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5G New Radio Key Performance Indicators Evaluation for IMT-2020 Radio Interface Technology

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ABSTRACT The International Telecommunication Union (ITU) has recently announced the detailed 5G specifications for International Mobile Telecommunications (IMT-2020). A number of candidate Radio Interface Technologies (RITs) were being evaluated by the independent evaluation groups of the ITU. Meanwhile, the roll out of fifth generation (5G) is now going on, and 5G services are offered by more than 160 mobile network operators (MNO). This paper presents the evaluation of the proponent technologies, including the ones specified as 3rd generation partnership project (3GPP) 5G new radio (NR). The entire 3GPP specifications were examined and evaluated through simulation using Matlab and a custom simulator based on the Go-language. The simulator facilitated the comprehensive evaluation of the 5G NR performance by using the IMT-2020 evaluation framework. Some of the submitted technologies displayed certain discrepancies which were reported to ITU as well as discussed with proponents to improvise the shortcomings. The detailed results and observations are presented in this paper.

INDEX TERMS 5G, data rate, energy efficiency, IMT-2020 evaluation, latency, mobility, new radio, spectral efficiency.

I. INTRODUCTION

The international telecommunication union radio communication sector (ITU-R) has set the requirements for international mobile telecommunications-2020 (IMT-2020) which defined the emergence of the fifth generation (5G) mobile communication standards [1]. The IMT-2020 system requirements for the radio access technologies (RAT) were finalized and adopted in the ITU-R report M.2410-0 [2] way back in 2017. Following this acceptance, developers of RATs have been developing 5G technologies to meet these requirements. Accordingly, the 3rd generation partnership project (3GPP) developed the 5G New radio (NR) RAT to satisfy the 5G requirements. It also informed that along with Long term evolution-M (LTE-M) and Narrow band-Internet of Things (NB-IoT), they satisfy all the performance requirements of IMT-2020 (3GPP TR 38.913) [3] as a set of RAT's. Additionally, proponents such as China, Korea, European telecommunications standards institute-Digital enhanced cordless telecommunications (ETSI-DECT) Forum, and NuFront have also developed suitable technology and submitted to ITU-R as candidate technology for IMT-2020.

The standardization of 5G technologies for IMT-2020 typically requires the verification of these submissions.

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The submission is then evaluated by independent evaluation groups (IEG) comprising researchers from academia and industry and, they should be registered to ITU. 5G India Forum (5GIF) is one of the IEGs who carried out the evaluation of 3GPP NR for NuFront, enhanced ultra high throughput (EUHT-5G) and many other proponents [4], [5]. Multiple levels of process like, inspection, analysis, simulation, experiments have been suggested by ITU. Complete guidelines, specifications to be evaluated, etc. are found in [2].

In the standardization process, every candidate technology is required to submit a self evaluation report to ITU-R. The IEGs evaluate the self report and the technology for the proposed radio interface technologies (RITs) and set of RITs (SRITs) by following the guidelines of evaluation process as listed by ITU-R in report M.2412 [6]. These evaluations are then submitted to ITU-R and discussed in the working party (WP) 5D meetings. It is expected that after a couple of such meetings, the RITs and SRITs will be accepted as IMT-2020 (5G) standard.

The 5GIF IEG is one of the independent evaluation groups registered with ITU-R for IMT-2020 candidate radio technology evaluation. This group was formed to evaluate the IMT-2020 candidates from the perspective of Indian network deployments. This is a group of operators, original equipment manufacturers (OEM's), universities and individual experts participating in a collaborative manner, in the evaluation of candidate IMT-2020 technologies of interest. This is a contribution driven activity in which decision is made through a consensus seeking approach. The technology and standards working group of the 5GIF is involved in creating use cases and specifications that are specifically designed for Indian adoption. This involves the assessment of core innovations coming from 5G standardisation bodies such as the 3GPP as well as integration concepts and migration paths.

The remainder of the paper is organised as follows. The technical aspects of 5G NR are briefly discussed in Section II. Section III discusses the 5G NR simulator, Section IV explains the evaluation process, and Section V presents and discusses the findings and outcomes. Finally, Section VI concludes the paper. Table 1 lists the acronyms used in the document.

II. TECHNICAL DETAILS OF 5G NR

A. NR NUMEROLOGY

In 5G NR, the term numerology defines a combination of subcarrier spacing (SCS) and cyclic prefix. The specifications [7] introduce the Greek letter μ to represent a given numerology according to Table 2.

As can be seen from the Table 2, SCS as large as 240 kHz is used. The reason for this is to transmit over a large bandwidth without increasing the number of subcarriers. This is important from the implementation standpoint because larger number of subcarriers implies large fast Fourier transforms (FFTs) that are complex/costly to implement. The SCS has

TABLE 1. List of acronyms.

3GPP	3rd generation partnership project
5G	Fifth generation
5GIF	5G India forum
CA	Carrier aggregation
CC	Carrier component
CCE	Control channel element
CDF	Cumulative distribution function
CQI	Channel quality indicator
CSI-RS	Channel state information reference signal
DL	Downlink
DM-RS	Demodulation reference signal
eMBB	Enhanced mobile broadband
EPC	Evolved packet core
EUHT-5G	Enhanced ultra high throughput
FFTs	Fast fourier transforms
FWA	Fixed wireless access
GP	Guard period
HARQ	Hybrid automatic repeat request
HPUE	High-performance user equipment
IEG	Independent evaluation groups
IMT-2020	International mobile telecommunications - 2020
ITU	International telecommunication union
ITU-R	International telecommunication union radio communication sector
KPI	Key performance indicators
LLS	Link-level simulations
LMLC	Low-mobility large-cell
LOS	Line-of-sight
LTE-M	Long term evolution-M
MCS	Modulation and coding scheme
mMTC	Massive machine type communications
NB-IoT	Narrow band-Internet of Things
NLOS	Non-line-of-sight
NR	5G new radio
OEM's	Original equipment manufacturers
OFDM	Orthogonal frequency division multiplexing
OoS	Out of service
OS	OFDM symbols
PBCH	Physical broadcast channel
PCell	Primary Cell
PDCCH	Physical downlink control channel
PDU	Protocol data unit
PF	Proportionally fair
PRB	Physical resource block
PT-RS	Phase tracking reference signal
PUCCH	Physical UL control channel
PUSCH	Physical UL shared channel
QoS	Quality-of-service
RAT	Radio access technologies
RB	Resource block
REs	Resource elements
RITs	Radio interface technologies
RLF	Radio link failures
SCells	Secondary cells
SCS	Subcarrier spacing
SLS	System-level simulations
SRITs	Set of RITs
SRS	Sounding reference symbol
SSB	Synchronization signal block
TCoE	Telecom centres of excellence
TRS	Tracking reference signal
TRxP	Transmission and reception point
UE	User equipment
UL	Uplink
URLLC	Ultra-reliable and low-latency communications
WDSL	Wireless DSL
WP	Working party
ZoD	Zenith angle Of Departure

TABLE 2. Supported transmission numerologies.

μ	$\Delta f = 2^{\mu} \cdot 15\ [kHz]$	Cyclic Prefix
0	15	Normal
1	30	Normal
2	60	Normal, Extended
3	120	Normal
4	240	Normal

a direct impact in the orthogonal frequency division multiplexing (OFDM) symbol duration.

B. CHANNEL BANDWIDTH

5G NR channel bandwidths [7] and resource block (RB) assignments enable higher spectrum usage as compared to LTE. For example: LTE 20 MHz channel vs. 5G NR 20 MHz channel using 15 kHz SCS. **LTE** 20 **MHz**: 100RB × 12 × 15 kHz = 18 MHz, which translates to 90% of the 20 MHz channel being nominally occupied with OFDM subcarriers. **5G NR** 20 **MHz**: 106RB × 12 × 15 kHz = 19.1 MHz, which translates to 95% of the 20 MHz channel being nominally occupied with OFDM subcarriers. It may be noted that 5G NR protocol does support arbitrary channel bandwidths with fewer RBs for applications requiring larger guard bands. For example, an operator could easily deploy 5G NR with only 100 RBs while using 15 kHz SCS over a 20 MHz spectrum block, resulting in an increased guard band as compared to that of the 5G NR example above.

Resource block is defined as 12 consecutive OFDM subcarriers in frequency, irrespective of the numerology. Therefore, the resource block bandwidth changes with numerology.

C. FRAME AND SUBFRAME STRUCTURE

In [7], 5G NR frame structure is defined. One radio frame lasts 10 milliseconds and is divided into ten sub-frames of 1 millisecond each as shown in Figure 1. The normal cyclic prefix slots have 14 OFDM symbols and the extended cyclic prefix slots have 12 OFDM symbols (supported only for the 60 kHz SCS). The total number of slots per sub-frame are shown in Figure 2 and Table 3. As seen from Figure 2, there are varying length of slots to enable different applications such as very low latency in the case of URLLC.

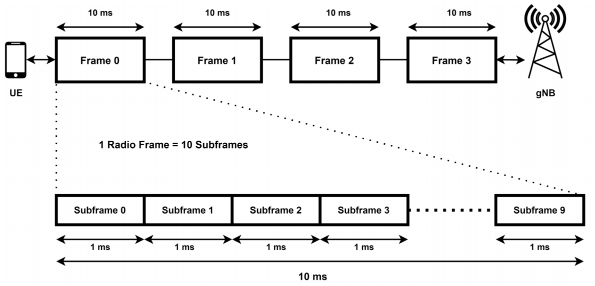

FIGURE 1. Frame and sub-frame.

The subframes in the case of 15 kHz can be aligned with the LTE subframe. Mini-slots with 2, 4, or 7 OFDM symbols are also supported by the subframe structure which can start at any symbol relative to the symbol 0 of each subframe. One of the motivations for a mini-slot is to support very low latency URLLC traffic. The mini-slots may transmit overlapping slots while carrying eMBB data which can cause errors in the eMBB data reception. However, this can be appropriately resolved with hybrid automatic repeat request (HARQ) retransmission [7]. Even though slots and mini-slots are the basic scheduling units, 5G NR also supports scheduling of a partial slot.

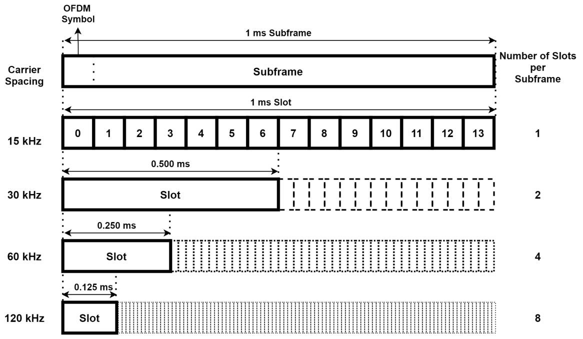

FIGURE 2. Slot.

TABLE 3. Number of slots per sub-frame.

SCS	$N_{\text{slot}}^{\text{subframe},\mu}$
15	1
30	2
60	4
120	8
240	16

IMT-2020 is intended to extend and enable a variety of usage scenarios and applications that will proceed beyond IMT-Advanced, as specified in recommendation ITU-R M.2083 [8]. The following are three possible applications for IMT-2020 [6]:

- *Enhanced Mobile Broadband (eMBB):* In comparison to current mobile broadband applications, this usage scenario would introduce additional application areas and standards for better functionality and a more streamlined user interface. This usage scenario includes a variety of scenarios, such as wide-area coverage and hotspot, each of which has its own set of specifications.
- *Massive Machine Type Communications (mMTC):* This use case is defined by a large number of linked machines exchanging a small amount of non-delay-sensitive data.
- *Ultra-Reliable and Low-Latency Communications (URLLC):* This use case has precise specifications for throughput, latency, and availability. Wireless management of industrial processing or development systems, remote medical surgery, delivery automation in a smart grid, transportation protection, and so on.

Standard is developed to work in different environment. IMT-2020 [6] is expected to work in different scenario and therefore, tested in the following environments:

1) *Indoor Hotspot-eMBB:* An indoor isolated area focused on stationary and pedestrian users with a very large traffic level at offices and/or shopping malls.
2) *Dense Urban-eMBB:* A dense urban area with large user intensity and traffic loads, with an emphasis on pedestrians and vehicular users.
3) *Rural-eMBB:* A rural community that supports pedestrian, vehicular, and high-speed vehicular users by providing a wider and consistent broad area coverage.
4) *Urban Macro–mMTC:* An urban macro ecosystem that focuses on a large range of wired computer style devices and aims to have continuous coverage.
5) *Urban Macro–URLLC:* An urban macro environment aimed at providing ultra-reliable and low-latency communications.

InH_x (Indoor Hotspot), UMa_x (Urban Macro), UMi_x (Urban Micro), and RMa_x (Rural Micro) are the channel models in each setting. The test environment and corresponding channel model is given in Table 4. When a channel type is applied with _x suffix, in this paper, we refer to all versions of the model, e.g., InH_x means both, InH_A and InH_B. Similarly, if a version is referred to as ''model A'' or ''model B,'' it refers to all instances of that variant, e.g., ''model A'' refers to all InH_A, UMa_A, UMi_A, and RMa_A variants.

TABLE 4. Mapping of channel models (reproduced from [6]).

Test environment	Indoor Hotspot –eMBB	Dense urban – eMBB	Rural – eMBB	Urban macro -mMTC	Urban macro - URLLC
Channel model	InH_A, InH_B	Macro layer: UMa_A, UMa_B Micro layer: UMi_A, UMi_B	RMa_A, RMa_B	UMa_A, UMa_B	UMa_A, UMa_B

III. 5G NR SIMULATOR

5GIF has developed a simulator for analyzing, interpreting and visualizing the performance of the major key performance indexes of 5G NR. The simulator is based on an abstract modeling approach which separates the simulation into both system level and link level. The system level simulations involve network evaluations, the generated statistics of which is used by link level simulation to obtain statistics for individual BS-UE pair.

Simulator modules include configuration setting, network layout, pathloss, fading effect, channel model and frame generation. Figure 3 shows the configuration settings, processing and output arrangement for the 5GIF simulator. The configuration settings are categorized into those given by the proponent technology, customizable simulation parameters, and those specified by ITU-R for M.2412 [6] evaluation purposes. Processing involves randomly sampled realizations of a scenario that is generated according to the parameters specified by the configuration setting. The individual link quality is determined as per the network layout, pathloss and fading effects. The generate statistics are then utilized to infer performance. 5GIF simulator is calibrated based on the SINR and coupling loss CDF for 19 cell cluster. The input simulation configuration files can be found at GitHub repository.[1]

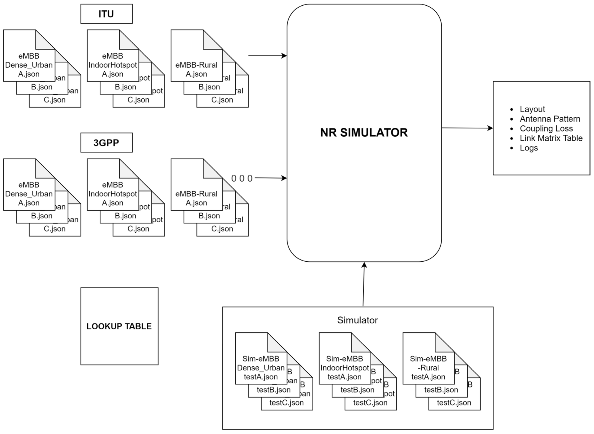

FIGURE 3. 5G new radio simulator setup.

A. KEY FEATURES

1) The simulator is capable to simulate various environments and scenarios such as indoor hotspot environment, dense urban environment, rural macro environment, urban macro environment: URLLC scenario, urban macro environment: mMTC environment. Other environments and scenarios can also be simulated by setting the relevant parameters in the configuration files. Two network layouts are supported: Indoor hotspot - Rectangular network layout with 3 Sectors (Transmission and reception point (TRxP)) each; Macro - Hexagon network layout with 3 sectors (TRxP) each.
2) The simulator is capable to provide visual representation of the coverage of gain provided by a number of transceiver units (TxRU) on each TRxP of a base station in horizontal and vertical direction. For any required configuration, both 2D and 3D antenna radiation patterns can be obtained and analysed providing gain for all the azimuth and zenith combinations. Figure 4 shows a 2D plot of antenna array radiation pattern and Figure 5 shows a 3D plot of antenna array radiation pattern for rural eMBB configuration A showing that the beam is narrow along vertical direction and wide along horizontal direction which is required in rural environment. The plots demonstrate the benefit when the angle of azimuth is 0° and the height angle

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[1] https://github.com/5gif

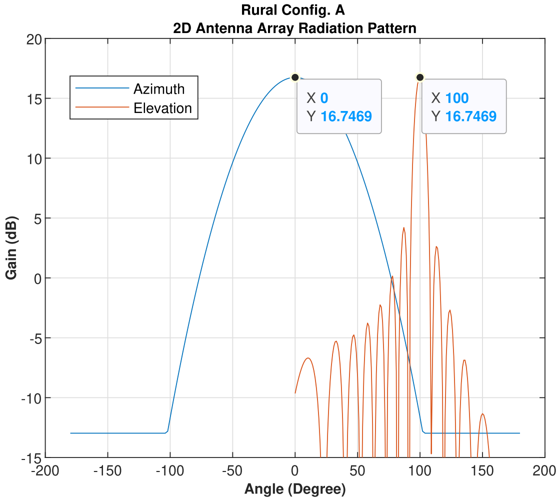

FIGURE 4. 2D Antenna array radiation pattern for rural eMBB config. A.

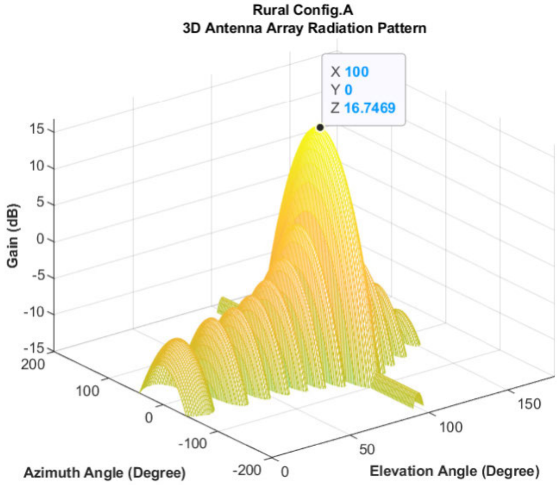

FIGURE 5. Antenna array radiation pattern for 8 × 1 elements with scan angle = 0° and etilt angle = 100°.

is 100°, which corresponds to the electric tilt and horizontal scan used for beamforming.

3) The simulator provides the primary metrics like coupling gain cumulative distribution function (CDF) plots, SINR CDF plots, BLER vs SINR plots, etc.
4) Inside a cell, a visual representation of the SINR distribution and antenna gains distribution can be created. The beamforming capacity to expand the propagation range is visualised in Figure 6. Figure 6 shows positive results in areas outside of the base station with adequate coverage for nearby consumers and negative gains in locations farther from the base station with no coverage within the cell.

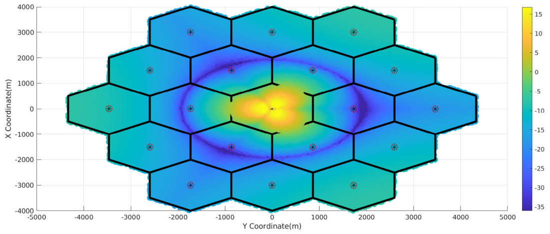

FIGURE 6. Antenna sector plot for RMa configuration A.

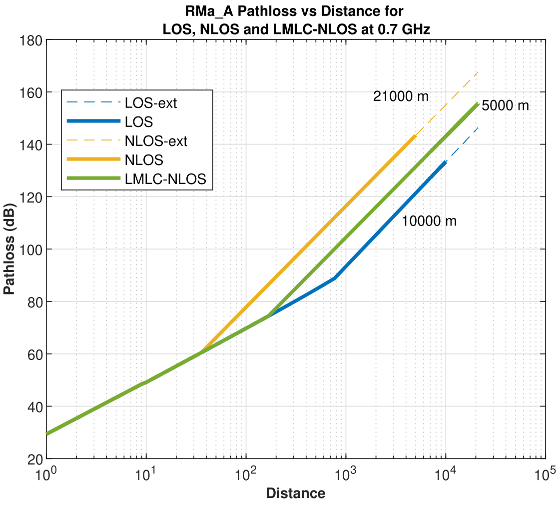

FIGURE 7. Pathloss vs. distance for channel model A.

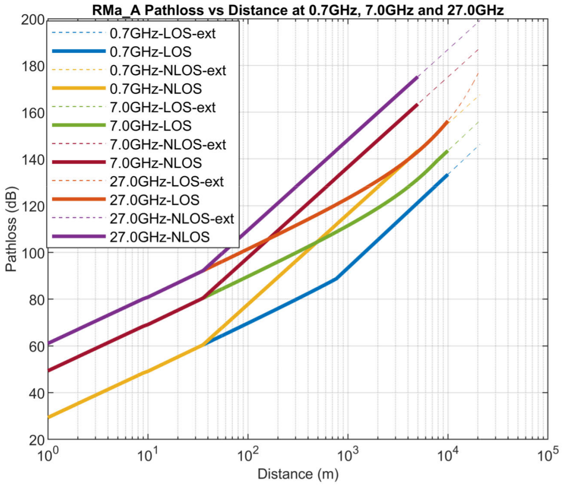

FIGURE 8. Pathloss vs. distance at 0.7 GHz, 7.0 GHz and 27.0 GHz.

5) Pathloss and shadow fading (large-scale fading) metrics can be generated. Figure 7 shows pathloss vs. distance for rural channel model A for LOS, NLOS and LMLC-NLOS scenario at 0.7 GHz frequency. Figure 8 shows pathloss vs. distance for rural channel model A for LOS and NLOS at 0.7 GHz, 7.0 GHz and 27.0 GHz frequency.
6) The simulator supports wrap around capability that is to have virtual base stations apart from the 19 base stations to remove the edge cell effect.

TABLE 5. Summary of evaluation methodologies (reproduced from [6]).

KPI	High-level assessment method
Peak data rate	Analytical
Peak spectral efficiency	Analytical
User experienced data rate	Analytical for single band and single layer; Simulation for multilayer
5th percentile user spectral efficiency	Simulation
Average spectral efficiency	Simulation
Area traffic capacity	Analytical
User plane latency†	Analytical
Control plane latency†	Analytical
Connection density‡	Simulation
Energy efficiency	Inspection
Reliability	Simulation
Mobility	Simulation
Mobility interruption time	Analytical
Bandwidth	Inspection
Support of wide range of services	Inspection
Supported spectrum band(s)/range(s)	Inspection

†Evaluation Completed in [9], ‡not discussed here in this work.

IV. EVALUATION METHODOLOGY

According to the guidelines described in M.2412 [6], the evaluation of candidate technologies consists of multiple steps such as, inspection, analytical evaluation and experimental verification of their self-evaluation submissions. The system performance is evaluated by considering the following key parameters as per the specified evaluation methodology is given in Table 5.

V. RESULTS AND OBSERVATIONS

Our team has evaluated most of these parameters following the guideline as described above. In this section, we discuss them briefly including the results.

A. PEAK SPECTRAL EFFICIENCY

Peak spectral efficiency is an important parameter in any wireless standard. It defines how many number of bits per second is sent in a given one Hz of bandwidth. It depends on many factors, such as, channel bandwidth, sub-carrier spacing, total number of subcarrier available in OFDM symbol, physical resource block (PRB) and so on [10]. Table 6 shows the maximum number of PRBs usable for a given SCS and the channel bandwidth as defined in 3GPP RAN4.

TABLE 6. Max. number of PRBs for FR1 and FR2.

SCS (kHz)	Channel Bandwidth (MHz)											
	5	10	15	20	25	40	50	60	80	100	200	400
For FR1 frequency range												
15	25	52	79	106	133	216	270					
30	11	24	38	51	65	106	133	162	217	273		
60		11	18	24	31	51	65	79	107	135		
For FR2 frequency ranges only (mmwave)												
60							66			132	264	
120							32			66	132	264

Each PRB can have 12 subcarriers and will span a bandwidth of 12 × SCS. For example in Table 6, for FR1 frequency range, row 2 has 273 PRBs. Each resource block has 12 carriers and each carrier in turn is 30 kHz, yielding a carrier bandwidth of $273 \times 12 \times 30$ kHz $= 98.28$ MHz. Similarly, row 3 yields a carrier bandwidth of $135 \times 12 \times 60$ kHz $= 97.20$ MHz.

In addition, NR can aggregate up to 16 such component carriers. The peak spectral efficiency for a particular component carrier (j^{th} CC) can be obtained from equation based on the specification and discussion in 3GPP [11].

$$\mathrm{SE}_{p_j} = \frac{(1 - OH^{(j)})}{BW^{(j)}} \times \left(v_{\text{Layers}}^{(j)} \cdot Q_m^{(j)} \cdot f^{(j)} \cdot R_{\max} \cdot \frac{N^{\mathrm{BW(j)},\mu \cdot 12}}{T_s^{\mu}} \right) \tag{1}$$

where $R_{\max} = \frac{948}{1024}$. For the j^{th} CC, $v_{\text{Layers}}^{(j)}$ represents the maximum number of layers, $Q_m^{(j)}$ is the maximum modulation order, $f^{(j)}$ is the scaling factor which takes values 1 and 0.75 at least. $f^{(j)}$ is signalled per band combination as per User equipment (UE) capability signalling, μ is the numerology as defined in TS 38.211 [7], T_s^{μ} is the average OFDM symbol duration in a subframe for μ, i.e. $T_s^{\mu} = \frac{10^{-3}}{14 \cdot 2^{\mu}}$ where the normal cyclic prefix is assumed. $N_{\text{PRB}}^{\mathrm{BW}(j)}$ is the maximum PRB allocation in bandwidth with μ, as given in section 4.5.1 of (TR 38.817 − 01) [12], where $\mathrm{BW}^{(j)}$ is the UE supported maximum bandwidth in the given band combination. $\mathrm{OH}^{(j)}$ is the overhead calculated as the average ratio of the number of resource elements (REs) occupied by L1/L2 control, synchronization signal, physical broadcast channel (PBCH) and reference signals, etc. with respect to the total number of REs in effective bandwidth time product $\alpha^{(j)} \cdot \mathrm{BW}^{(j)} \cdot (14 \times T_s^{\mu})$, $\alpha^{(j)}$ is the normalized scalar considering the downlink/uplink (DL/UL) ratio; for FDD $\alpha^{(j)} = 1$ for DL and UL; and for TDD and other duplexing $\alpha^{(j)}$ for DL and UL is calculated based on the frame structure. 50 percent of guard period (GP) symbols are called DL overhead, and 50 percent of GP symbols are considered UL overhead for GP. Given the maximum number of Tx/Rx elements in ITU-R configurations, the maximum number of TXRU allowed is upto 8 layers. Spectral efficiency is calculated for both, DL and UL.

1) DOWNLINK

For frequencies in FR1, e.g. the 3.5 GHz band is considered for early IMT-2020 deployments. This band is TDD band. In FR2, 26 GHz, 28 GHz and 39 GHz bands are supported in 3GPP NR specifications. 3GPP NR candidate supports various TDD slot patterns. Table 7 shows parameters for a DL centric configuration DDDSU (where D, S, and U stand for downlink, special, and uplink slots) (i.e. Five slots – 3 slots with all DL-only symbols, special slot and one slot with all UL-only symbols). The special slot (S) – has 11 DL symbols, 1 GP (Guard), 2 UL symbols.

Different SCS and bandwidth parameters for NR TDD DL peak spectral efficiency is shown in Table 8 where the DL dominant frame structure "DDDSU" (DL:UL = 4:1) is chosen and the results are summarized.

TABLE 7. Assumptions for TDD DL peak spectral efficiency (DDDSU).

Parameter	Values	Remarks
$v_{\text{Layers}}^{(j)}$	FR1: 8, FR2: 6	NR supports upto 8 layers for a single user for DL in FR1 and 6 layers in FR2 when PTRS is transmitted
$\alpha_{\text{DL}}^{(j)}$	0.7643	Corresponds to DL:UL=4:1 where 3 DL slots 1 UL slot is configured in every 5 slots S slot includes 11 DL symbols, 1 symbol for GP and 2 UL symbol
$Q_m^{(j)}$	8	supports upto 256 QAM for DL (TS 38.306 [13] and [14])
$f^{(j)}$	1	The value of 1 is chosen as scaling factor for DL peak spectral efficiency evaluation.
$R_{\max}$	948/1024 = 0.9258	NR supports highest coding rate as $R_{\max} = 948/1024$.
μ	0, 1, 2, 3	SCS : $\Delta f = 2^{\mu} \cdot 15[\text{kHz}]$
$N_{\text{PRB}}^{\text{BW(j)},\mu}$	For FR1: • 270 for 50 MHz with a 15 kHz SCS • 273 for 100 MHz with a 30 kHz SCS • 135 for 100 MHz with a 60 kHz SCS	Section 5.3.2 of (TS 38.104 v0.5.0) [15]
T_s^{μ}	$T_s^{\mu} = \frac{10^{-3}}{14 \cdot 2^{\mu}}$	SCS : $\Delta f = 2^{\mu} \cdot 15[\text{kHz}]$
$\text{OH}^{(j)}$	For FR1: • 0.121 for 50 MHz with a 15 kHz SCS • 0.118 for 100 MHz with a 30 kHz SCS • 0.124 for 100 MHz with a 60 kHz SCS For FR2: • 0.115 for 200 MHz with a 60 kHz SCS • 0.112 for 400 MHz with a 120 kHz SCS	Downlink overhead considered to be 50% of GP symbols For FR1: • CORESET of 24 PRBs (4 CCE) in every slot- 12 RE/PRB/slot • CORESET of 24 PRBs (4 CCE) in every slot - 12 RE/PRB/slot • TRS burst of 2 slots with periodicity of 20 ms and occupies 52 PRBs- 12 RE/PRB/20 ms • DMRS: 16 RE/PRB/slot in every slot and PRB • CSI-RS: 8 CSI-RS ports with 8 RE/PRB/slot with periodicity of 20 ms in every PRB • 1 SS/PBCH blocks per 20 ms; one SS/PBCH block occupies 960 REs = 4 OFDM symbols × 20 PRB × 12 REs/PRB FR2: • CORESET of 24 PPRBs (4 CCE) in every slot- 12 RE/PRB/slot • TRS burst of 2 slots with periodicity of 10 ms and occupies 52 PRBs- 12 RE/PRB/10 ms • DMRS: 12 RE/PRB/slot in every slot and PRB • PTRS: 1 port, frequency density is 4 PRB and time domain density is 1 symbol • CSI-RS: 8 CSI-RS ports with 8 RE/PRB/slot with periodicity of 10 ms in every PRB • CSI-RS for BM: 1 CSI-RS port with 2 RE/PRB/slot with periodicity of 10 ms in every PRB • 8 SS/PBCH blocks per 20 ms; one SS/PBCH block occupies 960 REs = 4 OFDM symbols × 20 PRB × 12 REs/PRB
$\text{BW}^{(j)}$	$5, 10, 15, 20, \cdots, 100, 200,$ 400 (FR1 and FR2, SCS)	Section 5.3.2 of TS 38.104 [15]
μ	0, 1, 2, 3	SCS : $\Delta f = 2^{\mu} \cdot 15[\text{kHz}]$

TABLE 8. Peak spectral efficiency (bits/s/Hz) for NR TDD DL (Frame structure: DDDSU, DL:UL = 4 : 1).

		Channel Bandwidth (MHz)													
SCS (kHz)		5	10	15	20	25	30	40	50	60	80	90	100	200	400	Req.
FR1	15	39.6	43.6	44.9	45.6	46.1	46.3	47.1	47.2							30
	30	31.7	38.4	42.1	43.1	44.4	44.6	45.9	46.3	47.1	47.5	47.7	47.9			30
	60		31.8	37.5	38.7	40.9	42.3	43.3	44.5	45.4	46.4	46.8	47.1			30
FR2	60								33.7				34.5	34.9		30
	120								31.7				34.0	34.7	35.0	30

2) UPLINK

Similarly, different SCS and bandwidth parameters for NR TDD UL peak spectral efficiency were evaluated for the same dominant frame structure "DDDSU" shown in Table 9.

The achievable peak spectral efficiency is shown Table 10 and, peak spectral efficiency is shown in Table 11.

B. PEAK DATA RATE

5G specification defines peak data rate for DL and UL. Again it depends on various factors, such as bandwidth, number of resource elements, overhead, etc. Our evaluation for this parameters for both DL and UL is presented.

1) DOWNLINK

For DL peak data-rate, the overheads due to synchronization signal block (SSB), tracking reference signal (TRS), physical downlink control channel (PDCCH), phase tracking reference signal (PT-RS), channel state information reference signal (CSI-RS), are considered. Typical values for these are shown in Table 12.

Bandwidths of the order of 400 MHz are required to achieve peak data rates of 20 Gbits/s. The peak data rate is evaluated as [16], [17] :

$$\begin{aligned} \text{DR}_{\text{dl}} &= (\text{repmat}(N_{\text{slots/s}}, N_{\text{rows}}, \text{size}(\text{BW}_{\text{SC}}, 2))) \\ &\quad \times \left(N_{\text{RE/slot}} * (1 - \text{OH}_{\text{dl}}) * N_{\text{layers}} * \text{Mod}_{\text{format}} * \text{CR}\right) \end{aligned} \tag{2}$$

TABLE 9. Parameter assumptions of NR TDD UL peak spectral efficiency.

Parameter	Values	Remarks
$v_{\text{Layers}}^{(j)}$	4	NR supports upto 4 layers for UL
$Q_m^{(j)}$	8	NR supports up to 256 QAM for UL
$f^{(j)}$	1	The value of 1 is chosen as scaling factor for UL peak spectral efficiency evaluation.
$R_{\max}$	$948/1024 = 0.9258$	NR supports highest coding rate as $R_{\max} = 948/1024$.
μ	$0, 1, 2, 3$	SCS : $\Delta f = 2^{\mu} \cdot 15$[kHz]
$N_{\text{PRB}}^{\text{BW(j)},\mu}$	For FR1: • 270 for 50 MHz with a 15 kHz SCS • 273 for 100 MHz with a 30 kHz SCS • 135 for 100 MHz with a 60 kHz SCS FR2: • 264 for 200 MHz with a 60 kHz SCS • 264 for 400 MHz with a 120 kHz SCS	Section 5.3.2 of TS 38.104 v0.5.0 [15]
T_s^{μ}	$\frac{10^{-3}}{14 \cdot 2^{\mu}}$	SCS : $\Delta f = 2^{\mu} \cdot 15$[kHz]
BW$^{(j)}$	Section 2.3 of TS 38.104 [15]	section 2.3 of TS 38.104 [15]
$\alpha_{UL}^{(j)}$	0.2357	This value corresponds to DL:UL=4 : 1 where 3 DL slots, 1 S slot mixing DL/UL symbols, and 1 UL slot are configured in every 5 slots; S slot includes 11 DL symbols, one symbol for GP, and two UL symbols.
OH$^{(j)}$	For FR1: • 0.167 for 50 MHz with a 15 kHz SCS • 0.16for 100 MHz with a 30 kHz SCS • 0.156 for 100 MHz with a 60 kHz SCS For FR2: • 0.202 for 200 MHz with a 60 kHz SCS • 0.195 for 400 MHz with a 120 kHz SCS	Uplink overhead considered to be 50% of GP symbols For FR1: • PUCCH: short PUCCH with 1 PRB and 1 symbol in every UL slot • DM-RS: 12 RE/PRB/slot • SRS: 1 symbols per slot with periodicity of 20 ms For FR2: • PUCCH: short PUCCH with 1 PRB and 1 symbol in every UL slot • DM-RS: 12 RE/PRB/slot • SRS: 1 symbols per slot with periodicity of 5 ms • PTRS: 2 ports PTRS, frequency density is 4 PRB, and time domain density is 1 symbol

TABLE 10. Peak spectral efficiency for NR TDD UL (bit/s/Hz) (Frame structure: DDDSU).

SCS (kHz)		Channel Bandwidth (MHz)														
		5	10	15	20	25	30	40	50	60	80	90	100	200	400	**Req.**
FR1	15	20.6	21.5	21.8	22.0	22.0	22.1	22.1	22.4							15
	30	18.2	20.0	21.1	21.3	21.7	21.7	22.2	22.2	22.6	22.7	22.8	22.8			15
	60		18.3	20.0	20.1	20.8	20.8	21.4	21.8	22.1	22.5	22.6	22.7			15
FR2	60								20.9				21.0	21.0		15
	120								20.4				21.1	21.2	21.2	15

TABLE 11. Peak spectral efficiency observations.

KPI	Category	Required value	Observed Value
Peak spectral efficiency (bit/s/Hz)	eMBB	Downlink: 30	$31.7 - 47.9$
		Uplink: 15	$18.2 - 22.8$

TABLE 12. Peak data rate evaluation assumptions (FR2).

Parameter	Configuration
SSB	8 SSBs per 20 ms
TRS	Minimum (52, BW in PRBs) PRB wide, occurs every 20 ms
PDCCH	4 CCE in every slot
DM-RS	2 complete symbols per slot
CSI-RS	8 RE per PRB, occurs every 10 ms
PT-RS	1 subcarrier every 4th PRB, every symbol
Number of layers	8
Modulation format	256QAM
Code rate	0.93

where DR_{dl} = data rate on the DL, B = repmat(A,m,n) produces a large matrix B with m-by-n tiling of copies of A, s = size(A) returns a row vector with elements containing the length of the corresponding dimension of A, N_{RE} = Number of resource elements, OH_{dl} = overhead on the DL.

For a 400 MHz wide component carrier, the peak data rate is 17.49 Gbits/s. Aggregating two such component carriers consume a bandwidth of 800 MHz and gives a peak data-rate of about 35 Gbits/s, well beyond the passing criterion of 20 Gbits/s shown in Table 13.

TABLE 13. Downlink peak data-rate in Gbps (1 CC).

SCS \ BW	50 **MHZ**	100 **MHZ**	200**MHZ**	400 **MHZ**	6400 **MHZ**
60 kHz	2.11	4.32	8.73	-NA-	-NA-
120 kHz	1.98	4.25	8.66	17.49	16 CC each of 400 MHz required $16 \times 17.49 = 279.84$ Gbps

The NR capability of maximum aggregated system bandwidth is presented in Table 8.1.1 − 1. of (TR 37.910) [18]. It is observed that the maximum aggregated bandwidth for FR1 is 800 MHz to 1600 MHz and that of FR2 is 3200 MHz to 6400 MHz.

2) UPLINK

The UL evaluation parameters are listed in Table 14. The overheads due to demodulation reference signal (DM-RS), PT-RS, sounding reference symbol (SRS), and physical UL control channel (PUCCH) are considered. The ITU peak data rate targets are fulfilled with a carrier aggregation of two

TABLE 14. Evaluation assumptions for peak data-rate for uplink.

Parameter	Setting
DM-RS	1 complete symbol per slot
PT-RS	1 subcarrier every 4th PRB, every symbol
SRS	1 complete symbol every 10 ms
PUCCH	Long PUCCH with 2 PRB over slot in every slot
Number of layers	4
Modulation format	256 QAM
Code rate	0.93

TABLE 15. Uplink peak data-rate in Gbps (per CC).

BW SCS	50 MHZ	100 MHZ	200 MHZ	400 MHZ	6400 MHZ
60 kHz	1.16	2.35	4.74	-NA-	-NA-
120 kHz	1.08	2.31	4.71	9.50	16 CC each of 400 MHz required $16 \times 9.50 = 152.0$ Gbps

TABLE 16. Peak data rate observations.

KPI	Category	Required value	Observed Value	Comment
Peak data rate (Gbit/s)	eMBB	Downlink: 20	$21.74 - 34.98$	Using multiple CC for BW $500 - 800$ MHz
	Environment: No specific	Uplink: 10	$11.81 - 19$	By using multiple CC for aggregate BW of $500 - 800$ MHz in FR2

400 MHz wide carrier component, (Table 15). Also, the peak data rate observations shown in Table 16.

C. USER EXPERIENCED DATA RATE

User experience data rate is another important service. It is evaluated in dense urban eMBB test environment for config. A (4 GHz). Table 17 lists the DL 5% spectral efficiency evaluated for config. A for different bandwidth and antenna configurations and, the corresponding user experienced data rate for both UL and DL.

TABLE 17. Spectral efficiency evaluation of TDD DL for different system bandwidths (FR1).

Dense Urban	Evaluation Configuration	1-CC Bandwidth		
		BW = 20 MHz	BW=40 MHz	BW=100 MHz
DL	Config. A (30 KHz SCS); 32T4R(5%SE)	0.375	0.437	0.479
	User Experience Calculation(Mbps)	14CC (280 KHz) $14 \times 20 \times 0.375 = 105$	6 CC (240 MHz) $6 \times 40 \times 0.437 = 104.88$	3 CC (300 MHz) $3 \times 100 \times 0.479 = 143.7$
	Config. A (30 KHz SCS); 64T4R(5% SE)	0.485	0.568	0.624
	User Experience Calculation(Mbps)	11 CC (220 MHz) $11 \times 20 \times 0.485 = 106.7$	5 CC (200 MHz) $5 \times 40 \times 0.568 = 113.6$	3 CC (300 MHz) $3 \times 100 \times 0.624 = 187.2$
UL	Config. A (30 KHz SCS); 4T32R (5% SE)	0.3	0.312	0.334
	User Experience Calculation(Mbps)	9 CC (180 MHz) $9 \times 20 \times 0.3 = 54$	4 CC (160 MHz) $4 \times 40 \times 0.312 = 50$	2 CC (300 MHz) $2 \times 100 \times 0.334 = 66.8$
	Config. A (30 KHz SCS); 4T64R (5% SE)	0.386	0.401	0.429
	User Experience Calculation(Mbps)	7CC (140 MHz) $7 \times 20 \times 0.486 = 54$	3CC (120 MHz) $3 \times 40 \times 0.401 = 48$	3 CC (300 MHz) $3 \times 100 \times 0.429 = 128.7$

The user-experienced data-rate in the case of one frequency band and one layer of transmission reception points (TRxP) [2], [6], is computed as in (3)

$$R_{\text{user}} = W \cdot SE_{5\%} \tag{3}$$

where $SE_{5\%}$ is the 5^{th} percentile user spectral efficiency and W denotes the channel bandwidth. In the case bandwidth is aggregated across multiple bands (one or more TRxP layers), the user-experienced data-rate will be summed over the bands. Similar case when using carrier aggregation to derive user-experienced data-rate.

3GPP self-evaluation report provides support for up to 16 CC aggregation and the user experienced data rate for maximum available bandwidth. This is provided in Table 18. User experienced data rate observations shown in Table 19.

TABLE 18. Downlink maximum user experienced data rate for different possible aggregated bandwidth.

Dense Urban	Evaluation Configuration	User Experienced Data Rate (Mbps)(> 50) $= \mathbf{N_{cc}} \times \mathbf{W} \times \mathbf{SE_5}$	
		W= 180 MHz	**W= 1600 MHz**
DL	Config. A (30 KHz SCS); 64T4R	3 CC required $100 \times 0.624 + 80 \times 0.568$ $=107.84$	16 CC required $6 \times 100 \times 0.624$ $=998.4$
UL	Config. A (30 KHz SCS); 4T64R	3 CC required $100 \times 0.429 + 80 \times 0.401$ $=74.98$	16 CC required $16 \times 100 \times 0.429$ $=686.4$

TABLE 19. User experienced data rate observations.

KPI	Category	Required value	Observed Value	Comments
User experienced data rate	eMBB-Dense Urban	Downlink: 100	Downlink: $107.8 - 187.2$	Corresponds to minimum aggregated bandwidth of 3 CC$\sim$ 180 MHz for Config. A (4 GHz) and using 3 CC (300 MHz) in 4 GHz band
		Uplink: 50	Uplink: $74.98 - 128.7$	

Note: upto 16 CC is supported in the technology for achieving higher user experienced date rate

Based on assessment of user experienced data rate, the following points can be observed:

1) Multiple carrier aggregation configurations are supported and can be used to improve spectrum utilization and hence user experienced data rate by using higher bandwidth carriers to reduce guard bands and overheads.
2) The maximum possible user experienced data rate for 3GPP for 16 CC configuration is 998.2 Mbps in DL and 686.4 Mbps in UL in FR1, for the given dense urban IMT-2020 evaluation configuration.
3) By employing carrier aggregation, it can be seen that the minimum bandwidth required in case of DL can be approximated to 180 MHz ($100 \times 0.624 + 2 \times 40 \times 0.568 = 107.84$ Mbps) when using 64T4R with one 100 MHz carrier and two 40 MHz carrier which are available for use in the n77 band ($3300 - 4200$ MHz).
4) In case of UL user experienced data rate, by using carrier aggregation it can be seen that the minimum bandwidth required can be approximated to 120 MHz ($100 \times 0.429 + 20 \times 0.386 = 50.62$Mbps) when using 4T64R* with one 100 MHz carrier and one 20 MHz carrier which are available for use in the n77 band ($3300 - 4200$ MHz).

This assures that Indian operators are well positioned to address the national digital communications policy NDCP [19] requirement using this candidate technology (IMT-2020/14), using a minimum bandwidth of 180 MHz in n77 Band.

D. AREA TRAFFIC CAPACITY

Area traffic capacity is evaluated based on achievable average spectral efficiency, TRxP density and the bandwidth. Let W denote the channel bandwidth and ρ the TRxP density (TRxP/m^2). The area traffic capacity C_{area} is related to average spectral efficiency SE_{avg} as in (4)

$$C_{area} = \rho \times W \times SE_{avg} \tag{4}$$

In the case multiple bands are aggregated, the area traffic capacity will be summed over the bands.

Area traffic capacity in indoor hotspot eMBB for config. A, based on the average spectral efficiency is evaluated.

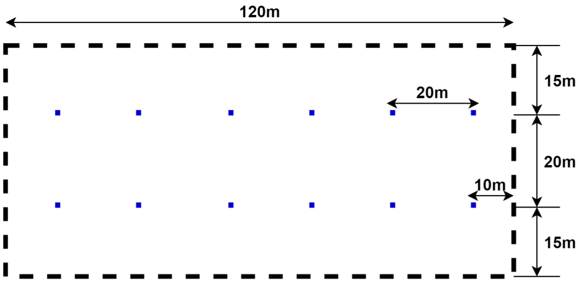

FIGURE 9. Indoor hotspot site layout (reproduced from [6]).

TABLE 20. TRxP density.

	12 **TRxP**	36 **TRxP**
$\rho(\mathrm{TRxP}/m^2)$	0.02	0.06

Indoor hotspot site layout is shown in Figure 9 as defined in [6], The TRxP density is calculated using (5) and the values: for 12 TRxP is 0.02 and 36 TRxP is 0.06 (Table 20), where the total area of the network layout is $120 \times 50 = 6,000\mathrm{m}^2$.

$$\rho(\mathrm{TRxP}/m^2) = \frac{\text{Number of TRxP}}{\text{Total Area of the network layout}} \tag{5}$$

For config. A Indoor hotspot-eMBB, the DL area traffic capacity (Mbit/s/m^2) is shown in Table 21. Area traffic capacity observations shown in Table 22.

Based on area traffic capacity assessment following points can be observed:

1) Three component carriers of 100 MHz are needed to be aggregated in n77 from the Indian perspective to satisfy the dense indoor area traffic capacity requirement.
2) The available bandwidth in the sub-6 GHz mid band (3300 – 3600 MHz) is less than the minimum required 300 MHz threshold, but the requirements can be met by employing a higher density of TRxP per Cell.

TABLE 21. Downlink area traffic capacity (Mbit/s/m^2) in indoor hotspot-eMBB at 4 GHz, Ch.Model-A.

System Bandwidth W (MHz)	**DL Average spectral efficiency SE_{avg} [bps/Hz/TRxP]**	**Area Traffic Capacity DDDSU : 54 DL out of 70 Symbols $SE_{eff} = SE_{avg} \star (54/70)$ $W \star \rho \star SE_{avg}$**	**Remark**
	TDD 100 MHz bandwidth per CC with 30 kHz SCS		
500	13.657	10.54	12 TRxP
300	13.637	18.94	36 TRxP

TABLE 22. Area traffic capacity observations.

KPI	**Category**	**Required value**	**Observed Value**	**Comments**
Area traffic capacity	eMBB (Indoor-Hotspot)	10	12 **TRxP** – 10.54 Mbit/s/m^2 36 **TRxP** – 18.94 Mbit/s/m^2,	Target met using a Minimum Bandwidth of 300 MHz (FR1 – 4 GHz)

TABLE 23. Mobility interruption time observations.

KPI	**Category**	**Required value**	**Observed Value**	**Comment**
Mobility interruption time (ms)	eMBB	0	0	Due to inherent support for Beam Mobility & CA mobility, make before break happens
	URLLC	0	0	

E. MOBILITY INTERRUPTION TIME

Mobility interruption time is defined according to [2], [6] as "The procedure of exchanging user plane packets with base stations during transitions shall be described based on the proposed technology including the functions and the timing involved". Mobility interruption time can be evaluated using two schemes supported by 3GPP NR: Beam mobility and Carrier aggregation (CA).

1) BEAM MOBILITY [2], [6]

In the beam mobility scenario, when moving within the same cell, the transmit-receive beam pair of the user equipment needs to be changed. gNB configures different beams for the UE at different slots during UE mobility for DL data transmission. UE and gNB allocate different beams between them for continuous DL transmission. Since there are different beams, even if one link fails, the other link maintains a connection as beam pair switching happens at different slots. For UL data transmission, physical UL shared channel (PUSCH) is sent using the beam configured by SRI (SRS resource indicator) by gNB. The UL communication is done by selecting a side beam for data transmission by selecting different slots.

2) CA MOBILITY [2], [6]

When moving within the same Primary Cell (PCell) with CA enabled, the set of configured Secondary Cells (SCells) of the UE may change. The SCell addition procedure and SCell release procedures can occur. During these procedures, UE can always exchange user plane packets with the gNB during transitions. The data transmission between the UE and the PCell is kept during the transition. Based on the above analysis and procedures supported by 3GPP NR, the UE can always exchange user plane packets with gNB during the mobility transitions. Therefore, 0 ***ms*** mobility interruption time is achieved by NR for this scenario. Mobility interruption time observations shown in Table 23.

F. SPECTRAL EFFICIENCY

1) 5th PERCENTILE USER SPECTRAL EFFICIENCY

The 5th percentile user spectral efficiency is evaluated by system level simulation using the evaluation configuration parameters of Indoor Hotspot-eMBB, Dense Urban-eMBB, and Rural-eMBB test environments.

Let user i in drop j correctly decode $R_i^{(j)}(T)$ accumulated bits in [0, T]. For non-scheduled duration of user i zero bits are accumulated. During this total time user i receives accumulated service time of $T_i \leq T$, where the service time is the time duration between the first packet arrival and when the last packet of the burst is correctly decoded. In case of full buffer, $Ti \leq T$. Hence the rate normalised by service time T_i and channel bandwidth W of user i in drop j, $r_i^{(j)}$ is given in (6)

$$r_i^{(j)} = \frac{R_i^{(j)}(T)}{T_i \cdot W} \tag{6}$$

Running N drops simulations leads to N drops $\times$ N values of $r_i^{(j)}$ which the lowest 5th percentile point of the CDF is used to estimate the 5th percentile user spectral efficiency.

2) AVERAGE SPECTRAL EFFICIENCY

Let $R^i(T)$ denote the number of correctly received bits by user i $(i = 1, \cdots, N)$ (downlink) or from user i (uplink) in a system comprising a user population of N users and M Transmission Reception Points (TRxPs). Further, let W denote the channel bandwidth and T the time over which the data bits are received. The average spectral efficiency may be estimated by running system-level simulations over number of drops N drops. Each drop gives a value of $\sum_{i=1}^{N} R^i(T)$ denoted as: $R^1(T), \cdots, R^{N_{\text{drops}}}(T)$ and the estimated average spectral efficiency resulting is given by (7)

$$\begin{aligned}\widehat{\text{SE}}_{\text{avg}} &= \frac{\sum_{j=1}^{N_{\text{drops}}} R^j(T)}{N_{\text{drops}} T \cdot W \cdot M}\\ &= \frac{\sum_{j=1}^{N_{\text{drops}}} \sum_{i=1}^{N} R^i(T)}{N_{\text{drops}} T \cdot W \cdot M}\end{aligned} \tag{7}$$

where $\widehat{\text{SE}}_{\text{avg}}$ is the estimated average spectral efficiency and will approach the actual average with an increasing number of N_{drops} and $R_i^{(j)}(T)$ is the simulated total number of correctly received bits for user i in drop j.

3) DUPLEXING SCHEME

In NR design, the flexible duplexing scheme is available, e.g.,

- Different transmission directions in either part of a paired spectrum,
- TDD operation on an unpaired spectrum where the transmission direction of most time resources can be dynamically changing.

In this document, the FDD is considered for evaluation configurations with 700 MHz and TDD is used for configurations with 4 GHz, 30 GHz

4) SPECTRAL EFFICIENCY CALCULATION (TDD/FDD)

The spectral efficiency of different duplexing schemes can be calculated according to Report ITU-R M.2412 [6].

For DL average spectral efficiency and 5th percentile spectral efficiency,

In case of FDD, the simulation bandwidth is 10 MHz for DL and 10 MHz for UL. The DL average spectral efficiency is given by

$$\text{SE}_{\text{avg}} = \frac{\sum_{i=1}^{N} R_i(T)}{T \cdot W \cdot M} \tag{8}$$

where W is the DL bandwidth of 10 MHz; $R_i(T)$ denotes the number of correctly received bits of user i, and the overhead of DL control and DL reference signals on the DL bandwidth of 10 MHz is taken into account when deriving $R_i(T)$; and T is the simulation time. Similar notations are applied to 5th percentile user spectral efficiency.

For TDD, the simulation bandwidth is 20 MHz for DL and UL. The DL average spectral efficiency is given by (8), where W is the effective DL bandwidth that accounts for the time frequency resource used for DL transmission (including GP symbols); $R_i(T)$ denotes the number of correctly received bits of user i, and the overhead of DL control, DL reference signal on the DL effective bandwidth is taken into account; and T is the simulation time. Similar notations are applied to 5th percentile user spectral efficiency.

For UL average spectral efficiency and 5th percentile spectral efficiency, similar way is employed to derive the evaluation results for these two metrics.

5) SPECTRAL EFFICIENCY CALCULATION (OH & GUARD-BAND)

To reflect the benefit of reduced guard band ratio and overhead for larger bandwidth in NR, i.e. when the system bandwidth is larger than simulation bandwidth (10 MHz in FDD and 20 MHz in TDD), the spectral efficiency can be derived from (9)

$$\text{SE}' = \text{SE}_{\text{avg}} \times \frac{(1 - \text{gb}(N_{\text{RB}}))}{(1 - \text{gb}(N_{\text{RB0}}))} \times \frac{(1 - \text{OH}(N_{\text{RB}}))}{(1 - \text{OH}(N_{\text{RB0}}))} \tag{9}$$

where $gb(N)$ and $OH(N)$ is the guard band ratio and the overhead at given number of RB- N, respectively, and SE_{avg} is calculated by (8) For FDD, $N_{\text{RB0}} = 52$ for 10 MHz simulation bandwidth and 15 kHz subcarrier spacing. For TDD, $N_{\text{RB0}} = 51$ for 20 MHz simulation bandwidth and 30 kHz subcarrier spacing. The overhead reduction for the larger bandwidth mainly comes from the PDCCH. In addition, SSB and TRS overhead will be reduced slightly. By assuming M_0 OFDM symbols for PDCCH at the bandwidth BW_0, the number of OFDM symbol for PDCCH at bandwidth BW could be

$$M = BW_0/BW \times M_0 \tag{10}$$

For example, if we assume $M_0 = 2$ for 20 MHz bandwidth system, then $M = 1$ for 40 MHz bandwidth system. The value of M could be a non-integer since NR supports PDCCH sharing with PDSCH. The guard band ratio and PDCCH overhead reduction model for larger bandwidth based on (9) is considered in DL.

For frequencies in FR1, the 4 GHz band is considered for early IMT-2020 deployments, this band is a TDD band. In the FR2, 30 GHz bands are considered for deployment.

6) DOWNLINK SE

The DL spectral efficiency evaluation results for NR are given in Tables 24-25.

TABLE 24. **Channel model A downlink spectral efficiency evaluation for different bandwidths (FR1).**

Test environment	Evaluation configuration	Average spectral efficiency (bit/s/Hz/TRxP)				5th percentile spectral efficiency (bit/s/Hz)			
		BW=20 MHz	BW=40 MHz	BW=100 MHz	Req.	BW=20 MHz	BW=40 MHz	BW=100 MHz	Req.
Indoor Hotspot	Config. A (15 KHz SCS) 32T4R	12.536	-	-	9	0.387	-	-	0.3
	Config. A (30 KHz SCS) 32T4R	12.725	14.888	16.368		0.37	0.433	0.476	
Dense Urban	Config. A (30 KHz SCS) 32T4R	12.8	14.904	16.346	7.8	0.375	0.437	0.479	0.225
	Config. A (30 KHz SCS) 64T4R	15.8	18.489	20.328		0.485	0.568	0.624	
Rural	Config. A 8T2R	6.594	7.383	7.927	3.3	0.138	0.155	0.166	0.12
	Config. B (30KHz SCS) 32T4R	15.061	17.54	19.238		0.374	0.436	0.478	
	Config. C 8T4R	7.597	8.51	9.138		0.18	0.202	0.217	

TABLE 25. **Channel model B downlink spectral efficiency evaluation (FR2).**

Test environment	Evaluation configuration	Average spectral efficiency (bit/s/Hz/TRxP)				5th percentile spectral efficiency (bit/s/Hz)			
		BW=80 MHz	BW=100 MHz	BW=200 MHz	Req.	BW=80 MHz	BW=100 MHz	BW=200 MHz	Req.
Indoor Hotspot	Config. B (60KHz SCS) 32T8R	11.384	11.984	12.998	9	0.302	0.318	0.345	0.3

7) UPLINK SE

The UL spectral efficiency evaluation results for NR are given in Tables 26-27.

TABLE 26. **Channel model A uplink spectral efficiency evaluation (FR1).**

Test environment	Evaluation configuration	Average spectral efficiency (bit/s/Hz/TRxP)				5th percentile spectral efficiency (bit/s/Hz)			
		BW=20 MHz	BW=40 MHz	BW=100 MHz	Req.	BW=20 MHz	BW=40 MHz	BW=100 MHz	Req.
Indoor Hotspot	Config. A (15 KHz SCS) 2T32R	7.545	-	-	6.75	0.419	-	-	0.21
	Config. A (15 KHz SCS) 4T32R	8.279	-	-		0.459	-	-	
	Config. A (30 KHz SCS) 2T32R	7.551	7.847	8.401		0.42	-	-	
	Config. A (30 KHz SCS) 4T32R	8.234	-	-		0.471	0.436	0.467	
Dense Urban	Config. A (30 KHz SCS) 2T32R	6.662	6.923	7.412	5.4	0.3	0.312	0.334	0.15
	Config. A (30 KHz SCS) 2T64R	7.633	7.932	8.492		0.386	0.401	0.429	
Rural	Config. A 1T8R	4.17	4.250	4.414	1.6	0.134	0.137	0.142	0.045
	Config. B (30 KHz SCS) 1T32R	3.457	3.593	3.846		0.123	0.128	0.137	
	Config. C 2T8R	4.038	4.116	4.274		0.081	0.083	0.086	

From Tables 24-27 and assessment of spectral efficiency following points can be observed:

1) 5G NR meets the requirements of IMT-2020 since InH-eMBB Config. A, Config. B, DU-eMBB Config. A satisfy the Spectral Efficiency requirements.

TABLE 27. **Channel model B uplink spectral efficiency evaluation (FR2).**

Test environment	Evaluation configuration	Average spectral efficiency (bit/s/Hz/TRxP)				5th percentile spectral efficiency (bit/s/Hz)			
		BW=80 MHz	BW=100 MHz	BW=200 MHz	Req.	BW=80 MHz	BW=100 MHz	BW=200 MHz	Req.
Indoor Hotspot	Config. B (30 KHz SCS) 8T32R	7.392	7.434	7.477	6.75	0.425	0.427	0.43	0.21
Hotspot	Config. B (60 KHz SCS) 8T16R	6.382	6.418	6.455		0.245	0.246	0.248	

2) InH Config. B (30 GHz) UL Avg Spectral Efficiency meets requirements in case where the minimum number of TxRU at UE are 8 and that of BS are 32.

3) It has being observed from the SER of 3GPP that DU config. B DL & UL both do not meet the 5th Percentile Spectral Efficiency requirements due to higher losses in the mmWave (30 GHz) which not being able to cover the cell edge users at ISD 200 m (3GPP TR 37.910) [18].

Summary of spectral efficiency observations are given in Table 28.

TABLE 28. **Spectral efficiency observations.**

KPI	Category	Required value	Observed Value BW: 20 MHz (TDD) & 10 MHz (FDD)	
			FR1 (Channel A)	FR2 (Channel B)
Average Spectral efficiency (bit/s/Hz)	Indoor Hotspot-eMBB FR1-Config. A FR2-Config. B	DL: 9	12.725	11.384
		UL: 6.75	7.551	7.392
	Dense Urban – eMBB FR1-Config. A	DL: 7.8	12.8	
		UL: 5.4	6.662	
	Rural– eMBB Config. A, B, C	DL:3.3	6.594, 15.061, 7.597	
		UL:1.6	4.17, 3.457, 4.038	
5th Percentile spectral efficiency (bit/s/Hz)	Indoor Hotspot – eMBB FR1-Config. A FR2-Config. B	DL: 0.3	0.37	0.302
		UL: 0.21	0.42	0.425
	Dense Urban – eMBB FR1-Config. A	DL: 0.225	0.375	
		UL: 0.15	0.3	
	Rural – eMBB Config. A, B, C	DL: 0.12	0.138, 0.374, 0.18	
		UL: 0.045	0.134, 0.123, 0.08	

G. SPECTRAL EFFICIENCY- SUPPLEMENTARY EVALUATION

1) FIXED WIRELESS ACCESS (FWA)

5G FWA can be used to offer an easy and affordable alternative to wired broadband in the lower bands of the wireless spectrum. FWA allows service companies to provide high-speed connectivity to suburban and remote areas where the expense of laying fibre is a limiting factor. It provides ultra-high-speed broadband services to both home and enterprise customers using standardised 3GPP technologies and Evolved packet core (EPC) networks. Option 3x gNBs that help FWA and other early 5G implementations run in NSA mode alongside the current 4G eNodeB. When applying 5G FWA for the first time, option 3 eliminates rollout uncertainties and variables.

5G FWA will have operation frequency capacities that are comparable to fibre optics at mmWave. 5G FWA will

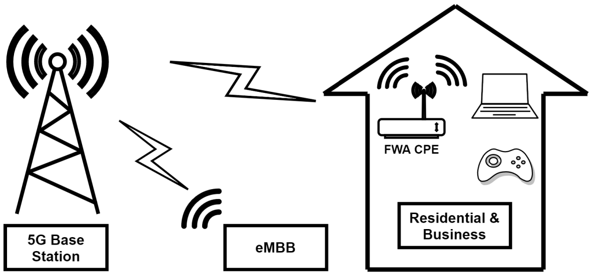

FIGURE 10. **3GPP gNodeB used for FWA applications.**

be a cost-effective alternative to fixed-line DSL, wire, and fibre in all markets with NR in the mmWave. They have thin beams, which allows for a higher user density without competing and interfering with other users. This satisfies the last-mile requirement by supplying the bandwidth needed to accommodate high-definition television networks and high-speed Internet access for suburban and rural residents. This increases prospects for both emerging countries with poor broadband penetration and industrialised countries with slow DSL lines.

At millimetre wavelengths, 5G FWA would be able to have data bandwidth equal to fibre optics (mmWave). In all markets with NR in the mmWave, 5G FWA would provide a cost-effective option to fixed-line DSL, wire, and fibre.

It's worth mentioning that the IMT-2020 KPI are geared for wireless applications. The KPIs for wireline and wireless networks are vastly different. Fixed line networks aim for fixed data speeds, while wireless systems aim for spectral quality values. This puts an unfair pressure on the wireless scheduler to service if an FWA targets those use cases. WP5D was given a performance comparison using a Wireless DSL (WDSL [20]) scheduler attributed to telecom centres of excellence (TCoE) India during the IMT-Advanced standardisation process. It used a rather basic modification to the proportionally fair (PF) scheduler, changing the fairness exponent (β) from 1 to 5. Since, there are no follow-up research about whether this has to be a comparative method, this method gives little insight into how the wireless device performs as timing limits are placed on the same IMT assessment process. The relation with various fairness coefficients (β) is shown in Figure 11. While the PF scheduler strives for a balance between fairness and overall system throughput, the WDSL scheduler strives to provide a minimum rate guarantee to the users admitted into the system as shown in Figure 11.

a: SCHEDULER DESCRIPTION

In this segment, we include a quick overview of the scheduler so that interested readers can catch up on our explanation. The MAC employs the following scheduling algorithm:

1) The gNodeB obtains input on the instantaneous Channel quality indicator (CQI) for each UE-k in time slot t in terms of a requested data rate $R_{k,n}(t)$ for any PRB-n.

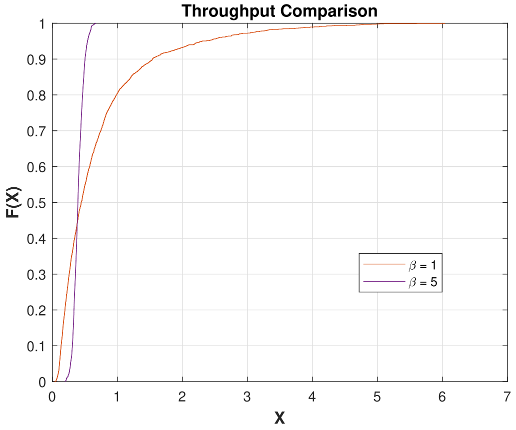

FIGURE 11. **Throughput comparison of PF and WDSL.**

2) The gNodeB monitors the moving average throughput $T_{k,n}(t)$ for UE-k.
3) UE-k^* and PRB-n that fulfil the optimal relative channel quality condition are prioritised in the t^{th} time slot by the scheduling process:

$$k^* = \underset{k=1,2,\ldots,K}{\arg\max} \frac{\left[R_{k,n}(t)\right]^{\alpha}}{\left[T_{k,n}(t)\right]^{\beta}} \tag{11}$$

4) The choice of values for α and β decide the nature of the scheduler.
    - $\alpha = 1$ and $\beta = 0$, represents a max-rate scheduler.
    - $\alpha = 0$ and $\beta = 1$, represents a round-robin scheduler.
    - $\alpha = 1$ and $\beta = 1$, represents a proportionally fair scheduler.
5) For the WDSL scheduler, we employ $\alpha = 1$ and $\beta = 5$.
6) The gNodeB updates $T_{k,n}(t)$ of the k^{th}- UE in the t^{th} slot using the exponential moving average filter:

$$T_{k,n}(t+1) = \begin{cases} \left(1 - \frac{1}{t_c}\right) T_{k,n}(t) & \\ + \frac{1}{t_c} R_{k,n}(t), & k^* = k \\ \left(1 - \frac{1}{t_c}\right) T_{k,n}(t) & \\ \cdots, & k^* \neq k \end{cases} \tag{12}$$

7) Individual PRBs are treated as separate entities by the scheduling algorithms, which update the system after each time slot.

While the PF scheduler aims for a combination of fairness and total device throughput, the WDSL scheduler aims to give users admitted to the system a minimum rate guarantee.

b: PERFORMANCE COMPARISON

The simulation setup follows the rural config. C scenario in V-F. The only tweak to the analysis is in rerunning the simulation with the new value for β for the PF scheduler. The cell capacity with different values of β is listed in Table 29.

If the simulation were a real deployment scenario, then with the WDSL scheduler about 8 Mbps data rate per user

TABLE 29. Cell capacity (Mbps) with different β values.

	PF ($\beta = 1$)	**WDSL** ($\beta = 5$)
Cell capacity (Mbps) 700 MHz, with 20 MHz in rural config. C	151.94	84.31

can be guaranteed. However, from the operator perspective, it only achieved about half of the call capacity.

2) UPLINK PERFORMANCE WITH HIGH POWER UE

Higher frequency signals can't travel far, so cellular carriers like Sprint worked within 3GPP as means to achieve higher output power, specifically in the uplink (uplink defines the cell range). Devices supporting a new power class, Power class 2 (PC2) were chosen. PC2 was originally developed to improve high-performance user equipment (HPUE) and improve the 2.5 GHz LTE TDD coverage. With 3GPP NR standardization, this functionality is being extended to several more frequency bands in Rel-15 specifications. PC2 allows for output power levels of 26 dBm which is twice the previous maximum output power of PC3 (23 dBm). The higher output power to PC2, compensates for higher propagation losses at higher TDD frequencies, allowing carriers to retain cell coverage without investing in costly infrastructure. PC2 devices could use the same architecture as PC3 UEs, but with different PAs and filters. Due to the additional power headroom available with the higher uplink transmit power, such devices help increase cell-edge spectral efficiency by using higher order modulation and transport block size (Figure 12, 13). It can also help improve overall cell-edge efficiency, especially where downlink performance is constrained by uplink acknowledgement speed. Given that there will be some connection imbalance during 5G NSA deployments, PC2 for dual connectivity UE (one LTE band + one NR band) would be the most realistic and suitable choice for improving uplink coverage for 5G NR NSA deployments. When compared to legacy systems, HPUE improves out of service (OoS) and radio link failures (RLF) dramatically with expanded coverage.

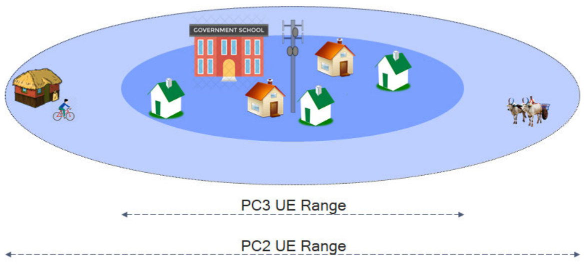

FIGURE 12. Extended coverage of PC2 devices over PC3.

a: SCHEDULER DESCRIPTION

To understand the value proposition of HPUE to devices, we devise a simple modification to the existing IMT-2020 rural low-mobility large-cell (LMLC) test scenario.

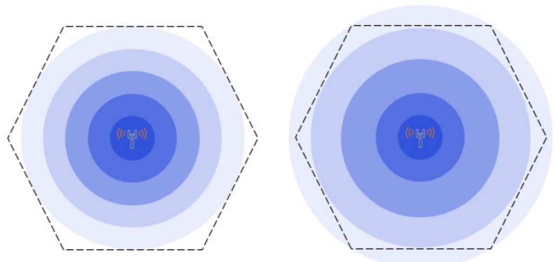

FIGURE 13. A typical cell coverage using PC3 and PC2 devices.

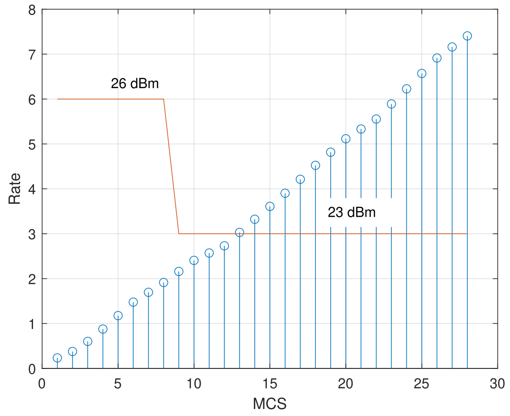

FIGURE 14. UE's reporting below MCS8 employing PC2 mode.

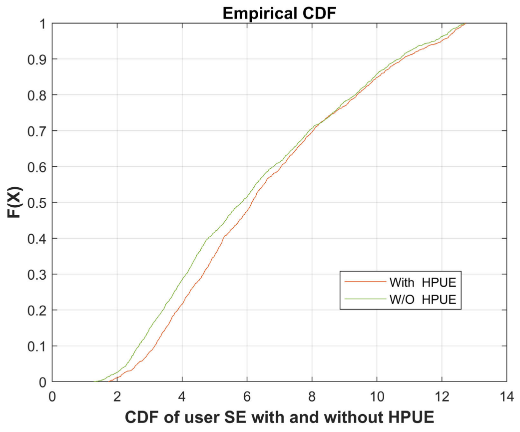

FIGURE 15. CDF of user SE with and without HPUE.

We assume that the UE's are capable of PC2 and allow the UE's reporting below a certain Modulation and coding scheme (MCS) value to employ PC2 (Figure 14).

b: PERFORMANCE COMPARISON

The simulation setup follows the same rural config. C scenario in V-F. The only tweak to the analysis is in rerunning the simulation with the link adaptation, where UE's reporting below a certain MCS index were changed from PC3 (without HPUE) capability to PC2 (with HPUE). The CDF of spectral efficiency values seen under these scenarios is plotted below for reference.

It can be inferred from the plots that the SE of those UE's with very low MCS increase, whereas those with higher rates did not change significantly. This is one move in the right direction by 3GPP whereby the operators now have a chance to deploy PC2 (HPUE) devices in their network to improve cell edge or outage issues, without focusing on the need for additional infrastructure.

Out of some supplementary studies on features supported by the 3GPP technologies and their application to networks, two of the studies sound promising.

1) The WDSL scheduler provided an insight into understanding a KPI not currently covered in IMT-2020. If the operator were to trade off individual user performance for cell capacity, then there is a huge trade off.
2) Similarly, a feature called HPUE defined in 3GPP allows for UEs deployed in certain TDD configurations to employ 26 dBm power amplifiers (PC2). HPUE becomes an additional tool in the hands of operators in addressing the coverage problem, without adding new infrastructure.

H. MOBILITY

Mobility is defined as "The maximum mobile station speed at which a defined Quality-of-service (QoS) can be achieved (in km/h)" [2], [6].

1) MEAN VALUE OF ZOD SPREAD

The mean value of Zenith angle Of Departure (ZoD) in degree is shown is Table 30, The CDF of mean value of ZoD spread for line-of-sight (LOS) and non-line-of-sight (NLOS) for Rural and Dense Urban test environment are plotted from Figure 16 to Figure 18, respectively.

TABLE 30. **Mean value of ZoD spread.**

Parameters	**Dense Urban-eMBB**				**Rural-eMBB**	
	Config. A (4 GHz)		Config. A (30GHz)		Config. A/B (700 MHz/4 GHz)	
Link-level Channel Model	LOS: CDL/TDL v	NLOS: CDL/TDL iii	LOS: CDL/TDL v	NLOS: CDL/TDL iii	LOS: CDL/TDL v	NLOS: CDL/TDL iii
ZoD angular spreads scaling parameter $AS_{desired}$ (degree)	3.3	4.6	TBD from 50% tile point of CDF of ZoD spread	TBD from 50% tile point of CDF of ZoD spread	1.25	1.44

2) SINR DISTRIBUTION

The pre-processing SINR CDFs for eMBB test environment are shown in Figures 19-22. From the Figures 19-22, different test environments 50 percentile point of the CDF are listed in Table 31.

3) LINK PROPERTIES

The results and observations of NR's link-level mobility assessment for various test environments are shown in Table 32 and Table 33 depending on the evaluation.

I. RELIABILITY

1) SYSTEM LEVEL SIMULATIONS

The system-level simulations (SLS) assumptions given in Table 34 are the results for the two test-configurations A and B (4 GHz and 700 MHz) respectively; detailed specifications of these test configurations can be found in [6].

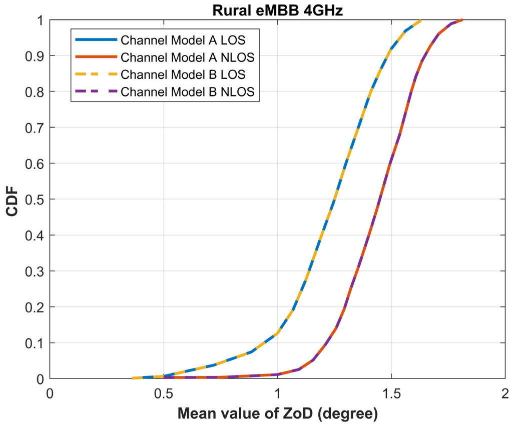

FIGURE 16. **Rural (4 GHz) ZoD (degree) mean value.**

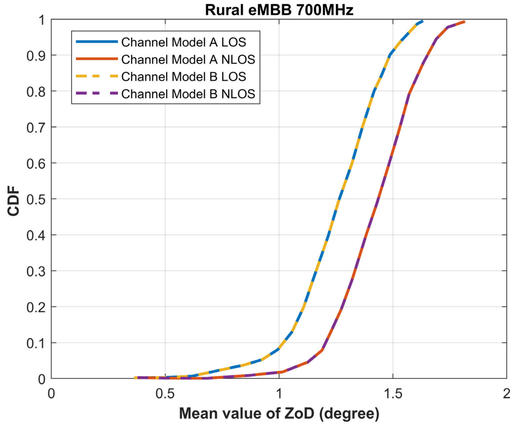

FIGURE 17. **Rural (700 MHz) ZoD (degree) mean value.**

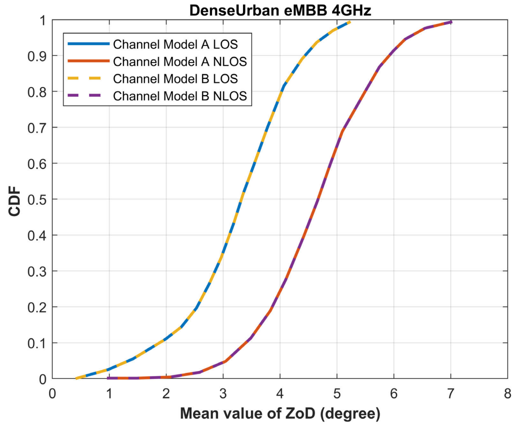

FIGURE 18. **Dense urban (4 GHz) ZoD (degree) mean value.**

For config. A, the total gain (including antenna gain) is presented in Figure 23 for UMa channel models A and B. The resulting SINR (cell utilization 1) illustrated in Figure 24 is at full load. The cell-edge (5th percentile) SINR is found to be

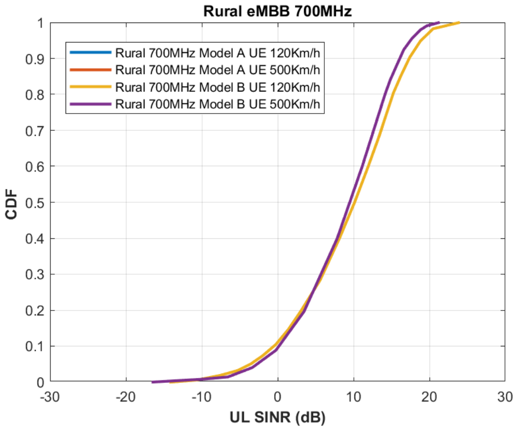

FIGURE 19. Rural-eMBB (700 MHz) UL SINR distribution test environment.

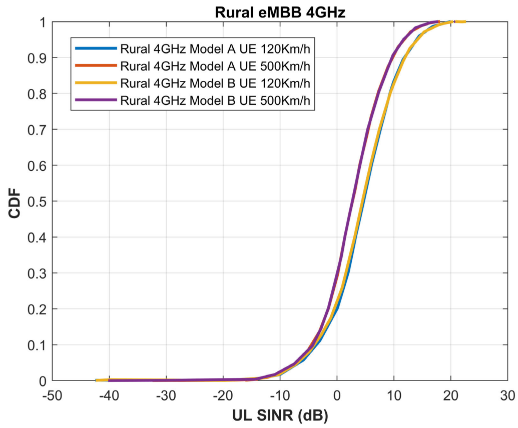

FIGURE 20. Rural- eMBB (4 GHz) UL SINR distribution test environment.

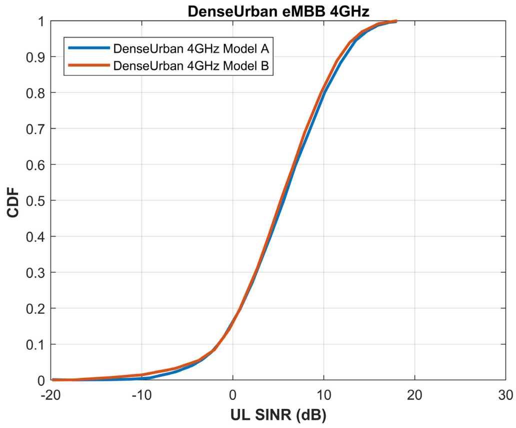

FIGURE 21. Dense urban-eMBB (4 GHz) UL SINR distribution test environment.

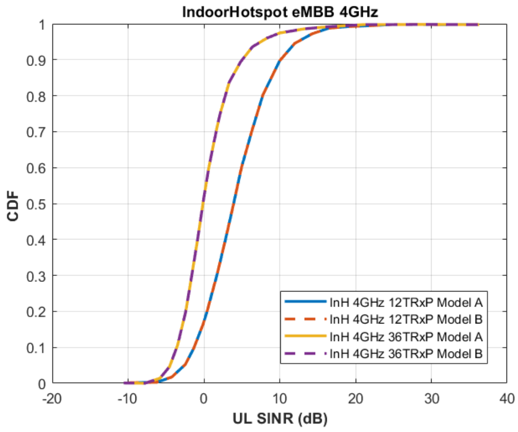

FIGURE 22. Indoor hotspot- eMBB (4 GHz) UL SINR distribution test environment.

TABLE 31. The 50%-tile point of SINR CDF for different test environments.

Test environment	Evaluation configuration	UE Mobility	50%-tile point of SINR CDF (dB)	
			Channel Model A	Channel Model B
Rural – eMBB	Config. A (700 MHz)	120 km/h	10.21	10.14
		500 km/h	9.67	9.65
Rural - eMBB	Config. B (4 GHz)	120 km/h	4.66	4.50
		500 km/h	2.90	2.72
Dense Urban – eMBB	Config. A (4 GHz)	30 km/h	5.52	5.32
Indoor Hotspot – eMBB (12 TRxP)	Config. A (4 GHz)	10 km/h	3.90	3.95
Indoor Hotspot – eMBB (36 TRxP)	Config. A (4 GHz)	10 km/h	-0.21	-0.07

TABLE 32. The uplink link level evaluation results for different test environments for NR.

Test environment	ITU requirement (bit/s/Hz)	Evaluation configuration	Channel Model	50%-tile point of SINR CDF (dB)	Uplink SE (bit/s/Hz)			
					FDD		TDD	
					NLOS	LOS	NLOS	LOS
Indoor Hotspot – eMBB (12 TRxP)	1.5	Config. A (4 GHz)	Channel model A	3.90	1.75	2.05	1.59	1.94
			Channel model B	3.95	1.75	2.07	1.60	1.95
Dense urban – eMBB	1.12	Config. A (4 GHz)	Channel model A	5.52	1.92	2.22	1.82	2.17
			Channel model B	5.32	1.89	2.19	1.79	2.06
Rural-eMBB (120 Km/h)	0.8	Config. A (700 MHz)	Channel model A	10.21	2.32	2.90	2.10	2.63
			Channel model B	10.14	2.31	2.90	2.09	2.63
		Config. B (700 MHz)	Channel model A	4.66	1.30	1.74	1.18	1.57
			Channel model B	4.50	1.28	1.68	1.16	1.52
Rural-eMBB (500 Km/h)	0.45	Config. A (700 MHz)	Channel model A	9.67	2.07	2.64	1.88	2.39
			Channel model B	9.65	2.07	2.64	1.87	2.39
		Config. B (700 MHz)	Channel model A	2.90	0.92	1.33	0.84	1.22
			Channel model B	2.72	0.91	1.33	0.83	1.22

TABLE 33. Mobility observations.

KPI	Category	Required value		Value (Bits/s/Hz)
		Normalized traffic channel link data rate(Bit/s/Hz)	Mobility (km/h)	
Mobility	Indoor Hotspot-eMBB	1.5	10	1.59 – 2.07
	Dense Urban-eMBB	1.12	30	1.79 – 2.17
	Rural-eMBB	0.8	120	1.28 – 2.90
		0.45	500	0.83 – 2.64

1.98 dB (on the DL) and 0.81 dB (on the UL) for channel model UMa A, and 1.98 dB (DL) and 1.77 dB (UL) for channel model UMa B as shown in Figure 25.

For config. B, the total gain (including antenna gain) is given in Figure 26. for UMa models A and B. The resulting SINR at full load (cell utilization 1) is given in Figure 27. The cell-edge (5th percentile) SINR is found to be 0.16 dB (on the DL) and 0.83 dB (on the UL) for channel model UMa

TABLE 34. Assumptions of the system-level simulations.

Configuration Parameters	URLLC Configuration A	URLLC Configuration B
Carrier frequency	4 GHz	700 MHz
Base station Antenna Height	25 m	25 m
Inter-site distance	500 m	500 m
Bandwidth	20 MHz	20 MHz
Device deployment	80% outdoor, 20%indoor	80%outdoor, 20%indoor
Number of UE antenna elements	4	4
UE noise figure	7	7
UE power	23 dBm	23 dBm
Path loss model	UMa A/B with SCM (for ZOD)	UMa A/B with SCM (for ZOD)
BS antenna VxH (vs x Hs x P)	$4 \times 8 (2 \times 1 \times 2)$	$4 \times 4 (2 \times 1 \times 2)$
BS Transmit power	49 dBm	49 dBm
BS noise figure	5	5
Electrical down tilt	9 degrees	9 degrees
Traffic model	Full buffer	Full buffer
UL power control	Alpha=1, P0=-106 dBm	Alpha=1, P0=-106 dBm
UL allocation	5 PRB (10 UEs sharing 50 PRBs)	5 PRB (10 UEs sharing 50 PRBs)

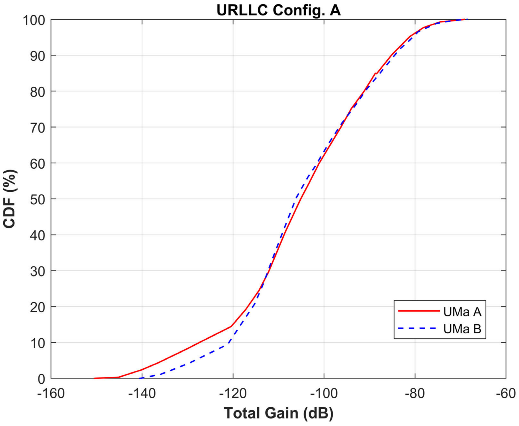

FIGURE 23. URLLC configuration A total gain.

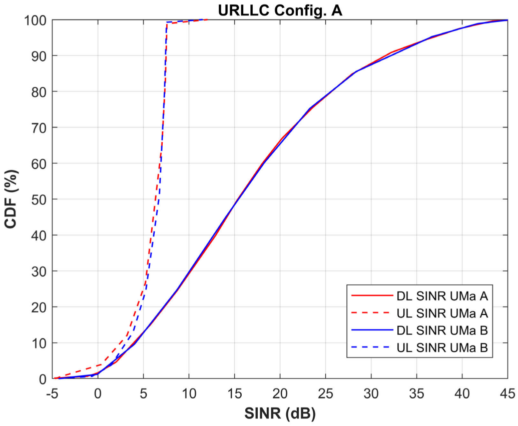

FIGURE 24. URLLC configuration A SINR distribution.

A and −0.06 dB (DL) and 0.65 dB (UL) for channel model UMa B as shown in Figure 28.

2) LINK LEVEL SIMULATIONS

The assumptions for link-level simulations (LLS) are described in Table 35. For the data and control channels, two separate datasets are used. For PDCCH, a DCI of 40 bits is presumed, without the CRC. PUCCH format 0 carries a 1-bit UCI with a length of 2 OFDM symbols (OS) and frequency hopping for PUCCH. Figure 29 shows the BLER for the control channels as a function of SNR, while

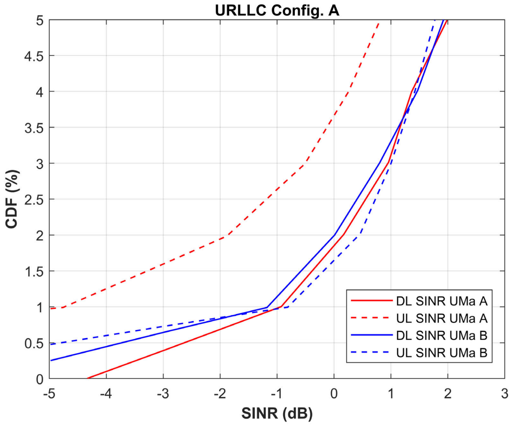

FIGURE 25. 5th percentile SINR distribution for URLLC configuration A.

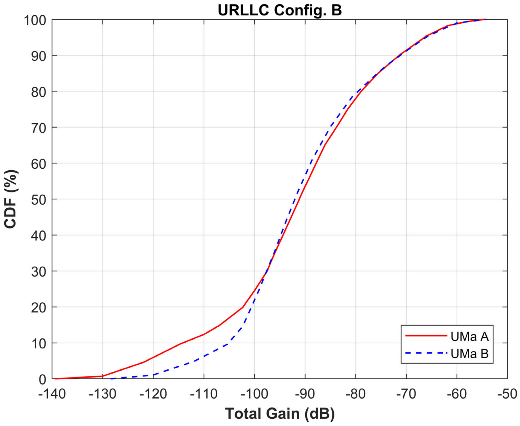

FIGURE 26. URLLC configuration B total gain.

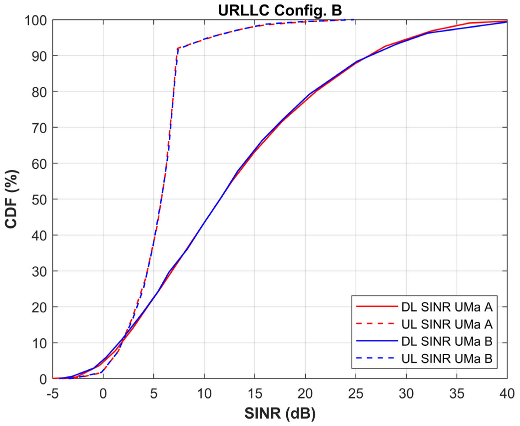

FIGURE 27. URLLC configuration B SINR distribution.

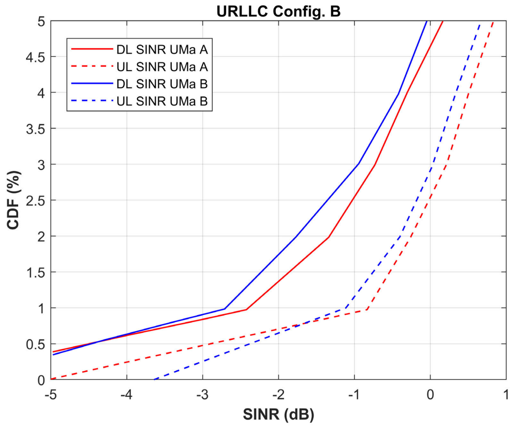

FIGURE 28. 5^{th} percentile SINR distribution for URLLC configuration B.

TABLE 35. Assumptions on the link-level simulations.

Parameter	Assumption
Channel model	TDL-C with 300 ns delay spread
Carrier	700 MHz
Bandwidth	20 MHz
Subcarrier spacing	30 kHz
Antenna setting	2TX 2RX (data), 1TX 2RX (control)
Tx diversity	Rank 1 (TX diversity precoding based on CSI reports with 5 slots periodicity).
Speed	3 km/h
Channel estimation	Practical: 4 OS mini-slot - 1 OS front-loaded DMRS type 2 7 OS mini-slot - 2 OS front-loaded DMRS type 2
Frequency allocation	type 1 (contiguous)
Time allocation	4 OS and 7 OS allocations type B
PUCCH	1 A/N bit, PUCCH format 0 with 2− symbol duration and frequency hopping between band edges
PDCCH	Polar codes, 40b payload excl. CRC. Distributed CCEs
Data	LDPC, BG2, 256b

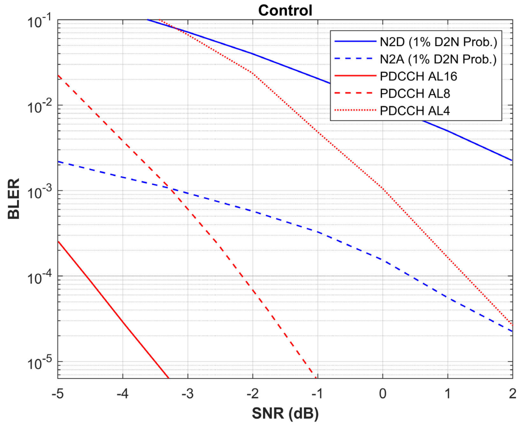

FIGURE 29. Short PDCCH and PUCCH sequence selection BLER as a function of SNR.

Figure 30 and Figure 31 displays the BLER for the data channels as a function of SNR.

J. TOTAL RELIABILITY

The success probabilities are written on the channel level according to Table 36, and expressions found for the total success rate $p_t = 1 - \epsilon$, where ϵ is the residual error rate. With some exceptions, it is assumed that the retransmissions are uncorrelated, which is reasonable to assume if they are done on a different frequency allocation.

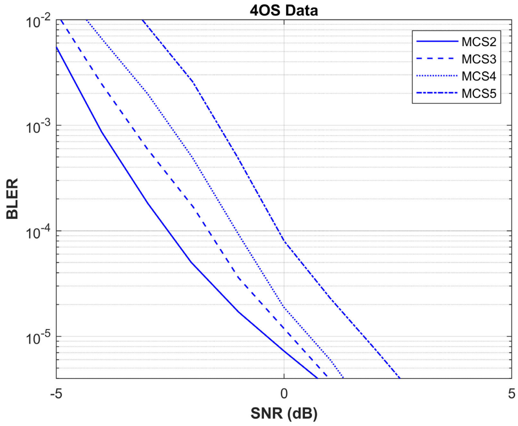

FIGURE 30. LDPC BLER 4 OS-data for QPSK (1^{st} attempt).

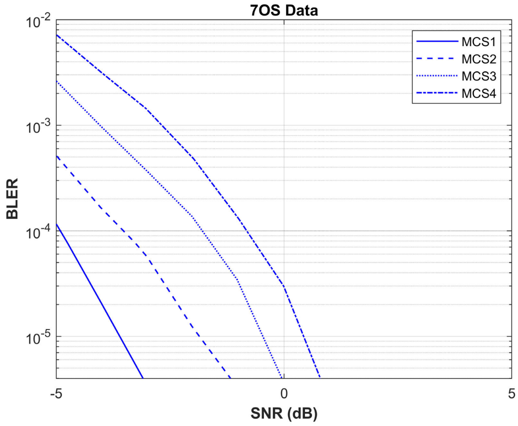

FIGURE 31. LDPC BLER 7 OS-data for QPSK (1^{st} attempt).

TABLE 36. Success probabilities for calculating total reliability.

Probability	Description
p_0	Success of SR detection
p_1	Success of PDCCH transmission
p_2	Success of PDSCH/PUSCH transmission
p_3	Success of PUCCH NACK detection
p_4	Success of PUCCH DTX detection

TABLE 37. Required number of PRBs for 32B packet and 1 OFDM symbol overhead, at different coding rates.

No. of PRBs	14 OS TTI	7 OS TTI	4 OS TTI	2 OS TTI
Code rate MCS1	22	46	92	274
Code rate MCS2	17	37	73	219
Code rate MCS3	14	29	57	171
Code rate MCS4	11	24	47	141
Code rate MCS5	9	19	37	111

TABLE 38. **Maximum number of transmissions including re-transmissions in FDD within 1 ms.**

No. of TX within 1 ms	15kHz SCS				30 kHz SCS				120 kHz SCS			
	14 OS TTI	7 OS TTI	4 OS TTI	2 OS TTI	14 OS TTI	7 OS TTI	4 OS TTI	2 OS TTI	14 OS TTI	7 OS TTI	4 OS TTI	2 OS TTI
DL data	0	0	0	1	0	1	1	2	1	2	2	3
UL data (SPS)	0	0	0	1	0	1	1	2	1	1	1	2

1) DL DATA, HARQ-BASED

The total reliability after N transmissions on the DL can be described as in (13)

$$p_t = \sum_{n=1}^{N}\sum_{i=1}^{n}\left\{\binom{n-1}{n-i}[(1-p_1)p_4]^{n-i} \times p_1 p_{2,i}\prod_{j=1}^{i-1} p_1 p_3(1-p_{2,j})\right\} \qquad (13)$$

where for any positive integer $p_{2,k}$, k is the probability of a data block being correctly received after exactly k transmissions are soft-combined. In this expression, the DL control transmissions are seen as uncorrelated with each other and with data. This is an approximation, but can be motivated by, for example, moving the DL control between attempts. The data attempts are correlated with each other.

2) UL DATA, CONFIGURED GRANT

With configured grant-based UL scheduling, the SR step and the first DL control can be removed, and the total reliability can be described as in (14)

$$p_t = p_{2,1} + (1-p_{2,1})\sum_{n=2}^{N} p_1 p_{2,n}\prod_{i=2}^{n-1}(1-p_1 p_{2,i}) \qquad (14)$$

Here, the PDCCH reliability starts from the first retransmission, assuming perfect energy detection performance on the PUSCH resource.

3) RELIABILITY ESTIMATE URLLC CONFIGURATION B, UMA B

By observing at the lower percentiles of the SINR distributions for URLLC config. B, UMa B, the channel BLER can be found at the corresponding DL and UL SINR points. The total error rates for DL and UL data respectively can then be computed. The results are shown in Figure 32-34.

AL16 is assumed for PDCCH and 1% D2A level for PUCCH. On the UL, SPS is assumed with a configured resource every TTI. For both DL and UL, $1-3$ transmission attempts (including HARQ retransmissions) are considered. The data transmissions are assumed to be correlated and are soft-combined.

a: PACKET SIZE

The ITU specifies a packet size of 32 bytes to meet the latency and reliability targets. With QPSK modulation and a coding rate from MCS1 to MCS5, along with one OFDM symbol overhead, the required number of PRBs is given in Table 37. Here, the CRC is not considered and TBS is 32B.

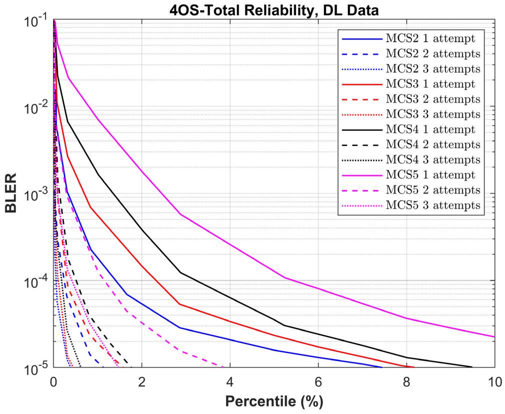

FIGURE 32. **4 OS – DL data total reliability with 1 – 3 HARQ transmissions.**

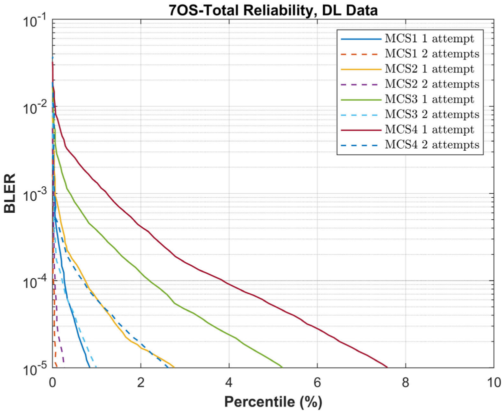

FIGURE 33. **7 OS – DL data total reliability with 1 – 3 HARQ transmissions.**

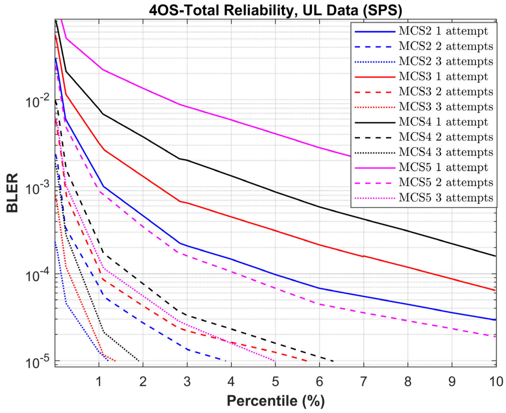

FIGURE 34. **4 OS UL data total reliability with 1 – 2 HARQ transmissions.**

b: TOTAL LATENCY

UP latency was evaluated in [9] for a sequence of transmissions. It was found that DL and configured-grant UL

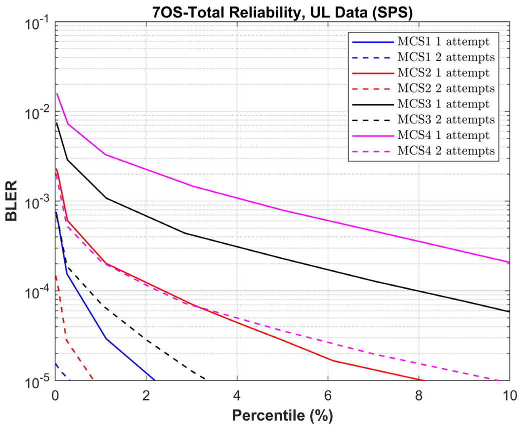

FIGURE 35. 7 OS UL data total reliability with 1 – 2 HARQ transmissions.

TABLE 39. Reliability observations.

KPI	Category	Required value	Obtained Value
Reliability	Urban Macro-URLLC	10^{-5} probability of successfully transmitting a 32-byte layer 2 protocol data unit (PDU) within 1 ms	With 1 transmission using MCS1, the reliability target of 10^{-5} error can be met on the DL and the UL

TABLE 40. Bandwidth.

	SCS [kHz]	Maximum bandwidth for one component carrier (MHz)	Maximum number of component carriers for carrier aggregation	Maximum aggregted bandwidth (MHz)	Minimum Require-ment as per ITU-R
FR1	15	50	16	800	100
	30	100	16	1600	
	60	100	16	1600	
FR2	60	200	16	3200	> 1 GHz
	120	400	16	6400	

TABLE 41. Bandwidth observations.

KPI	Usage Scenario	Required value	Value
Bandwidth and Scalability	-NA-	Atleast 100 MHz	FR1: upto 1600 MHz
		upto 1 GHz	FR2: upto 6400 MHz
		support of multiple different bandwidth values	5 MHz to 400 MHz (in various bands)

transmissions with 7 OS and 30 kHz SCS are possible within the latency bound of 1 ms, as shown in Table 38. Thus, the ITU reliability of 10^{-5} error within 1 ms can be met.

Reliability observations are shown in Table 39. Based on the assessment of Reliability following points can be observed.

1) The cell-edge SINR for URLLC config. A is approximately 1.98 dB (DL) and 0.81 dB (UL) for channel model UMa A and 1.93 dB (DL) and 1.77 dB (UL) for channel model UMa B.
2) The cell-edge SINR for URLLC config. B is approximately 0.16 dB (DL) and 0.83 dB (UL) for channel model UMa A and −0.06 dB (DL) and 0.65 dB (UL) for channel model UMa B.

TABLE 42. Summary of all KPI's.

KPI	Category			Required value	Observed Value	Requirement met status
	Usage scenario	Test environment	Downlink or uplink			
Peak data rate (Gbit/s)	eMBB	Not applicable	Downlink	20	21.74 - 34.98	☑ Yes
			Uplink	10	11.81- 19.0	☑ Yes
Peak spectral efficiency (bit/s/Hz)	eMBB	Not applicable	Downlink	30	31.7 – 47.9	☑ Yes
			Uplink	15	18.2 – 22.8	☑ Yes
User experienced data rate (Mbit/s)	eMBB	Dense Urban – eMBB	Downlink	100	107.8-187.2	☑ Yes
			Uplink	50	74.98 – 128.7	☑ Yes
5^{th} percentile user spectral efficiency (bit/s/Hz)	eMBB	Indoor Hotspot – eMBB	Downlink	0.30	0.37 (FR1) 0.302(FR2)	☑ Yes
			Uplink	0.21	0.42 (FR1) 0.425(FR2)	☑ Yes
	eMBB	Dense Urban – eMBB	Downlink	0.225	0.375	☑ Yes
			Uplink	0.15	0.3	☑ Yes
	eMBB	Rural – eMBB (Required to meet for Config. A or B)	Downlink	0.12	-NA-	☑ Yes
					0.138(Config. A) 0.374(Config. B)	
			Uplink	0.045	-NA-	☑ Yes
					0.134 (Config. A) 0.123 (Config. B)	
Average spectral efficiency (bit/s/Hz/ TRxP)	eMBB	Indoor Hotspot – eMBB	Downlink	9	12.725 (FR1) 11.384 (FR2)	☑ Yes
			Uplink	6.75	7.551(FR1) 7.392 (FR2)	☑ Yes
	eMBB	Dense Urban – eMBB	Downlink	7.8	12.8	☑ Yes
			Uplink	5.4	6.662	☑ Yes
	eMBB	Rural – eMBB	Downlink	3.3	7.597 (Config. C)	☑ Yes
					6.594 (Config. A) 15.061 (Config. B)	☑ Yes
			Uplink	1.6	4.038 (Config. C)	☑ Yes
					4.17 (Config. A) 3.457 (Config. B)	☑ Yes
Area traffic capacity (Mbit/s/m^2)	eMBB	Indoor-Hotspot – eMBB	Downlink	10	10.51-18.9	☑ Yes
User plane latency (ms) [9]	eMBB	Not applicable	Uplink and Downlink	4	0.86 – 3.9	☑ Yes
	URLLC	Not applicable	Uplink and Downlink	1	0.31 – 0.96	☑ Yes
Control plane latency (ms) [9]	eMBB	Not applicable	Not applicable	20	8.5– 20	☑ Yes
	URLLC	Not applicable	Not applicable	20	6.5 – 10	☑ Yes
Energy efficiency	eMBB	Not applicable	Not applicable	Capability to support a high sleep ratio and long sleep duration	Yes	☑ Yes
Reliability	URLLC	Urban Macro –URLLC	Uplink or Downlink	1-10^{-5} success probability of transmitting a layer 2 PDU (protocol data unit) of size 32 bytes within 1 ms in channel quality of coverage edge	Yes	☑ Yes
Mobility classes	eMBB	Indoor Hotspot – eMBB	Uplink	Stationary, Pedestrian	Yes	☑ Yes
	eMBB	Dense Urban – eMBB	Uplink	Stationary, Pedestrian, Vehicular (up to 30 km/h)	Yes	☑ Yes
	eMBB	Rural – eMBB	Uplink	Pedestrian, Vehicular, High speed vehicular	Yes	☑ Yes
Mobility Traffic channel link data rates (bit/s/Hz)	eMBB	Indoor Hotspot – eMBB	Uplink	1.5 (10 km/h)	1.59 (1.94)	☑ Yes
	eMBB	Dense Urban – eMBB	Uplink	1.12 (30 km/h)	1.82 (2.17)	☑ Yes
	eMBB	Rural – eMBB	Uplink	0.8 (120 km/h)	2.32 (2.90)	☑ Yes
				0.45 (500 km/h)	2.07(2.64)	☑ Yes
Mobility interruption time (ms)	eMBB and URLLC	Not applicable	Not applicable	0	0	☑ Yes
Bandwidth and Scalability	Not applicable	Not applicable	Not applicable	At least 100 MHz	100 MHz and more	☑ Yes
				Up to 1 GHz	1 GHz and more	☑ Yes
				Support of multiple different bandwidth values [6]	Supported	☑Yes

3) With 1 transmission using MCS1, the reliability target of 10^{-5} error can be met on the DL and the UL (with a configured grant).

4) With MCS1 and a 7 OS mini-slot, 46 PRBs are required for a 32B packet.
5) With 30 kHz SCS and 7 OS mini-slot, 1 transmission can be made in FDD mode within 1 ms.

K. BANDWIDTH

Based on the (Section 5.3.2) [15] bandwidth evaluation and observations were tabulated in Tables 40-41.

VI. CONCLUSION

Key performance metrics corresponding to the evaluation of the 3GPP 5G NR IMT-2020 radio interface technology as well as their related findings are discussed in this paper. The core criteria for IMT-2020 technological efficiency specifications were fulfilled by the 5G NR technology, according to our findings. However, certain small variations are found in few situations such as, peak spectral efficiency, peak data rate, user experienced data rate, and area traffic capacity, though still meeting the requirements. This is most certainly due to such biases or the lack of adequate information in the proponents self-evaluation report. We were able to recommend that the 3GPP 5G NR technology be accepted as a valid IMT-2020 technology based on these assessments. Summary of all KPI's with requirement met status is given in Table 42.

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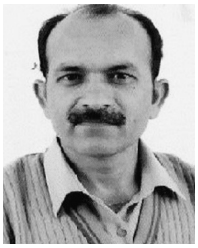

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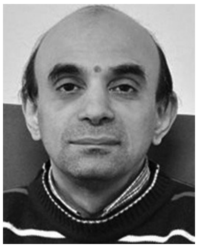

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