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5G New Radio Evaluation Against IMT-2020 Key Performance Indicators

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ABSTRACT The fifth generation (5G) of mobile radio technologies has been defined as a new delivery model where services are tailored to specific vertical industries. 5G supports three types of services with different and heterogeneous requirements, i.e. enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC) and massive Machine-Type Communications (mMTC). These services are directly related to exemplary verticals such as media, vehicular communications or the Industry 4.0. This work provides a detailed analysis and performance evaluation of 5G New Radio (NR) against a set of Key Performance Indicators (KPI), as defined in the International Mobile Telecommunications 2020 (IMT-2020) guidelines, and provides an overview about the fulfillment of their associated requirements. The objective of this work is to provide an independent evaluation, complementing the Third Generation Partnership Project (3GPP) contribution. From the original group of sixteen KPIs, eleven of them have been carefully selected to cover the three usage scenarios, paying special attention to eMBB services. Results show that 5G NR achieves all considered requirements, therefore fulfilling the specific market's needs for years to come.

INDEX TERMS 5G, New Radio, IMT-2020, KPI, requirements, data rate, spectral efficiency, latency, mobility, energy efficiency.

I. INTRODUCTION

THE fifth generation (5G) of mobile communications represents a change of paradigm in the way that wireless transmissions are conceived. 5G New Radio (NR) not only brings a large number of technical improvements compared to the fourth generation (4G) Long Term Evolution (LTE), but also expands the mobile communications concept to new industry sectors. 5G aims at supporting three major service types with different and heterogeneous requirements, i.e. enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC) and massive Machine-Type Communications (mMTC). 5G is expected to cover an extensive number of use cases for the digitalization of new verticals [1] [2] such as media, the Industry 4.0 or vehicular communications, among others.

5G NR is expected to fulfill a wide set of high-demanding and stringent requirements to cover multiple use cases of targeted verticals [3]. 5G requirements are linked to specific Key Performance Indicators (KPIs), which were defined by the International Telecommunication Union - Radiocommunication (ITU-R) sector towards the International Mobile Telecommunications for 2020 (IMT-2020) landmark [4].

5G was specified for the first time in the Third Generation Partnership Project (3GPP) Release (Rel') 15, structured in three phases [5]. An early drop non-standalone (NSA) version was initially approved in December 2017. It relies on both LTE and NR air interfaces and reuses the LTE core network. It also focuses on the user plane and makes use of LTE for the control plane [6]. In June 2018, a 5G stand-alone (SA) version was specified. It additionally includes a

5G compliant core network with full user and control plane capabilities. The last drop of Rel'15 was provided at the end of 2018 and it permits the 5G core to inter-work equally with both LTE and NR Radio Access Network (RAN).

In the air interface, 5G includes a set of enhancements to fulfill such stringent requirements. The main improvements in the air interface include more efficient Forward Error Correction (FEC) codes, larger bandwidths, new numerologies that adapt to the new spectrum bands and bandwidth (BW) allocations, dynamic frame structures, or massive Multiple-Input Multiple-Output (MIMO) schemes, among others [7]. 5G systems are expected to support extremely high data rates. It was shown in [8] that user and service demands in terms of mobile data traffic will increase seven-fold from 2017 to 2022. But not only this, 5G also needs to support an extensive group of heterogeneous requirements. For instance, massive connections will be necessary, since the number of devices connected to networks will be triple by 2022 [8]. Low-latency communications are also key in 5G to enable all kind of services in critical environments.

In October 2018, 3GPP hosted a workshop to inform the ITU Evaluation Groups and experts on the progress of 3GPP to meet the IMT-2020 requirements [9]. The main objective was to help these Evaluation Groups to study the technical merits of 5G NR and LTE against these requirements. The final reports of the Evaluation Groups were presented in February 2020. The different results can be found in references [10]–[17]. The 3GPP submission to ITU-R also provided a 5G performance self-evaluation against all IMT-2020 KPIs [18]. Nevertheless, it does not include the detailed procedures and examples necessary to understand how results are obtained. Previous works in the literature also analyzed the performance of 5G NR in different scenarios. Reference [19] evaluated the IMT-2020 performance requirements for a selected number of KPIs related to mMTC, URLLC and eMBB services, i.e. connection density, reliability and spectral efficiency (SE). Other recent books on 5G NR [20]–[23] contain evaluation results. Reference [24] also provides an exhaustive review of the 5G technology. However, these works mainly focus on the technology and requirements definition, and their results are scattered.

The objective of this manuscript is to provide an independent evaluation, complementing the 3GPP contribution. It summarizes the results and elaborates more on the methodology and procedures to follow, giving clear examples, providing results for particular configurations and comparing against the requirements defined in [3]. The work is derived from the discussions on evaluation methodologies and results carried out in the 5G Infrastructure Association (5G IA) IMT-2020 Evaluation Group [10]. A wide set of eleven KPIs has been carefully selected. The set covers the three main usage scenarios but focuses on eMBB, as it is the one mostly covered by 5G Rel'15. To the best of the authors' knowledge, there are no papers in the current literature that evaluate such number of KPIs in a precise and concrete manner. The present manuscript provides a unique perspective that helps

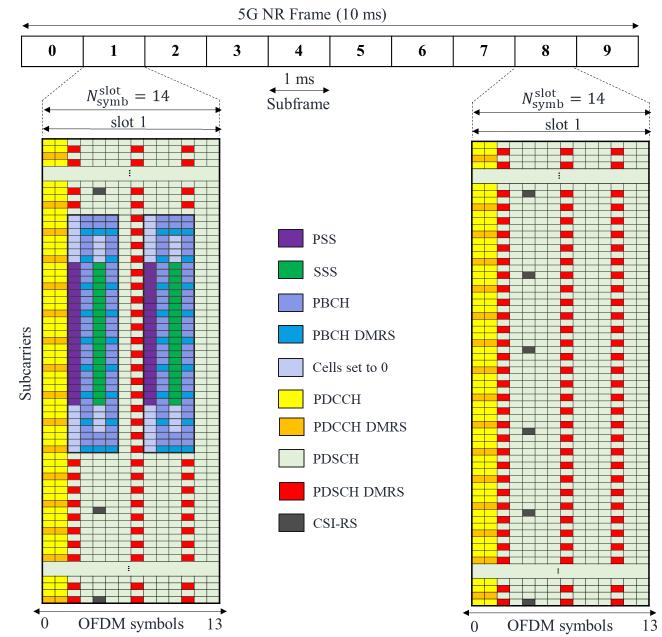


FIGURE 1. SS/PBCH, PDCCH and PDSCH physical channels allocation within a frame with SFI = 0 (DL only).

to quickly understand 5G and its potential towards the future.

The results presented in this paper have been partially published in [25], where only three KPIs are evaluated. Note that the objective of this reference is different, since it compares the current 5G NR Rel'15 specification against a new broadcasting solution as defined in [6] and [26].

The rest of the paper is structured as follows. Section II provides a high-level description of the 5G NR air interface as specified in 3GPP Rel'15. Section III presents the evaluation methodology. Section IV describes the considered KPIs. Section V evaluates the 5G NR Rel'15 air interface performance against these KPIs, through analysis and simulations. Finally, Section VI summarizes the findings of this work and discusses the fulfillment of the IMT-2020 requirements.

II. 5G NEW RADIO AIR INTERFACE OVERVIEW

This section provides a brief description of the 5G NR physical layer components that are relevant to this work, as specified in [27]–[30].

A. FRAME STRUCTURE

Figure 1 shows an example of the frame structure adopted in 5G when a single layer is transmitted. In time domain, NR transmissions are organized into frames with 10 ms duration. Each frame is divided in ten subframes, with a fixed duration of 1 ms. Subframes are in turn split into one or several slots. With a normal Cyclic Prefix (CP), each slot is formed by 14 Orthogonal Frequency-Division Multiplexing (OFDM) symbols, while 12 are only available when using an extended CP. Each symbol can be assigned to Downlink (DL) or Uplink (UL) transmissions depending on the Slot Format Indicator (SFI), which allows flexible assignment for Time

TABLE 1. Numerology (μ), subcarrier spacing, useful symbol (T_U) and CP duration (T_{CP}).

μ	Δ_f (kHz)	T_U (μ s)	CP type	T_{CP} (μ s)	Slot (μ s)	slots/sf
0	15	66.67	normal	5.21/4.69	1000	1
1	30	33.33	normal	2.60/2.34	500	2
2	60	16.67	normal	1.30/1.17	250	4
3	120	8.33	extended	4.16		
				0.65/0.59	125	8

Division Duplexing (TDD) or Frequency Division Duplexing (FDD) operation modes. In the particular example shown in Figure 1, SFI = 0 (DL only) is selected. In frequency domain, each OFDM symbol contains a fixed number of subcarriers, where one subcarrier allocated in one OFDM symbol is defined as 1 Resource Element (RE). A group of 12 REs is defined as a Resource Block (RB), where the total number of RBs transmitted in one OFDM symbol depends on the system bandwidth and numerology.

Multiple numerology options are defined by μ , a positive integer factor with an impact on the subcarrier spacing, the OFDM symbol and CP length. More specifically, the subcarrier spacing is calculated as $\Delta_f = 2^\mu \cdot 15$ kHz, the symbol length is $T_U = 1/\Delta_f$ and the slot duration is $T_{slot} = N_{symb}^{slot}(T_U + T_{CP})$, where N_{symb}^{slot} is the number of symbols per slot. The impact of the numerology on these parameters is shown in Table 1.

B. PHYSICAL CHANNELS AND SIGNALS

Physical channels are defined as flows of information transmitted between the physical (PHY) and the medium access control (MAC) layer. On the other hand, physical signals are flows of information transmitted only at the physical layer.

In the DL, three physical channels are used: the *Physical Broadcast Channel (PBCH)* to transmit the static part of the system information, known as the Master Information Block (MIB), to all UEs requiring to access the network; the *Physical Downlink Control Channel (PDCCH)* to specify the data scheduling and allocation by means of Downlink Control Information (DCI) for every User Equipment (UE) and to configure other aspects such as HARQ retransmissions, link adaptation and MIMO; and the *Physical Downlink Shared Channel (PDSCH)* that transmits the data content to UEs. Additionally, there are four types of reference signals: *Primary and Secondary Synchronization Signals (PSS, SSS)*, needed by UEs to access the network and, more specifically, to receive radio frame timing information and cell ID; *Demodulation Reference Signals (DMRS)*, used for channel estimation to retrieve the data in PBCH, PDCCH and PDSCH; *Phase Tracking Reference Signals (PT-RS)* to estimate the phase noise in the PDSCH (only used at Frequency Range 2, FR2); and *Channel State Information Reference Signals (CSI-RS)*, used to provide CSI needed for link adaptation.

In the UL, other three physical channels are defined: the

Physical Random Access Channel (PRACH), used by the UE to request initial access as well as during the beam management process; the *Physical Uplink Control Channel (PUCCH)*, which carries Uplink Control Information (UCI) and contains different information such as CSI, HARQ or scheduling requests; and the *Physical Uplink Shared Channel (PUSCH)*, which transmits the data content to the gNB. In the case of the UL, similar reference signals are used, i.e. DMRS, PT-RS and *Sounding Reference Signals (SRS)*, equivalent to CSI-RS in the DL.

III. METHODOLOGY

In this evaluation, each KPI is evaluated following a specific methodology. This work follows the procedures defined by the ITU-R for the IMT-2020 evaluation process in [4]. The considered methods, namely inspection, analysis, link-level and system-level simulations, are described as follows.

A. INSPECTION AND ANALYSIS

On the one hand, inspection is defined as the review of functionalities and parameters of the technology under evaluation. This method is applied to design-dependent KPIs that can be assessed by looking into the general system information. On the other hand, analysis is characterized by mathematical procedures. This evaluation is based on calculations that use technical information of the technology [4].

B. LINK-LEVEL SIMULATIONS

This method is applied to KPIs that are heavily dependent on the physical layer and radio channels. Link-level simulations are used to determine the performance between the gNB and the UE under specific channel conditions. In this paper, results are provided according to the Block Error Rate (BLER) metric, which is determined as a function of the present Carrier-to-Noise Ratio (CNR) for a specific radio frame configuration and channel model. Since both PDSCH and PUSCH channels share the same physical layer structure, simulations are focused on the DL, using a bandwidth of 5 MHz. Link-level simulations are performed in this work by considering a single layer and transmit/receive antenna. Other specific parameters depend on the KPI under evaluation and therefore are detailed in Section V.

C. SYSTEM-LEVEL SIMULATIONS

System-level simulations are applied to KPIs that depend on instantaneous network conditions such as available infrastructure, radio resources, number of users or radio conditions. In this work, system-level simulations focus on FR1 and eMBB services. The configurations are chosen according to those defined by 3GPP for self-evaluation towards IMT-2020 [18]. Prior to this work, an exhaustive calibration process has been carried out. For more details, see [31].

The antenna parameters for each scenario are provided in Table 2, while the main common applied parameters are listed in Table 3. The considered test environments are Indoor Hotspot (InH), Dense Urban (UMa) and Rural (RMa) [3].

TABLE 2. Scenario specific antenna parameters.

	InH Config. A 1 sector	InH Config. A 3 sectors	UMa Config. A	RMa Config. A	RMa Config. B
gNB [M, N, P]	[4, 4, 2]	[8, 16, 2]	[8, 8, 2]	[8, 4, 2]	[8, 8, 2]
TXRUs at gNB	32 (1×1)	32 (4×2)	32 (4×1)	8 (8×1)	32 (4×1)
gNB (dH,dV)	(0.5, 0.5) λ	(0.5, 0.5) λ	(0.5, 0.8) λ	(0.5, 0.8) λ	(0.5, 0.8) λ
UE [M, N, P]	[1, 2, 2]	[1, 2, 2]	[1, 2, 2]	[1, 2, 2]	[1, 2, 2]
TXRUs at UE	4 (1×1)	4 (1×1)	4 (1×1)	2 (1×1)	4 (1×1)
UE (dH,dV)	(0.5, -) λ	(0.5, -) λ	(0.5, -) λ	—	(0.5, -) λ

TABLE 3. System-level simulation parameters.

Parameters	Value
Duplexing	TDD
Frame structure	DSUUD, S (11D, 1G, 2U)
System bandwidth	20/40 MHz
Subcarrier spacing	15 kHz ($\mu = 0$)
Carrier frequency	4 GHz (700MHz for RMa, Config. A)
Transmission scheme	Mixed SU-/MU-MIMO
MU dimension	up to 12 layers (8 layers for RMa, Config. A)
SU dimension	up to 2 layers
SRS transmission	precoded SRS (2Tx ports)
Channel model	IMT-2020 model B (3GPP TR 38.901 [32])

For the test environment InH Config. A, it is possible to distinguish between two modes, operating with one or three sectors per site. Note that SU and MU stand for single-user and multi-user respectively. The parameters M , N and P refer to the number of antenna elements at the gNB or UE in vertical, horizontal and polarization dimensions respectively. The number of transceiver units (TXRU) and the number of antenna elements in vertical and horizontal directions per TXRU is indicated by the parameter *TXRUs at gNB/UE*. The distance between the antenna elements in horizontal and vertical directions is denoted as (dH, dV).

IV. KEY PERFORMANCE INDICATORS

Table 4 shows the KPIs selected as well as their related IMT-2020 scenarios (eMBB, URLLC or mMTC) and associated methodology. eMBB is the most demanding scenario in terms of data rate, SE or traffic capacity. URLLC scenarios demand for reliable communications with a very short latencies and high user speeds. mMTC scenarios rely on an excellent coverage that ensures the correct transmission to energy-efficient devices. This work mainly focuses on KPIs related to eMBB, although mMTC and URLLC services are also considered. Connection density, reliability, mobility interruption time, support of wide range and spectrum bands are out of the scope of this work.

TABLE 4. Selected KPIs, high-level assessment method and scenario.

KPI	Units	Method	Scenario
Bandwidth	Hz	Inspection	Generic
Peak data rate	bit/s	Analysis	eMBB
Peak SE	bit/s/Hz	Analysis	eMBB
UP latency	ms	Analysis	URLLC, eMBB
CP latency	ms	Analysis	URLLC, eMBB
Energy efficiency	%	Analysis	mMTC, eMBB
5th perc. user SE	bit/s/Hz	System-level	eMBB
User exp. data rate	bit/s	System-level	eMBB
Average SE	bit/s/Hz	System-level	eMBB
Area traffic capacity	bit/s/m ²	System-level	eMBB
Mobility	km/h	System-level	URLLC, eMBB

A. BANDWIDTH

This KPI is defined as the maximum aggregated system bandwidth in Hz, including frequency guard bands. The maximum supported bandwidth may be composed of either a single or multiple radio frequency (RF) carriers. It is calculated by inspection. The IMT-2020 minimum requirement is 100 MHz in FR1 (450 MHz - 6 GHz) and 1 GHz in FR2 (24.25 GHz - 52.6 GHz) [3].

B. PEAK DATA RATE

The peak data rate is the maximum achievable date rate when excluding radio resources used for physical layer synchronization, reference and control signals, guard bands and guard times [18]. The minimum requirement for this KPI is 20 Gbit/s in the DL and 10 Gbit/s in the UL [3]. The peak data rate in NR can be calculated as follows [18]:

$$\gamma_p = \sum_{j=1}^J \left(\alpha \cdot \nu \cdot Q_m \cdot f \cdot R_{max} \frac{12 \cdot N_{PRB}^{BW,\mu}}{T_s^\mu} (1 - OH) \right) \quad (1)$$

where J is the number of aggregated component carriers (CC) in a frequency band, α is a scaling factor related to percentage of resources used for DL transmissions in the carrier j , ν is the number of layers when multiple antennas

are used, Q_m is the maximum modulation order, f is the scaling factor used to reflect the capability mismatch between baseband and RF for both types of standalone and non-standalone UEs, R_{max} is the maximum Coding Rate (CR), μ is the numerology, T_s is the average symbol duration in seconds, $N_{PRB}^{BW,\mu}$ is the maximum RB allocation in the available bandwidth in a single carrier and OH is the overhead as calculated in (2).

The impact of frequency guard bands and guard times overhead is implicitly introduced in both terms $N_{PRB}^{BW,\mu}$ and T_s^μ . As a consequence, we only consider the overhead introduced by physical channels and signals. The overhead in the DL is calculated as shown in (2).

$$OH = \frac{N_{SS/PBCH} + N_{PDCCH} + N_{RS}}{N_{RE-DL}} \quad (2)$$

where $N_{SS/PBCH}$, N_{PDCCH} and N_{RS} are the overheads, expressed in number of REs, introduced by the Synchronization Signals in PBCH (SS/PBCH), PDCCH and PDSCH reference signals respectively, and N_{RE-DL} is the number of REs available for DL in a frame. The number of REs is calculated as follows:

$$N_{RE-DL} = N_{sf} \times N_{slot}^{sf} \times N_{symb}^{slot} \times N_{RB}^{max} \times N_{RE}^{RB} \quad (3)$$

where N_{sf} is the number of subframes per frame, i.e. 10; N_{slot}^{sf} is the number of slots per subframe, which depends on the numerology; N_{symb}^{slot} are the OFDM symbols per slot; N_{RB}^{max} is the maximum number of RBs in the available bandwidth; and N_{RE}^{RB} is the number of REs per RB, i.e. 12. The individual OH introduced by SS/PBCH is calculated as:

$$N_{SS/PBCH} = N_{sf}^{SS/PBCH} \times N_{slot}^{sf} \times N_{SS/PBCH}^{slot} \times N_{RE}^{SS/PBCH} \times N_p^{SS/PBCH} \quad (4)$$

where $N_{sf}^{SS/PBCH}$ is the number of subframes allocating SS/PBCH blocks, which in turn depends on the FR and numerology; $N_{slot}^{SS/PBCH}$ is the number of SS/PBCH blocks per slot; $N_{RE}^{SS/PBCH}$ is the number of REs per SS/PBCH block; and $N_p^{SS/PBCH}$ is the SS/PBCH periodicity. Moreover, the PDCCH overhead is calculated as follows:

$$N_{PDCCH} = N_{sf}^{CORESET} \times N_{slot}^{sf} \times N_{CORESET}^{slot} \times N_{RE}^{CORESET} \quad (5)$$

where $N_{sf}^{CORESET}$ is the number of subframes containing control-resource sets (CORESETs) [33] and therefore subframes without SS/PBCH blocks; $N_{slot}^{CORESET}$ is the number of CORESETs per slot; and $N_{RE}^{CORESET}$ is the number of REs in a CORESET, which depends on the Aggregation Level (AL) or number of Control Channel Elements (CCE) and is calculated as in (6).

$$N_{RE}^{CORESET} = N_{CCE} \times N_{RB}^{CCE} \times N_{RE}^{RB} \quad (6)$$

Note that N_{RB}^{CCE} is the number of RBs in a CCE, which is always 6. In addition, N_{CCE} is the AL and takes five

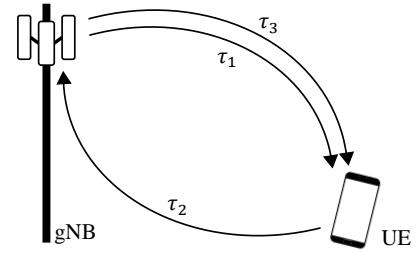


FIGURE 2. User plane latency scheme.

possible values, i.e. {1,2,4,8,16}. Finally, the OH introduced by reference signals is given by the following formula:

$$N_{RS} = N_{sf}^{PDSCH} \times N_{slot}^{sf} \times (N_{DMRS} + N_{CSI} + N_{PT-RS}) \quad (7)$$

where N_{sf}^{PDSCH} is the number of subframes dedicated to PDSCH; N_{DMRS} is the number of DMRS subcarriers per slot calculated as $N_{RB} \times N_{DMRS}^{RB,slot}$; N_{CSI} is the number of CSI reference signals per slot, including non-zero power (CSI-RS NZP), interference measurement (CSI-IM) and tracking reference signals (TRS); and N_{PT-RS} is the number of PT-RS per slot and is only used in FR2. In this FR, it depends on the Modulation and Coding Schemes (MCS) and scheduled bandwidth and is calculated as $N_{RB} \times N_{PT-RS}^{RB,slot}$. Note that the OH calculation can be extended to the UL by recalculating (2) and considering the number of REs used for PRACH, PUCCH, DMRS, PT-RS and SRS.

C. PEAK SPECTRAL EFFICIENCY

The peak spectral efficiency is calculated as the peak data rate in a single Component Carrier (CC) normalized by the system bandwidth, including frequency bands. It is calculated as shown in (8).

$$\eta_p = \frac{\gamma_p}{\alpha \cdot BW} \quad (8)$$

where α is the scaling factor considering the percentage of resources used in the DL/UL. The IMT-2020 requirement in this case is 30 bit/s/Hz in the DL and 15 bit/s/Hz in the UL [3].

D. USER PLANE LATENCY

The user plane (UP) latency is defined as the delay necessary to transmit data between the gNB and the UE. It consists of the transmission (τ_1), HARQ request (τ_2) and retransmission (τ_3) between both entities, as shown in Figure 2. The requirements for this KPI are 4 ms for eMBB services and 1 ms for URLLC respectively [3]. The transmission process can be modeled as follows:

$$\tau = \tau_1 + p(\tau_2 + \tau_3) \quad (9)$$

where p represents the probability of retransmission. The latency in the first transmission, τ_1 , can be calculated as:

$$\tau_1 = t_{gNB,tx} + t_{FA1} + t_{TTI} + t_{UE,rx} \quad (10)$$

where $t_{gNB,tx}$ is the processing time in the gNB, t_{FA1} is the time needed for frame alignment, t_{TTI} is the time of data transmission and $t_{UE,rx}$ is the processing time in the UE. The processing time in the gNB is in turn given by [30], calculated as:

$$t_{gNB,tx} = \frac{\max \left[N_2 (2048 + 144) \cdot \kappa \cdot 2^{(-\mu)} \cdot \frac{T_c}{2048 \cdot \Delta_f}, 0 \right]}{2} \quad (11)$$

where N_2 is a parameter that depends on the subcarrier spacing [30], κ is a constant with value 64 and the number of time units is $T_c = 1/(\Delta_{f_{max}} \cdot N_f)$. In 5G, $\Delta_{f_{max}}$ is always $480 \cdot 10^3$ and $N_f = 4096$, as specified in [27]. Note that the latency in the gNB is the same when transmitting and receiving. The same applies to the UE. In this case, the processing time is calculated as follows:

$$t_{UE,rx} = \frac{\max \left[N_1 (2048 + 144) \cdot \kappa \cdot 2^{(-\mu)} \cdot \frac{T_c}{2048 \cdot \Delta_f}, 0 \right]}{2} \quad (12)$$

where N_1 also depends on the subcarrier spacing and is specified in [30]. If the reception is correct, then $\tau = \tau_1$. Otherwise, the UE needs to ask for a retransmission through a HARQ petition that requires the following time:

$$\tau_2 = t_{UE,tx} + t_{FA2} + t_{HARQ} + t_{gNB,rx} \quad (13)$$

where t_{FA2} is the time for frame alignment in this case and t_{HARQ} is the time of a petition (1 OFDM symbol). After receiving and processing the HARQ request, the gNB retransmits the content:

$$\tau_3 = t_{gNB,tx} + t_{FA3} + t_{TTI} + t_{UE,rx} \quad (14)$$

E. CONTROL PLANE LATENCY

The control plane (CP) latency in 5G NR refers to the UE transition time required from inactive to connected state. The UE will naturally require some time to go from a battery efficient state to a starting point with continuous data transfer [18]. The IMT-2020 requirement is 20 ms [3]. The procedure is divided into several stages, as Figure 3 shows. The CP latency is calculated as follows:

$$T = \sum_{i=1}^{10} T_i + \sum_{j=1}^3 T_{FAj} \quad (15)$$

As shown in Figure 3, the CP latency calculation process is divided into 10 steps related to scheduling, processing and transmissions aspects, and 3 additional steps associated with frame alignment. The transmission process can only start in OFDM symbols where a PRACH preamble is used. The first step is related to the delay due to the Random Access Procedure (RACH) scheduling period. Since the transition from

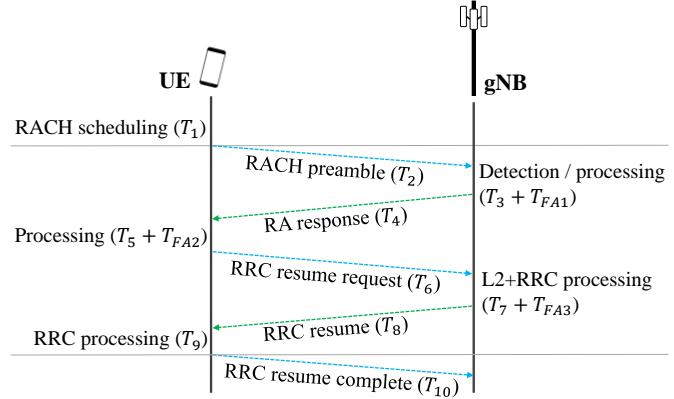


FIGURE 3. Control plane latency scheme.

idle to a different state does not start until the transmission of the PRACH preamble, this step is considered irrelevant and therefore $T_1 = 0$ ms [18]. The RACH delay T_2 logically depends on the preamble length as specified in [27]. The third step is the preamble detection and processing in the gNB. The delay is calculated as $T_3 = t_{gNB}/2$, with t_{gNB} as calculated in (11). After time for frame alignment, T_{FA1} , the gNB sends the RA response, which takes the length of 1 slot or non-slot, depending on the configuration used, that includes PDCCH and PDSCH. Hence, $T_4 = T_s$. The UE processing delay comprehends the decoding of scheduling grant, timing alignment, Cell Radio Network Temporary Identifier (C-RNTI) assignment and L1 encoding of the Radio Resource Control (RRC) resume request. It is calculated as follows [29]:

$$T_5 = N_{T,1} + N_{T,2} + T_{wait} \quad (16)$$

where $N_{T,1}$ is the time to transmit N_1 symbols for PDSCH reception with processing capability 1 and additional DMRS configuration; $N_{T,2}$ is the time to transmit N_2 symbols for PUSCH reception with processing capability 1; and T_{wait} is the average waiting time between the reception and transmission of data, which is assumed to be 0.5 ms [18]. These values can be obtained from tables 5.3-1 and 6.4-1 in [30] respectively. After frame alignment, T_{FA2} , the next step is the transmission of the RRC resume request, which takes $T_6 = T_s$. The gNB then processes the L2 and RRC request. Following the procedure given in [18], it is assumed that $T_7 = 3$ ms. The following step is the slot alignment T_{FA3} and transmission of RRC resume, which takes $T_8 = T_s$. Finally, the UE processes the RRC. As done in step 7, we assume $T_9 = 7$ ms. The step 10 is considered to be the start of the data transfer, since it includes the transmission of RRC resume complete signal but user plane data. Therefore, it is assumed that $T_{10} = 0$ ms.

In this work, we consider a series of assumptions to simplify the final calculation. The evaluation is for UL, since one can consider that DL data transfers are always shorter

due to the UE processing delay assumed in step 9. Results are also lower in FDD scenarios.

F. ENERGY EFFICIENCY

The energy efficiency KPI can be evaluated both from network and device perspectives. In IMT-2020, it is considered as a qualitative measure [3]. The network energy efficiency is defined in [18] as the capability of a Radio Interface Technology (RIT) or a set of RITs (SRIT) to minimize the energy consumption at the RAN, in relation to the existing traffic capacity. On the other hand, the device energy efficiency is defined as the capability of a RIT/SRIT to minimize the device power consumption in relation to the traffic characteristics. Note that this KPI can be in turn calculated either as the sleep ratio, which is the fraction of unoccupied resources in a period of time (%), or the sleep duration, i.e. the absolute value of time with no transmission and reception of data.

In this work, we focus on the network energy efficiency, since it has been proved in [18] that it is the one providing the most restrictive results. In an unloaded case, that is, when no data transfer takes place, 5G networks perform periodical transmission of SS/PBCH blocks (SSB) and Remaining Minimum System Information (RMSI) paging signals, so that UEs can access the RAN. The sleep ratio per slot is therefore calculated as follows:

$$E_{\text{slot}} = 1 - \frac{\lceil L/2 \rceil}{2^\mu \cdot P_{\text{SSB}}} \quad (17)$$

where L is the number of SSB in an SS burst set, and P_{SSB} is the SS burst periodicity. The sleep duration can be easily derived by just multiplying the sleep ratio, E_{slot} , by P_{SSB} . Additionally, the sleep ratio can be calculated per symbol as:

$$E_{\text{symb}} = 1 - \frac{L(2/7)}{2^\mu \cdot P_{\text{SSB}}} - \beta \frac{L/7}{2^\mu \cdot P_{\text{RMSI}}} \quad (18)$$

where β is a flag variable ($\beta = 1$ for FR1 and $\beta = 0$ for FR2) and P_{RMSI} is the RMSI periodicity. In this work, we focus on FR1 and therefore $\beta = 1$.

G. 5TH PERCENTILE USER SPECTRAL EFFICIENCY

Throughput is defined as the rate of correctly received bits [3]. For the normalized user throughput, r_i , of user i , the correctly received bits $R_i(T_i)$, meaning the bits contained in the Service Data Units (SDUs) delivered to upper layers, are added up over a certain period of time T_i and divided by T_i as well as the effective channel bandwidth, BW .

$$r_i = \frac{R_i(T_i)}{T_i \cdot \alpha \cdot BW} \quad (19)$$

where $\alpha \cdot BW$ is the operating bandwidth normalized appropriately by the ratio between UL and DL. Using the normalized user throughput of all users in a scenario and simulating many times the determined period of time, a Cumulative Distribution Function (CDF) can be created. The 5% point of this CDF is defined as the 5th percentile user

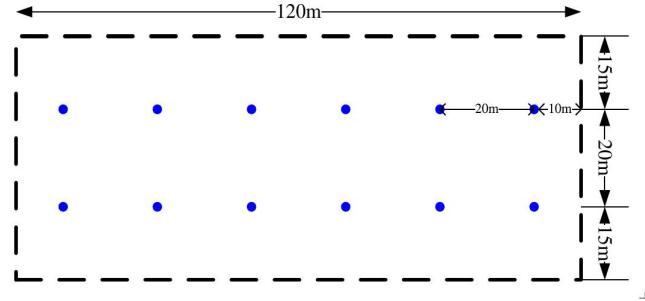


FIGURE 4. Layout for the Indoor Hotspot scenario [4].

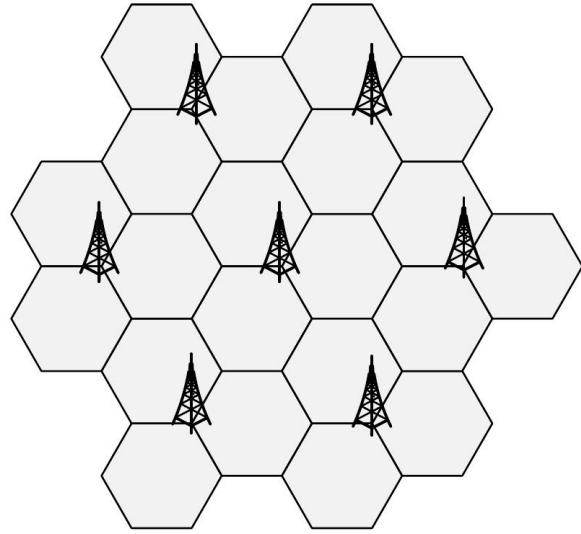


FIGURE 5. Hexagonal site layout for UMa and RMa [4].

spectral efficiency η_{user} . This KPI is obtained via system-level simulations.

In the course of the IMT-2020 evaluation, ITU-R defined minimum requirements for three different test environments within the eMBB usage scenario, namely InH, UMa and RMa [3]. The network layouts of the test environments are defined in [4]. For InH test environment, 12 sites are placed at a height of 3 m in a confined and isolated area of 120 m × 50 m with an inter-site distance of 20 m, as shown in Figure 4. There are two variants configurable, since a site can consist of one or three sectors.

For UMa and RMa test environments, a regular hexagonal layout is used, as Figure 5 illustrates. Each site has three sectors. The two test environments differ with respect to the inter-site distance and the base station height. For UMa, the gNB is located at 25 m height and the inter-site distance is 200 m, while the gNB height in a RMa environment is 35 m and the distance between two sites is 1732 m.

In this paper, we restrict ourselves to the evaluation of DL system-level simulations. The IMT-2020 requirements for 5th percentile user spectral efficiency are 0.3 bit/s/Hz for InH, 0.225 bit/s/Hz for UMa and 0.12 bit/s/Hz for RMa [3].

H. USER EXPERIENCED DATA RATE

The user experienced data rate, γ_{user} , is easily derived from the 5th percentile user spectral efficiency η_{user} , by using (20) and applying one frequency band and one layer of transmission reception points (TRxPs). In case of Carrier Aggregation (CA), the user experienced data rate is aggregated over the bands [3].

$$\gamma_{\text{user}} = BW \cdot \eta_{\text{user}} \quad (20)$$

In other words, the user experienced data rate is the 5% point of the CDF of the user throughput. The ITU-R describes for DL a minimum requirement of 100 Mbit/s for IMT-2020 in UMa test environment.

I. AVERAGE SPECTRAL EFFICIENCY

The average spectral efficiency is obtained by summing up the throughput of all users and dividing it by the effective bandwidth and the number of TRxPs. Considering a scenario where N users have M TRxPs each and are transmitting with effective bandwidth BW , the average spectral efficiency η_{avg} is calculated as follows:

$$\eta_{\text{avg}} = \frac{\sum_{i=1}^N R_i(T)}{T \cdot BW \cdot M} \quad (21)$$

where $R_i(T)$ is the number of correctly received bits by the user i over a period of time T . As done for the 5th percentile user SE, ITU-R defined the average SE minimum requirements for all three eMBB test environments for IMT-2020, i.e. 9 bit/s/Hz/TRxP for InH, 7.8 bit/s/Hz/TRxP for UMa and 3.3 bit/s/Hz/TRxP for RMa [3].

J. AREA TRAFFIC CAPACITY

When a single frequency band and one TRxP layer are applied, the area traffic capacity, C_{area} , can be derived from the achievable average spectral efficiency, η_{avg} , as follows:

$$C_{\text{area}} = \rho \cdot BW \cdot \eta_{\text{avg}} \quad (22)$$

where ρ is the density of TRxPs per m^2 . As done for the user experienced data rate, the area traffic capacity is summed over all frequency bands when CA is used. The IMT-2020 requirement for this KPI is 10 Mbit/s/ m^2 for DL in InH test environment.

K. MOBILITY

Mobility is evaluated in this work following two different methodologies, i.e. spectral efficiency evaluation as described in [4] and compared against the requirements in [3]; and an additional the Doppler analysis, providing complementary results.

1) Spectral efficiency evaluation

The mobility evaluation is based on system- and link-level simulations, as mentioned in [4]. Note that, for system-level simulations, the pre-processing signal-to-interference-plus-noise ratio (SINR) is used. The pre-processing SINR is defined on an Rx antenna port with respect to a Tx antenna port.

It is divided in several steps. The first step is to run system-level simulations as done for the 5th percentile user and average spectral efficiency (see Sections IV-G and IV-I respectively), but with user speeds as provided in Table 4 of [3], using link-level simulations for a set of three selected test environments: InH, UMa and RMa. The statistics for uplink SINR values and CDF over these values are then collected. The second step is to use the CDF to save the 50th-percentile SINR value. The third step is to run new uplink link-level simulations for either NLoS or LoS conditions, using the speeds provided in Table 4 of [3], to obtain link data rate and residual packet error ratio as a function of SINR. Finally, the obtained results are compared with the threshold values or requirements provided in [3]. These thresholds are defined as the normalized traffic channel link spectral efficiency (bit/s/Hz), assuming the user is moving at a certain speed. The values are 1.5 bit/s/Hz at 10 km/h for InH and 1.12 bit/s/Hz at 30 km/h for UMa. Two requirements need to be fulfilled for RMa, being 0.8 bit/s/Hz at 120 km/h and 0.45 bit/s/Hz at 500 km/h.

2) Doppler analysis

The considered scenario for this analysis is a Typical Urban (TU-6) with variable Doppler spread and therefore user speed [34]. In mobile environments, a channel realization is a time-variant function that depends on the relative speed of the transmitted and received pair. This time-dependent variation produces a frequency shift at the receiver known as Doppler effect. The maximum frequency shift (f_D) in Hz due to the Doppler effect is calculated in (23):

$$f_D = \frac{\nu f_c \cos \alpha}{c} \quad (23)$$

where ν is the receiver speed, f_c is the signal carrier frequency, c is the speed of light and α is the angle between the receiver direction and the line that connects both transmitter and receiver. This work considers for this analysis the mobility requirement defined in the IMT-2020 recommendation [36], which is set to 500 km/h.

V. 5G NEW RADIO ANALYSIS AND EVALUATION

This section follows the procedures described in Sections III and IV and presents the numerical results. The values are also compared against the IMT-2020 requirements previously defined in Section IV.

A. BANDWIDTH

In FR1 (450 MHz - 6 GHz), 5G allows bandwidths from 5 MHz to 100 MHz. In FR2 (24.25 GHz - 52.6 GHz), 5G offers

TABLE 5. Maximum supported bandwidth of 5G NR.

FR	μ	BW (MHz)	N_{RB}^{max}	CA CC	CA BW (GHz)
	0	50	270		0.8
FR1	1	100	273		1.6
	2	100	135	16	1.6
FR2	2	200	264		3.2
	3	400	264		6.4

TABLE 6. Peak data rate (Gbit/s) of 5G NR.

μ	Overhead	γ_p	γ_p	γ_p	γ_p
		SISO	MIMO	SISO+CA	MIMO+CA
DL	0	0.1037	0.30	2.40	4.81
	1	0.1036	0.60	4.87	9.75
	2	0.1076	0.59	4.78	9.57
UL	0	0.0834	0.30	1.22	4.90
	1	0.0815	0.62	2.49	9.99
	2	0.0826	0.62	2.49	9.98

values from 50 MHz to 400 MHz. The minimum amount of paired spectrum is therefore 2×5 MHz, while the minimum amount of unpaired spectrum is 5 MHz. Regarding the maximum theoretical bandwidth, Table 5 shows the specific values for all numerology and FR combinations [33]. As shown in the table, CA of up to 16 CCs can be performed with every configuration, as specified in [37]. The maximum supported bandwidth is 1.6 and 6.4 GHz in FR1 and FR2 respectively, and therefore the IMT-2020 requirements are met (100 MHz and 1 GHz). In particular, a minimum number of 1 and 3 CCs are needed in FR1 and FR2 respectively to fulfill this criterion. Note that the maximum values obtained per FR could be reduced in practical implementations due to specific spectrum assignments [38].

B. PEAK DATA RATE

This work focuses on Frequency Division Duplex (FDD) and therefore, from now on, FR1 is analyzed. In this section, the peak data rate is first calculated as an example for numerology $\mu = 0$ and DL with 8 layers, extrapolating the results to the rest of configurations.

First, it is necessary to calculate the overhead. The number of REs, N_{RE-DL} , is computed according to (3). In 5G NR, the number of subframes per frame is 10, the number of slots per subframe is 1, there are 14 OFDM symbols per slot due to the use of normal CP and the maximum number of RBs in the total bandwidth is 270 for $\mu = 0$ as shown in Table 5. Since the number of REs per RB is always 12, a total of 453600 REs are available in a NR frame.

The independent overheads coming from the SSB, PD-CCH and RS are calculated using formulas (4), (5) and (7) respectively. The SSB overhead depends on the 2 SSBs

TABLE 7. Peak spectral efficiency (bit/s/Hz) of 5G NR.

	μ	DL		UL	
		η_p SISO	η_p MIMO	η_p SISO	η_p MIMO
FR1	0	6.02	48.17	6.12	24.51
	1	6.09	48.78	6.24	24.99
	2	5.98	47.89	6.17	24.71

per slot and the periodicity of 20 ms. Since there are 240 subcarriers in 4 OFDM Symbols, 960 REs are used. For the PDCCCH overhead calculation, it is assumed that all subframes contain CORESETs, with 1 CORESET per slot as the minimum amount of bits that provide the peak data rate, and 144 REs per CORESET transmitted (12 REs per RB, with 6 RBs per CCE and AL 2). In total, 1440 REs are used for PDCCH. Regarding the reference signals in PDSCH, again all subframes are used for PDSCH transmissions. We assume a total of 16 RE/RB/slot in all RBs in all slots in all subframes for DMRS, 8 RE/RB/slot in all RBs each 20 slots for CSI-RS NZP, 4 RE/RB/slot in all RBs each 20 slots for CSI-IM, and 12 RE/RB/slot in 52 RBs each 20 slots for TRS. Since 270 RBs are transmitted, 44976 REs are used for reference signals in PDSCH. Hence, the minimum overhead introduced for numerology 0, using (2), is 10.37%. This calculation can be extrapolated to all considered numerologies, as Table 6 shows.

The peak data rate is calculated using (1) with the following parameters. The maximum number of aggregated carriers is $J = 16$. The parameter α has always value 1 for FDD. When MIMO is used, the maximum number of layers in the DL is $\nu = 8$. In UL, only 4 can be used. Moreover, NR specifies the use of several MCS indexes that transmit different modulation orders and CR combinations. The maximum MCS defined in NR is an MCS 27 from Table 5.1.3.1-2 [30], which uses a 256QAM constellation, that is, modulation order $Q_m = 8$ and a coding rate $R_{max} = 948/1024 = 0.925$. The maximum value for f is 1. As Table 5 shows, the maximum number of RBs for $\mu = 0$ is 270, and the T_s is $71.37 \cdot 10^{-6}$. Taking into account the overhead of 10.37%, the peak data rate is 38.54 Gbit/s.

Table 6 also shows the peak data rate calculated for lower-profile configurations, i.e. transmission without CA and Single-Input Single-Output (SISO), without CA and MIMO or with CA and SISO, and additional numerologies. Table 6 also expands the analysis to numerologies 1 and 2. It can be observed that the DL peak data rate in FDD transmissions is 78.05 Gbit/s with numerology 1, when using 8 layers and a total BW of 6.4 GHz (16 CCs). This value clearly outperforms the one provided by the IMT-2020 evaluation guidelines, where the minimum peak data rate required is 20 Gbit/s. As can be observed, CA and MIMO are fundamental technologies to meet the requirement.

The results can be extrapolated to the UL, as shown in Table 6. The extrapolation includes the overhead calcula-

TABLE 8. User plane latency (ms) for all considered configurations.

Slot configuration	HARQ probability	$\mu = 0$	$\mu = 1$	$\mu = 2$
2 symbols	$p = 0$	0.50	0.27	0.23
	$p = 0.1$	0.58	0.32	0.27
	$p = 1$	1.35	0.77	0.66
4 symbols	$p = 0$	0.71	0.38	0.28
	$p = 0.1$	0.82	0.44	0.34
	$p = 1$	1.85	0.95	0.78
7 symbols	$p = 0$	1.03	0.54	0.36
	$p = 0.1$	1.18	0.62	0.41
	$p = 1$	2.53	1.29	0.86
14 symbols	$p = 0$	1.80	0.92	0.55
	$p = 0.1$	1.98	1.02	0.63
	$p = 1$	3.78	1.91	1.30

tion for PRACH, PUCCH and PUSCH DMRS. Note that the results are roughly half when using MIMO due to the maximum number of supported antennas in the UL, which is 4 instead of 8. The peak data rate in this case is 39.99 Gbit/s, which thoroughly outperforms the IMT-2020 requirement of 10 Gbit/s.

C. PEAK SPECTRAL EFFICIENCY

The peak spectral efficiency can be calculated using (8), by dividing the peak data rate by the total effective bandwidth. Table 7 shows the peak spectral efficiency for SISO and MIMO, and the three considered numerologies. The maximum obtained value is $\eta_p = 48.78$ bit/s/Hz for MIMO with 8 layers, with numerology 1. As occurred with the peak data rate, this value outperforms the IMT-2020 value, i.e. 30 bits/s/Hz. In addition, the numbers obtained in the UL are roughly half of those in the DL, due to the number of antennas. A peak spectral efficiency of 24.99 bit/s/Hz clearly outperforms the IMT-2020 requirement of 15 bit/s/Hz. Note that the use of MIMO is mandatory to meet both requirements.

D. USER PLANE LATENCY

This section first introduces an example to better understand the implications of selecting a specific numerology and slot configuration. It extends the analysis to other possible combinations in 5G. We assume UE capability 2, as it provides lower values than UE capability 1 [18]. This example considers numerology 0 and slot based scheduling of 14 symbols with probability of retransmission $p = 1$. The numbers considered below are illustrated in Figure 6.

1) First transmission

Prior to the transmission, the gNB spends some time to process the data. Using (11), with $N_2 = 5$ (numerology 0 and UE capability 2), the processing time at the gNB, $t_{gNB,tx}$, is $178.4\mu s$. Before transmitting the data, the gNB needs to

be aligned with the first possible symbol, in this case the symbol number 0. This value depends on the moment when the gNB starts the process. The gNB waits a minimum time t_{FA1} of $35.9\mu s$ and a maximum time of $964.5\mu s$. On average, the time needed is $500\mu s$ as shown in the figure. The TTI is afterwards transmitted. 14 OFDM symbols with numerology 0 spend 1 ms, i.e. the subframe length. When receiving the data, the UE processing time is calculated using (12). In this case, N_1 takes the value 8 [30]. Hence, the processing time, $t_{UE,rx}$, is $107\mu s$. The total amount of time needed for the data transmission without HARQ retransmissions, τ_1 , is 1.8 ms.

2) HARQ request

When the data is not received, the UE sends a HARQ petition. Processing times at both the UE and gNB are the same. The UE spends $107\mu s$ to process the petition and does not need to wait for this particular case, as Figure 6 shows. Therefore, t_{FA2} is $0\mu s$. The time for the HARQ petition is 1 OFDM symbol, and thus t_{HARQ} is $71.4\mu s$. Afterwards, the gNB processes the request in $178.4\mu s$. In total, the HARQ petition uses $\tau_2 = 356.4\mu s$.

3) HARQ retransmission

In a third step, the gNB again needs time to process the retransmission, with the same value of $178.4\mu s$. Time for frame alignment in this case is $357\mu s$ in any case, in order to reach first symbol of the subframe and retransmit. The TTI is retransmitted in 1 ms, and the UE processes the data in $107\mu s$. The total time of retransmission is $\tau_3 = 1.59$ ms. The user plane latency with a probability of retransmission $p = 1$ is therefore $\tau = 3.78$ ms.

The process can be extrapolated to all numerologies and slot configurations available in 5G NR. In this work, we assume FDD. The results are summarized in Table 8. The lowest CP value achieved without retransmission is 0.23 ms, which fulfills both IMT-2020 requirements of 1 and 4 ms [3] for URLLC and eMBB respectively.

E. CONTROL PLANE LATENCY

Following the same methodology than the UP latency, in this calculation we first provide a particular example to better explain the CP procedure. The results are then extrapolated to a wider range of configurations. In this example, resource mapping type A, UE capability 2 [18], numerology 0 with mini-slot based scheduling of 7 symbols, PRACH length of 1 ms and FDD mode have been selected.

In this process, the methodology provided in section IV-E and shown in Figure 3 is carried out. The different delays calculated can be observed in Figure 7. The CP procedure from inactive to connected state is divided into two main stages: RACH and RRC, and calculated as in (15). The first delay to consider is $T_2 = 1$ ms, which is related to the PRACH length selected. Then, T_3 is calculated according to the methodology as $t_{gNB}/2$, which in turn is given by (11). As a result, $T_3 = 0.357$ ms. Since T_4 cannot cross any slot boundary, the gNB needs to wait $T_{FA1} = 0.714$

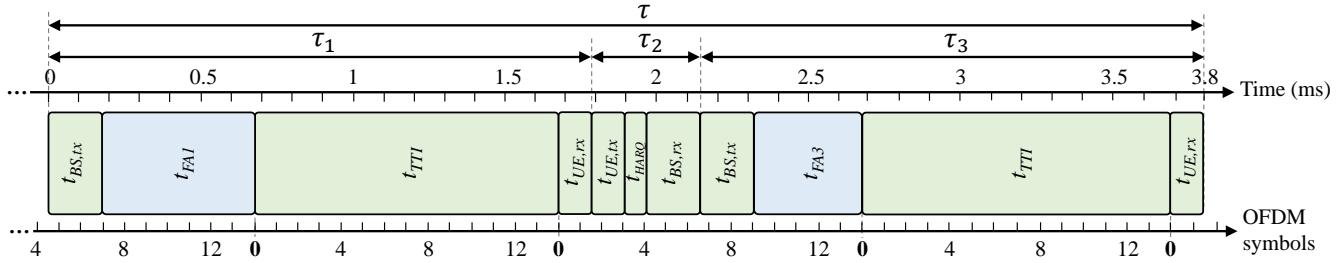


FIGURE 6. User plane latency for numerology 0, with slot based scheduling of 14 symbols (1 ms). Average frame alignment.

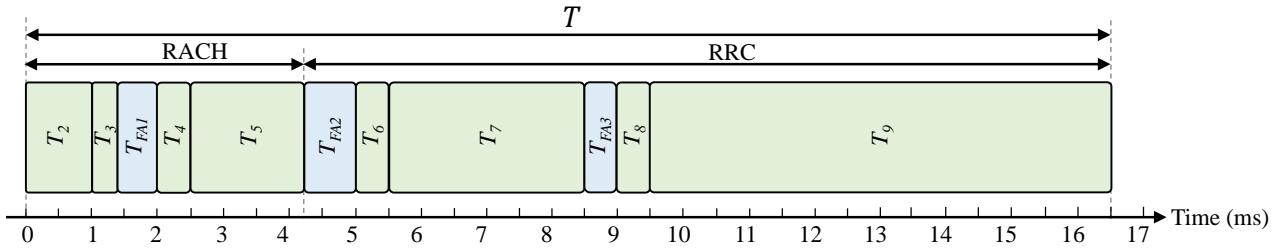


FIGURE 7. Control plane latency for $\mu = 0$, PRACH of 1 ms, mini-slot based scheduling of 7 symbols (0.5 ms), resource mapping type A and UE capability 1.

TABLE 9. Control plane latency (ms) for all considered configurations.

Mapping	Slot	PRACH 1 ms		PRACH 2 symbols		
		$\mu = 0$	$\mu = 1$	$\mu = 0$	$\mu = 1$	$\mu = 2$
Type A	4 symbols	16.3	13.6	15.3	12.6	12.1
	7 symbols	16.5	14.3	15.5	13.3	12.1
	14 symbols	17	14.5	-	-	-
Type B	2 symbols	13.6	12.7	12.7	11.8	11.6
	4 symbols	14	12.9	13.3	12	11.7
	7 symbols	15	13.3	14	12.8	11.9

ms, as shown in Figure 6. The transmission of a RA response takes $T_4 = T_s = 0.5$ ms. The UE processing delay T_5 is calculated as in (16). From [30], this particular configuration takes values $N_1 = 8$ and $N_2 = 10$ and therefore $N_{T,1} = 0.57$ ms, $N_{T,2} = 0.71$ ms and $T_5 = 1.785$ ms.

The UE waits until the next slot is available to start the RRC resume request, with $T_{FA2} = 0.714$ ms. The transmission of the RRC resume request needs one mini-slot, equivalent to the PUSCH allocation length, i.e. $T_6 = T_s = 0.5$ ms. As denoted in the methodology, the processing delay in the gNB takes $T_7 = 3$ ms and the UE waits $T_{FA3} = 0.5$ ms. Finally, the gNB transmits the RRC resume signal, which takes $T_8 = T_s = 0.5$ ms, and the UE processes it in $T_9 = 7$ ms. The total CP latency in this example is $T = 16.5$ ms. Assuming UE capability 2, the process in this work is extrapolated to all possible numerologies in FR1, both resource mapping types, all slot configurations and different PRACH lengths. The results are summarized in Table 9. The lowest CP value achieved is 11.6 ms, which fulfills the requirement of 20 ms [3].

TABLE 10. Network energy efficiency or sleep ratio (%) in 5G NR. Numerology 0 and FR1.

	L	5 ms	10 ms	20 ms	40 ms	80 ms	160 ms
Slot	1	80	90	95	97.5	98.75	99.38
	2						
Symbol	1	93.57	96.43	97.86	98.93	99.46	99.73
	2	87.14	92.86	95.71	97.86	98.93	99.46

F. ENERGY EFFICIENCY

The network energy efficiency KPI can be calculated as the sleep ratio when using (17) at slot level and (18) at symbol level. For this calculation, each SS/PBCH block is assumed to occupy 4 OFDM symbols with 20 RBs in one slot. In addition, one or multiple SS/PBCH blocks compose an SS burst, which occupies half frame, i.e. 5 ms. The SSB periodicity (P_{SSB}) can be 5, 10, 20, 40, 80 or 160 ms [18]. It is also assumed that the RMSI occupies 2 OFDM symbols in a slot, with the slot accommodating two RMSI transmissions. RMSI is usually time-division multiplexed with SS/PBCH and therefore it can be transmitted in the same slot. The RMSI periodicity is 20 ms if $P_{SSB} \leq 20$ ms and P_{SSB} ms otherwise.

In this work we focus on FR1 and numerology 0. Table 10 shows the network energy efficiency in terms of sleep ratio (%) for the selected configurations at both slot and symbol levels. These values are obtained by applying the aforementioned assumptions and equations 17 and 18 respectively. As observed, efficiencies up to 99.73% are achieved in 5G NR. The minimum value obtained is 80% and it is considered that all possible values fulfill the IMT-2020 requirement.

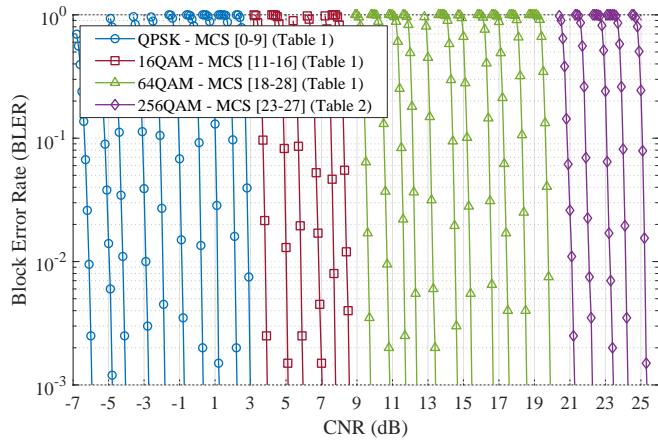


FIGURE 8. Block error rate (BLER) vs CNR (dB) for SISO AWGN channel.

G. 5TH PERCENTILE USER SPECTRAL EFFICIENCY

For this calculation, it is first necessary to determine with link-level simulations specific BLER vs. CNR curves for each MCS available in NR [30], using an Additive White Gaussian Noise (AWGN) channel and ideal channel estimation. These values will be used as a basis in system-level simulations afterwards. A numerology $\mu = 0$ is selected in the calculation, i.e. carrier spacing of 15 kHz. Figure 8 shows the BLER vs. CNR waterfall, where each color and marker combination represents a specific modulation order. Curves with the same color represent different CRs. Note that both tables included in [30] have been considered. As shown in the figure, NR Rel'15 provides an excellent granularity.

These results are then used in combination with Mutual Information per Symbol (MIS)-based effective SINR computation, for channels involving fast fading and variable interference power [39]. As explained in section IV, the CDF is then created using the normalized user throughput of all users and simulating many times the determined period of time. Figure 9 shows an example of the CDF distribution for the InH scenario with 3 sectors.

The values shown in Figure 10 (top) are obtained for DL in the different test environments, when performing system-level simulations with sufficient statistics. The ITU-R requirements for IMT-2020 are also depicted for comparison. It can be observed that for all test environments defined for eMBB in FR1, these requirements [3] are met. The InH Config. A scenario provides 0.47 and 0.43 bit/s/Hz when using 1 and 3 sectors respectively. These values are higher than the 0.3 bit/s/Hz requirement. The maximum value with this KPI is obtained for the UMa usage scenario with 0.6 bit/s/Hz, being the requirement 0.225 bit/s/Hz.

Additionally, the figure shows that RMa Config. A usage scenario achieves the lowest 5th percentile user spectral efficiency, with 0.23 bit/s/Hz. There are two factors that reduce the 5th percentile user spectral efficiency in RMa. On the one hand, the large inter-site distance of 1732m in RMa scenarios, different from the 200m available in UMa.

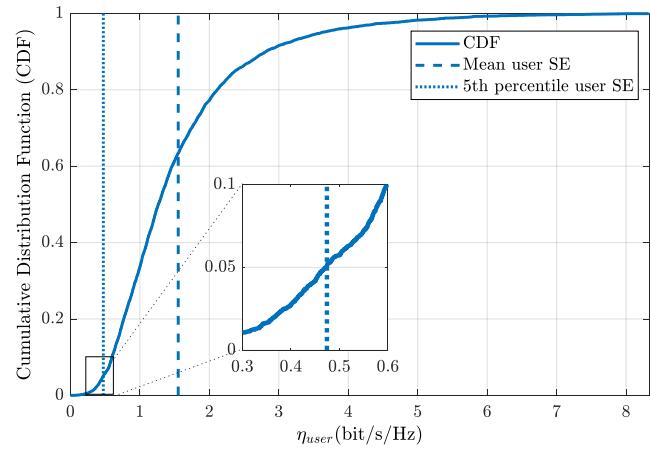


FIGURE 9. CDF distribution vs. user spectral efficiency (bit/s/Hz), Indoor Hotspot scenario with 3 sectors.

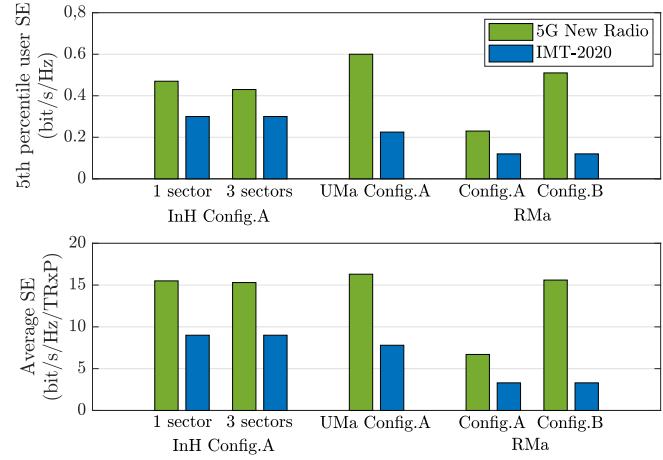


FIGURE 10. 5th percentile (top) and average (bottom) spectral efficiency of 5G NR, compared to IMT-2020 requirements for the considered scenarios.

On the other hand, there are only two TXRUs at the UE side making the interference cancellation difficult. Despite the low efficiency, 5G NR also satisfies the requirement in this scenario, which is 0.12 bit/s/Hz.

H. USER EXPERIENCED DATA RATE

In order to get a sufficiently large user experienced data rate, system-level simulations are performed with a frequency bandwidth of 40 MHz, which provides a more efficient usage of bandwidth and a smaller overhead. In this study, the user experienced data rate for the UMa test environment results in 15.5 Mbit/s for one CC and in 247.6 Mbit/s for 16 CC, where 16 is the maximum number of aggregated carriers specified for NR. In order to satisfy the IMT-2020 requirement of 100 Mbit/s user experienced data rate, CA of 7 CC is needed. This number of carriers entails a system bandwidth of 480 MHz, with a user experienced data rate of 108.3 Mbit/s.

TABLE 11. Mobility evaluation results for different test environments.

Scenario	ITU Requirement (bit/s/Hz)	Frequency (GHz)	50%-ile SINR CDF (dB)	Uplink SE (bit/s/Hz)			
				FDD		TDD	
				NLoS	LoS	NLoS	LoS
InH (12 TRxP)	1.5	4	3.90	1.75	2.05	1.59	1.94
UMa	1.12	4	5.52	1.92	2.22	1.82	2.17
RMa (120 km/h)	0.8	0.7	10.21	2.32	2.90	2.10	2.63
		4	4.66	1.30	1.74	1.18	1.57
RMa (500 km/h)	0.45	0.7	9.67	2.07	2.64	1.88	2.39
		4	2.90	0.92	1.33	0.84	1.22

I. AVERAGE SPECTRAL EFFICIENCY

Figure 10 (bottom) gives an overview of the system-level simulation results and the IMT-2020 requirements for the DL average spectral efficiency. It is notable that the values for InH Config. A are similar, i.e. 15.5 and 15.3 bit/s/Hz/TRxP, irrespective of whether 1 sector or 3 sectors are configured. Both clearly outperform the requirement of 9 bit/s/Hz/TRxP. This happens because an establishment of three times as much antennas on the same area means a larger interference level. However, in case of this 3 sectors scenario, 8 antenna elements form one TXRU or beam at the gNB while in the 1 sector scenario a gNB TXRU consists of one antenna element. With a larger number of antenna elements, the beams become sharper and cause less interference to users in neighbored cells.

The DL average spectral efficiency for the RMa Config. A scenario is significantly lower than that of the other scenarios, with 6.7 bit/s/Hz/TRxP. The reasons are the same as for 5th percentile user spectral efficiency explained in subsection V-G. In any case, Figure 10 concludes that the 5G NR system specified by 3GPP outperforms the requirements for eMBB given by ITU-R for IMT-2020. Considering these large numbers in comparison to the requirements, one should bear in mind that ideal channel estimation is used in this work.

J. AREA TRAFFIC CAPACITY

In the same line as the user experienced data rate, evaluated in Section V-H, the area traffic capacity is calculated by means of system-level simulations with a frequency bandwidth of 40 MHz per carrier with additional CA. With an aggregated bandwidth of 520 MHz meaning 13 CCs, an area traffic capacity of 10.3 Mbit/s/m² is obtained for InH Config. A applying one sector per site, which meets the IMT-2020 requirement of 10 Mbit/s/m². For the scenario with three sectors per site, where the density of TXRUs is three times larger, it is sufficient to aggregate 5 CCs to fulfill the IMT-2020 requirement, namely by 11.7 Mbit/s/m².

Applying the maximum of 16 aggregated CC, the area traffic capacity for the 1 sector scenario results in 12.7 Mbit/s/m² and in 37.5 Mbit/s/m² for the 3 sectors scenario. Without CA,

the area traffic capacity achieved for 40 MHz is 0.8 Mbit/s/m² for InH Config. A 1 sector and 2.3 Mbit/s/m² for InH Config. A 3 sector scenario.

K. MOBILITY

This section follows the same structure than Section IV-K. Mobility is evaluated first in terms of spectral efficiency with a maximum user speed. Later, an additional Doppler analysis is provided to complement the results.

1) Spectral efficiency evaluation

The mobility results are provided in Table 11. A carrier frequency of 4 GHz is assumed for all considered scenarios. In addition, following [4], 700 MHz is also considered for rural environments. Both FDD and TDD modes are evaluated. For the sake of simplicity, these results are provided for the channel model A, described in [4], since the difference of the values with channel model B is negligible. Note that readers can refer to [10] for those results. Table 11 shows the values in terms of 50%-ile point of SINR CDF (dB) and uplink SE (bit/s/Hz), for the evaluation scenarios described in Section IV-K. It is observed that NR meets the mobility requirements in all test environments and evaluated configurations. As can be observed, the highest value is obtained at 700 MHz, in RMa environment with a maximum speed of 120 km/h, FDD mode and LoS.

2) Doppler analysis

In this section, a wide range of Doppler shifts is evaluated. The obtained results can be easily mapped to the frequency bands under evaluation by using (23). Two representative FR1 bands are evaluated, i.e. 700 MHz and 4 GHz. Three numerologies 0, 1 and 2 are considered in the analysis. Mapping Type A with DMRS configuration type 1 is assumed. Two pilot patterns, i.e. with 1 front-loaded and 1 or 3 additional DMRS, are also explored. Real channel estimation (linear in time and frequency) with MCS 3 is used in all cases.

Figure 11 shows that for Doppler shifts up to 500 Hz, the performance with all configurations is good enough to keep an acceptable CNR. In this case, the higher the speed the lower the CNR required. However, for higher user speeds

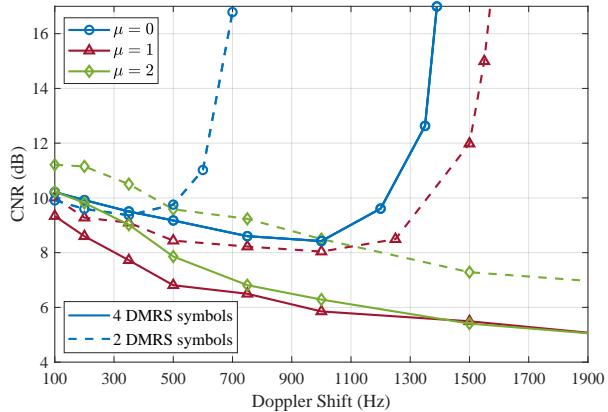


FIGURE 11. CNR (dB) against Doppler shift (Hz) for 5G New Radio in TU-6 mobile channel. Numerologies 0,1 and 2, MCS 3.

and some configurations, the Doppler shift starts to cause significant Inter-Carrier Interference (ICI) and channel estimation errors. This leads to performance degradation. The way to increase the Doppler shift limits is by increasing the DMRS symbols or the numerology. The configuration with the poorest performance is $\mu = 0$ with 2 DMRS symbols per subframe, which permits to reach 600 Hz, i.e. 925 km/h at 700 MHz, but only 162 km/h at 4 GHz. Configurations with a numerology higher than 0 and dense DMRS patterns are good enough to support user speeds higher than 500 km/h at both frequencies. A numerology 1 with more than 2 DMRS symbols is recommended with this modulation and coding scheme, despite the introduction of additional overheads.

VI. CONCLUSION

This work has evaluated the performance of 5G against relevant KPIs as defined in the IMT-2020 guidelines [4]. The paper has studied whether the requirements specified in [3] are met or not. The analysis has been done from an independent perspective, complementing the one provided by 3GPP and emphasizing the role of 5G NR towards the IMT-2020 landmark. In particular, eleven KPIs have been addressed in this work. Table 12 summarizes the best values achieved for each specific KPI and compares them against the IMT-2020 requirements [3].

It is shown that 5G NR fulfills all considered requirements under specific conditions. By aggregating 16 CCs, transmission bandwidths up to 6.4 GHz are supported. This permits to transmit a peak data rate in FDD mode of 78.05 Gbps when 8 layers and numerology 1 are used. The peak spectral efficiency, directly related to this KPI, is 48.78 bit/s/Hz. The 5th percentile spectral efficiency, on the other hand, depends on the scenario under evaluation. The most demanding scenario is InH, where up to 0.47 bit/s/Hz have been achieved. In UMa test environment, 5G NR also permits a user experienced data rate of 247.6 Mbit/s, if 16 CCs are selected. The obtained system-level results revealed that the maximum average SE is 15.5 bit/s/Hz/TRxP in a RMa scenario with configuration B. It was observed that a maximum area traffic capacity

TABLE 12. Summary: 5G New Radio against most stringent IMT-2020 requirements.

KPI	IMT-2020	5G NR	Fulfillment
Bandwidth (GHz)	1	6.4	✓
Peak data rate (Gbit/s)	20	78.05	✓
Peak SE (bit/s/Hz)	30	48.78	✓
User plane latency (ms)	1	0.23	✓
Control plane latency (ms)	20	11.6	✓
Energy efficiency (%)	Qualitative	99.73	✓
5th perc. user SE (bit/s/Hz)	0.3	0.47	✓
User exp. data rate (Mbit/s)	100	247.6	✓
Average SE (bit/s/Hz/TRxP)	9	15.5	✓
Traffic capacity (Mbit/s/m ²)	10	37.5	✓
Mobility SE (bit/s/Hz)	0.45	2.64	✓

of 37.5 Mbit/s/m² in the InH scenario is achieved, when 3 sectors are used. Furthermore, results have shown that the latency is highly dependent on the numerology. Without retransmission, our analysis has provided a minimum value of 0.23 ms for the user plane. Regarding the control plane, values down to 11.6 ms have been obtained. Finally, our mobility results have shown that the requirements are met in both analyzed bands, i.e. 700 MHz and 4 GHz. The maximum spectral efficiency is 2.9 bit/s/Hz in FDD mode with LoS in RMa scenarios (120 km/h) at 700 MHz. This value is reduced to 2.64 bit/s/Hz at 500 km/h.

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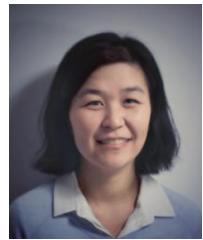
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