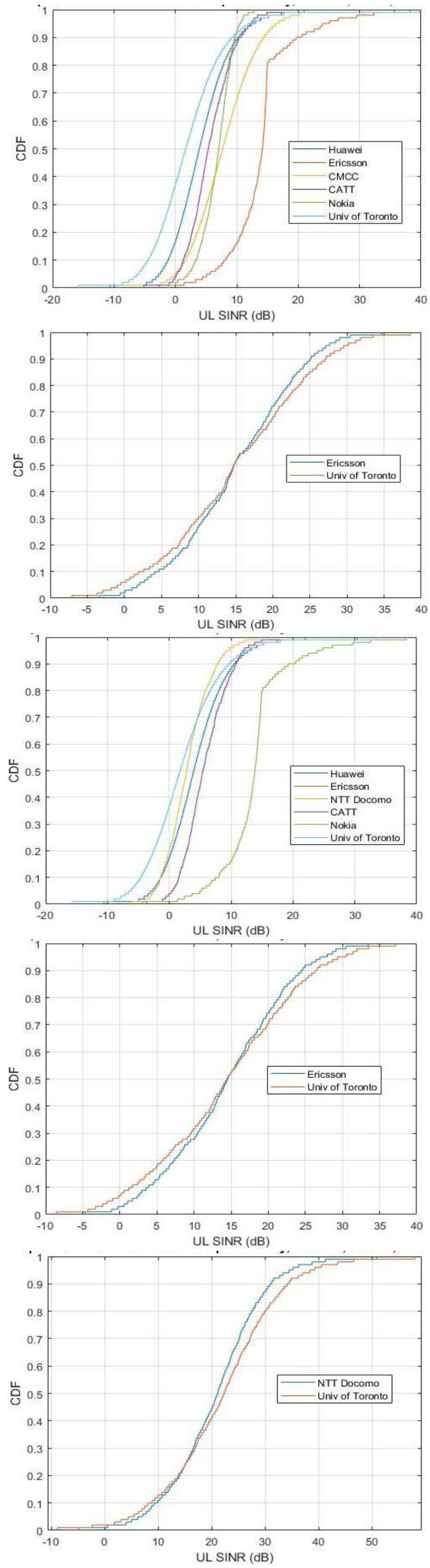

FIGURE 13. CDF of Uplink SINR, Mobility, Indoor Hotspot Test Scenario for 4 GHz, Model A, 12 TRxP – 4 GHz, Model B, 12 TRxP - 4 GHz, Model A, 36 TRxP – 4 GHz, Model B, 36 TRxP- 30 GHz, Model A, 12 TRxP (top to bottom).

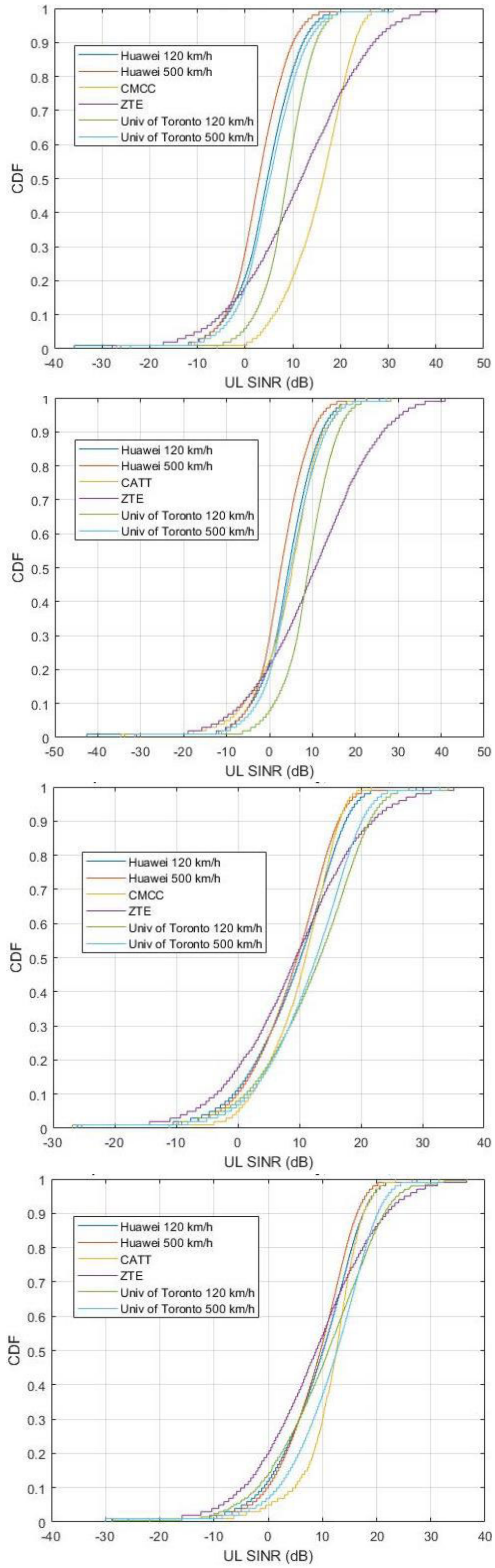

FIGURE 14. CDF of Uplink SINR, Mobility, Rural Test Scenario for 700 MHz, Model A– 700 MHz, Model B – 4 GHz, Model A– 4 GHz, Model B (top to bottom).

TABLE 16. Simulation Results for eMBB Indoor Hotspot Uplink Mobility, 4 GHz, 12 TRxP, Channel Model A.

RIT	Antenna config & Tx scheme	Numerology	Frame structure	Req.		Channel cond.	Huawei	Univ of Toronto
FDD								
NR	1x8 SIMO, OFDMA	15 kHz SCS		Normalized traffic channel link data rate (bit/s/Hz)	1.5	NLOS	1.75	1.63
					1.5	LOS	2.05	2.1
TDD								
NR	1x8 SIMO, OFDMA	30 kHz SCS	DDDSU	Normalized traffic channel link data rate (bit/s/Hz)	1.5	NLOS	1.59	1.38
					1.5	LOS	1.94	1.82

in Sections III and IV. The tables and figures provided in this section detail the simulation results for the 3GPP 5G NR system and compare them to the ITU IMT-2020 requirements. The results indeed show the compliance of the 3GPP 5G NR system with the ITU IMT-2020 performance requirements for all parameters evaluated by simulations.

A. CONNECTION DENSITY SIMULATION RESULTS

Taking into account layers 1 and 2 overhead information provided by the proponents, the connection density requirement is fullfilled if it is greater than the ITU report in [11] as shown in Tables 7-10. These four tables compare full-buffer and non full-buffer modes, scenarios A and B, and base-station inter-site distances of 1732 m and 500 m for system-level simulations between the University of Toronto, Huawei, and Ericsson simulators. The tables show that full-buffer outperforms non full-buffer for NB-IoT, mMTC, and NR technologies, and are compliant with ITU requirements.

B. CONNECTION DENSITY CDF

In addition to the connection density values, figure 10 displays the cumuative distribution function of the aforementioned technologies in the previous section and the higher-then-average uplink SINR of the University of Toronto simulator compared to other industry simulators.

C. RELIABILITY SIMULATION RESULTS

Ultra-high reliability and good resilience capability are needed to achieve the reliability requirement for ensuring the 5^{th} percentile downlink or uplink value within the required delay obtains a success probability equal to or higher than the required success probaility. Figure 11 and Table 11 both display the Uplink SINR for a 4 GHz spectrum and reliability results for 700MHz/4GHz respectively for 5-7 evaluators, and our simulator hence achieves the reliability requirements (>99.999%) as well as exceeding all testing scenarios and antenna configurations.

D. SPECTRAL EFFICIENCY

Enhanced spectral efficiency results are included in Tables 12-15 for Indoor hotspot, dense urban, and rural evaluation scenarios for different TRxP and simulation

TABLE 17. Simulation Results for eMBB Indoor Hotspot Uplink Mobility, 30 GHz, 12TRxP, Channel Model A/B.

RIT	Antenna config & Tx scheme	Numerology	Frame structure	Req.		Channel cond.	NTT DOCOMO	Intel (SNR margin)	Samsung	Univ of Toronto
FDD										
NR	1x4 SIMO	60kHz		Normalized traffic channel link data rate (bit/s/Hz)	1.5	NLOS	2.84			2.71
					1.5	LOS				

TABLE 18. Simulation Results for eMBB Indoor Hotspot Uplink Mobility, 4 GHz, 36 TRxP, Channel Model A.

RIT	Antenna config & Tx scheme	Numerology	Frame structure	Req.		Channel cond.	Intel (SNR margin)	Univ of Toronto (SNR margin)
FDD								
NR	2x8 SIMO	15kHz SCS				NLOS	0.39	0.34
		30kHz SCS				NLOS	0.38	0.39

TABLE 19. Simulation Results for eMBB Rural Uplink Mobility, 700 MHz, 120 km/h Channel Model A.

RIT	Antenna config & Tx scheme	Numerology	Frame structure	Req.		Channel cond.	Huawei	Ericsson	Intel (SNR margin)	Univ of Toronto
FDD										
NR	1x4 SIMO, OFDMA	15 kHz SCS		Normalized traffic channel link data rate (bit/s/Hz)	0.8	NLOS	2.32			2.13
					0.8	LOS	2.90			2.57
TDD										
NR	1x4 SIMO, OFDMA	15 kHz SCS	DDDSU	Normalized traffic channel link data rate (bit/s/Hz)	0.8	NLOS	2.10			1.92
					0.8	LOS	2.63			2.18

TABLE 20. Simulation Results for eMBB Dense Urban Uplink Mobility, 4 GHz, 12 TRxP, Channel Model A.

RIT	Antenna config & Tx scheme	Numerology	Req.		Channel cond.	Huawei	Ericsson	Univ of Toronto
FDD								
NR	1x8 SU-MIMO, OFDMA	15 kHz SCS	Normalized traffic channel link data rate (bit/s/Hz)	1.12	NLOS	1.92		2.03
				1.12	LOS	2.22		2.29
TDD								
NR	1x8 SU-MIMO, OFDMA	30 kHz SCS	Normalized traffic channel link data rate (bit/s/Hz)	1.12	NLOS	1.82		1.76
				1.12	LOS	2.17		1.95

bandwidths. Using the evaluation configuration parameters, the results show the data conforms with reference values and industry evaluators.

E. MOBILITY

5G systems support low to high mobility applications and much enhanced data rates in accordance with user and service demands in multiple user environments. Figures 12-14 and Tables 16-21 exhibit the uplink SINR and the normalized channel link data rate for NLOS/LOS conditions under various spectrum bandwidths.

F. UE DATA RATE

Coupled with NR usage scenario, Table 22 illustrates the data rate for different antenna configurations for uplink and

TABLE 21. Simulation Results for eMBB Dense Urban Uplink Mobility, 700 MHz, 500 km/h, Channel Model A.

RIT	Antenna config & Tx scheme	Numerology	Frame structure	Req	Channel cond.	Intel (SNR margin)	Univ of Toronto
FDD							
NR	2x2 SIMO	15kHz SCS			NLOS		1.28
					LOS		

TABLE 22. Simulation Results for User Experience Data, Model A, Downlink/Uplink Respectively.

RIT	Detailed config. For multi-band/layer	Antenna config & Tx scheme	Numerology	Req.		Huawei	Univ of Toronto
Multi-band Macro layer							
NR	Macro layer only 4 GHz	32x4 MU-MIMO, CB based OFDMA	15 kHz SCS	User experienced data rate (Mbit/s)	100		152.482
Single-band Macro layer							
NR	Macro layer only 4 GHz	32x4 MU-MIMO, CB based OFDMA	15 kHz SCS	User experienced data rate (Mbit/s)	100		132.561
Multi-band Macro layer							
NR	Macro layer only 30 GHz (TDD) + 4 GHz (SUL) 50% offload	4 GHz (SUL band): 2x32 SU-MIMO, CB based OFDMA 30 GHz (TDD band): 8x32 SU-MIMO, CB based, OFDMA (2 panel@UE)	4 GHz: 15 kHz SCS 30 GHz: 60 kHz SCS	User experienced data rate (Mbit/s)	50	52.11	62.9103
Single-band Macro layer							
NR	Macro layer only 4 GHz	16x16 SU-MIMO, CB based OFDMA	15 kHz SCS	User experienced data rate (Mbit/s)	50		59.3013
NR	Macro layer only 30 GHz	32x32 SU-MIMO, CB based OFDMA (2 panel@UE)	120 kHz SCS	User experienced data rate (Mbit/s)	50		72.4814

mMTC Simulation Algorithm:

Loop over number of drops:
  Distribute users over environment
  Loop over users:
    1-Set environment, network layout, and antenna array parameters
    2-Assign propagation condition (LOS/NLOS)
    3-Calculate pathloss
    4-Generate large scale parameters
    5-Generate delays
    6-Generate cluster powers
    7-Generate arrival angles and departure angles for both azimuth and elevation
    8-Couple of rays within a cluster for both azimuth and elevation
    9-Generate the cross polarization power ratios
    10-Draw initial random phases
    11-Generate channel coefficients
    12-Apply pathloss and shadowing
Calculate Connection Density and SINR

FIGURE 15. Procedure algorithm for evaluating Connection Density for mMTC scenarios.

downlink, showing multi-band macro layer data rates are greater than that of the single-band macro layer, hence fulfilling the Data Rate requirement of 100 Mbit/s (downlink) and 50 Mbits/s (uplink).

TABLE 23. Parameters for Evaluating mMTC Connection Density (reproduced from [5]).

Connection Density Evaluation (Full-Buffer)		
	Configuration A	Configuration B
Thermal noise level	-174 dBm/Hz	-174 dBm/Hz
Traffic model	With layer 2 PDU (Protocol Data Unit) message size of 32 bytes: 1 message/day/device or 1 message/2 hours/device Packet arrival follows Poisson arrival process for non-full buffer system-level simulation	With layer 2 PDU (Protocol Data Unit) message size of 32 bytes: 1 message/day/device or 1 message/2 hours/device Packet arrival follows Poisson arrival process for non-full buffer system-level simulation
Simulation bandwidth	Up to 10 MHz	Up to 50 MHz
UE density	Not applicable for non-full buffer system-level simulation as evaluation methodology of connection density For full buffer system-level simulation followed by link-level simulation, 10 UEs per TRxP NOTE – this is used for SINR CDF distribution derivation	Not applicable for non-full buffer system-level simulation as evaluation methodology of connection density For full buffer system-level simulation followed by link-level simulation, 10 UEs per TRxP NOTE – this is used for SINR CDF distribution derivation
UE antenna height	1.5 m	1.5 m
Carrier frequency for evaluation	700 MHz	700 MHz
BS antenna height	25 m	25 m
Total transmit power per TRxP	49 dBm for 20 MHz bandwidth 46 dBm for 10 MHz bandwidth	49 dBm for 20 MHz bandwidth 46 dBm for 10 MHz bandwidth
UE power class	23 dBm	23 dBm
Percentage of high loss and low loss building type	20% high loss, 80% low loss	20% high loss, 80% low loss
Additional parameters for system-level simulation		
Inter-site distance	500 m	1732 m
Number of antenna elements per TRxP[1]	Up to 64 Tx/Rx	Up to 64 Tx/Rx
Number of UE antenna elements	Up to 2Tx/Rx	Up to 2Tx/Rx
Device deployment	80% indoor, 20% outdoor Randomly and uniformly distributed over the area	80% indoor, 20% outdoor Randomly and uniformly distributed over the area
UE mobility model	Fixed and identical speed |v| of all UEs, randomly and uniformly distributed direction	Fixed and identical speed |v| of all UEs, randomly and uniformly distributed direction
UE speeds of interest	3 km/h for indoor and outdoor	3 km/h for indoor and outdoor
Inter-site interference modelling	Explicitly modelled	Explicitly modelled
BS noise figure	5 dB	5 dB
UE noise figure	7 dB	7 dB
BS antenna element gain	8 dBi	8 dBi
UE antenna element gain	0 dBi	0 dBi

VI. SUMMARY, CONCLUSIONS, AND FUTURE WORK

This paper utilized an independent simulator to assess the compliance of the 3GPP submitted 5G NR self-evaluation simulations with the ITU IMT-2020 performance requirements. The results indeed confirm the compliance of the 3GPP 5G system with the ITU connection density, reliability, and mobility requirements to support the anticipated 5G applications and use cases. Building on this work, additional simulations can be performed for a wide range of

```
URLLC Simulator Algorithm

Loop over number of drops:
  Distribute users over environment
   Loop over users:
        1-Set environment, network layout, and
        antenna array parameters
        2-Assign propagation condition (LOS/NLOS)
        3-Calculate pathloss
        4-Generate large scale parameters
        5-Generate delays
        6-Generate cluster powers
        7-Generate arrival angles and departure
        angles for both azimuth and elevation
        8-Couple of rays within a cluster for both
        azimuth and elevation
        9-Generate the cross polarization power
        ratios
        10-Draw initial random phases
        11-Generate channel coefficients
        12-Apply pathloss and shadowing
Calculate Reliability and SINR
```

FIGURE 16. Procedure algorithm for evaluating reliability for URLLC scenarios.

TABLE 24. URLLC Performance Metrics (reproduced from [4]).

URLLC Performance Metric	Minimal Value
User plane latency (URLLC)	1 ms (URLLC)
Control plane latency (URLLC)	(10 ms encouraged)
Reliability (URLLC)	99.999%
Mobility interruption time (URLLC)	0 ms

TABLE 25. Assessment Methods for URLLC Performance (reproduced from [5]).

Characteristic for evaluation	Assessment method	Related section of ITU-R Reports
User plane latency	Analytical	Report ITU-R [IMT 2020.TECH PERF REQ], § 4.7.1
Control plane latency	Analytical	Report ITU-R [IMT 2020.TECH PERF REQ], § 4.7.2
Reliability	Simulation	Report ITU-R [IMT 2020.TECH PERF REQ], § 4.10
Mobility interruption time	Analytical	Report ITU-R [IMT 2020.TECH PERF REQ], § 4.12

frequency ranges and system configurations (rural, highway, etc.) to determine performance gaps and potential areas for improvement for the 3GPP 5G NR system.

TABLE 26. Parameters for Evaluating URLLC Reliability (reproduced from [5]).

Parameters	Urban Macro–URLLC Reliability Evaluation Configuration A	Urban Macro–URLLC Reliability Evaluation Configuration B
Baseline evaluation configuration parameters		
Carrier frequency for evaluation	4 GHz	700 MHz
BS antenna height	25 m	25 m
Total transmit power per TRxP	49 dBm for 20 MHz bandwidth 46 dBm for 10 MHz bandwidth	49 dBm for 20 MHz bandwidth 46 dBm for 10 MHz bandwidth
UE power class	23 dBm	23 dBm
Percentage of high loss and low loss building type	100% low loss	100% low loss
Additional parameters for system-level simulation		
Inter-site distance	500 m	500 m
Number of antenna elements per TRxP[1]	Up to 256Tx/Rx	Up to 64 Tx/Rx
Number of UE antenna elements	Up to 8Tx/Rx	Up to 4Tx/Rx
Device deployment	80% outdoor, 20% indoor	80% outdoor, 20% indoor
UE mobility model	Fixed and identical speed |v| of all UEs, randomly and uniformly distributed direction	Fixed and identical speed |v| of all UEs, randomly and uniformly distributed direction
UE speeds of interest	3 km/h for indoor and 30 km/h for outdoor	3 km/h for indoor and 30 km/h for outdoor
Inter-site interference modelling	Explicitly modelled	Explicitly modelled
BS noise figure	5 dB	5 dB
UE noise figure	7 dB	7 dB
BS antenna element gain	8 dBi	8 dBi
UE antenna element gain	0 dBi	0 dBi
Thermal noise level	-174 dBm/Hz	-174 dBm/Hz
Traffic model	Full buffer Note: This is used for SINR CDF distribution derivation	Full buffer Note: This is used for SINR CDF distribution derivation
Simulation bandwidth	Up to 100 MHz Note: This value is used for SINR CDF distribution derivation	Up to 40 MHz Note: This value is used for SINR CDF distribution derivation
UE density	10 UEs per TRxP Note: This is used for SINR CDF distribution derivation	10 UEs per TRxP Note: This is used for SINR CDF distribution derivation
UE antenna height	1.5 m	1.5 m
Evaluated service profiles	Full buffer best effort	Full buffer best effort
Simulation bandwidth	Up to 100 MHz (for carrier frequency of 4 GHz)	Up to 40 MHz (for carrier frequency of 700 MHz)

APPENDIX

A. CONNECTION DENSITY PARAMETERS

See Figure 15 and Table 23.

B. RELIABILITY REQUIREMENTS AND PARAMETERS

See Tables 24–26 and Figure 16.

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