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5G New Radio Base-Station Sensitivity and Performance

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***Abstract*—In this paper, we address and analyze the receiver reference sensitivity requirements for the 5G New Radio (NR) wireless communications systems, which relate to the SNR requirements at the base station to reach 95 % of the maximum throughput defined for fixed reference channels. Based on the latest 3GPP specifications and evaluation assumptions agreed for Release 15, a wide set of different transmission bandwidths and radio interface numerologies are investigated, at sub-6GHz and millimeter-wave frequency ranges, covering both AWGN and fading channel scenarios as well as varying mobility conditions. The performance results in terms of the relative throughput and block error rate using LDPC coding scheme are presented and analyzed, while for comparison purposes also LTE turbo code based results are provided. The results show that in frequency-selective channels, the reference sensitivity and UL radio link performance are systematically better with LDPC code compared to turbo code. The results also indicate that the purely front-loaded demodulation reference signal (DM-RS) based system can outperform the corresponding two DM-RS based system even at higher velocities and high center frequencies, allowing low decoding latency and efficient pipelined receiver processing.**

***Keywords*—5G NR, PHY layer, link performance, reference sensitivity, channel coding, LDPC codes, turbo codes**

I. Introduction

5G New Radio (NR) wireless communication systems are mainly developed for three usage scenarios or services [1], namely, enhanced mobile broadband (eMBB), massive machine-type communications (mMTC) and, ultra-reliable low-latency communications (URLLC). In order to satisfy the diverse requirements of these scenarios, 5G NR physical layer has a flexible and scalable design. General physical layer features for 5G NR have been recently approved and specified by 3GPP [2], defining its main aspects such as orthogonal frequency division multiplexing (OFDM) based uplink (UL) and downlink (DL) waveforms, multi-antenna transmission techniques, modulation and channel coding schemes (MCS), optimized frame structures, and scalable numerology.

To this end, physical layer design is the first step towards the deployment of next generation radio access networks, which will operate from sub-6GHz frequency range to millimeter-wave carrier frequencies. 5G NR operation is currently defined over two distinct frequency ranges: frequency range 1 (FR1) covers frequencies between 450 MHz and 6000 MHz, and frequency range 2 (FR2) covers frequencies from 24250 MHz to 52600 MHz. 5G NR is also intended to support wider bandwidths and scalable sub-carrier spacing (SCS) compared to LTE systems [3]. Systems using smaller SCS can be utilized for lower carrier frequencies and can tolerate higher multi-path delay spread scenarios. On the other hand, larger SCS makes a slot duration shorter and is thus more favorable for fast transmissions while being also more robust against rapid time variations in high-speed scenarios. Besides, higher bandwidth allocations under high mobility conditions are required to provide high wireless access capacity in eMBB scenarios as well as very low latency and high reliability in URLLC services.

In general, the demodulation reference signals (DM-RSs) refer to the known training signals used for channel estimation (CE) to support data channel demodulation in 5G NR [2]. The basic DM-RS pattern in 5G NR is front-loaded to enable low-latency applications with fast decoding. With increasing user velocities, however, higher DM-RS densities in the time domain are commonly considered necessary to be able to adapt to the fast variations in the channel. In general, the DM-RS design aims to find a compromise between CE performance and system overhead, especially in high-speed scenarios where Doppler effects are significant. It is common to assume small-cell deployment scenarios in FR2 with lower user speeds while networks deployed at FR1 are primarily of larger cell sizes and designed to support higher user velocities. Addressing the feasibility of a single front-loaded DM-RS allocation per slot and the associated 5G NR radio link performance in UL direction, under different velocities, network center-frequencies, subcarrier spacings and transmission bandwidths, is one of the main objectives of this paper. We also consider several DM-RS allocation designs to evaluate the 5G NR uplink reference sensitivity (REFSENS) and link performance in diverse mobility scenarios and channel propagation conditions.

Recently, low-density parity-check (LDPC) codes have been selected as the channel coding scheme for 5G NR shared data channels whereas turbo codes are used in LTE [4]. The complexity and latency restrictions of LTE turbo and LDPC codes have been investigated in previous studies [5] [6], where they show similar error-correction performance under similar decoder complexity with long codewords. However, significant performance improvement can be achieved for short message lengths with LDPC codes in comparison to turbo codes. Although turbo codes are commonly used in 4G/LTE, they may not satisfy the 5G NR performance requirements for all use cases with highly varying code rates and block lengths. In particular, how large performance improvement LDPC codes really provide over turbo codes, in emerging 5G NR systems, has not been systematically reported in UL radio link and

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REFSENS context. Hence, this is one of the main topics addressed and analyzed in this paper. Particular emphasis is placed on the 5G NR performance analysis under the so-called fixed reference channels (FRCs), defined in [3], comprising selected radio link bandwidth allocations, subcarrier spacings and MCS values.

The results in this paper outline first physical layer performance measurements within several deployment scenarios incorporating different OFDM numerologies, carrier frequencies, and velocities to assess the 5G base station (gNB) REFSENS requirements. In general, the REFSENS measurements are defined as the minimum receiver signal-to-noise-ratio (SNR) level at which the base station reaches at least 95% of the corresponding maximum throughput of the evaluated MCS [7]. The main purpose of the REFSENS requirements is to verify the desired throughput performance with different allocation sizes to ensure robust UL operation, and also to evaluate the allowed receiver noise figure in the base station [8]. The performance analysis builds on the concept of 5G NR FRCs, whose parameters for REFSENS evaluations are defined in the latest Release 15 for both FR1 and FR2 in terms of MCS and physical resources allocation [3], [7]. Importantly, the results reported in this paper show that in frequency-selective channels, the reference sensitivity and UL radio link performance are systematically better with LDPC code compared to LTE-like turbo code. The results also indicate that the purely front-loaded DM-RS based system can outperform the corresponding two DM-RS based system even at higher velocities and high center frequencies, allowing low decoding latency. These are important findings for the first practical deployments and optimization of 5G NR networks in different use cases, and are not available in the existing literature.

The rest of the paper is organized as follows: Section II presents the 5G NR scenarios and the considered 5G NR reference channels and system parameterization. Section III presents the 5G NR performance results for both FR1 and FR2 scenarios, different DM-RS densities and coding schemes in AWGN and fading channels under several mobility conditions. Finally, in Section IV, the conclusions are drawn.

II. 5G NR Reference Channels and System Parameterization

A. 5G NR Scenarios: Fixed Reference Channels

The REFSENS measurements are defined [7] as the minimum received power level at which the gNB reaches at least 95% of the maximum relative throughput, and they will be used for the wanted signal power calculation according to:

$$P_{refsens} = -174 \text{ dBm} + 10\log_{10}(B) + N_F + I_M + \text{SNR} \quad (1)$$

where B is the transmission bandwidth (BW), N_F is the base station noise figure equal to 5 dB, 10 dB or 13 dB for Wide Area BS, Medium Range BS, or Local Area BS, respectively, I_M is the implementation margin equal to 2 dB, and SNR is the value for which 95 % of the maximum throughput is reached [7]. To limit the complexity of gNB receiver (Rx) REFSENS testing, the number of different FRCs has been agreed reasonably small [3].

In [3], the maximum BW is specified for the Rx REFSENS requirements in terms of physical resource blocks (PRBs) for each channel bandwidth (CBW) and SCS, and for both frequency ranges. We focus our evaluations on a few representative FRCs defined in Table I for FR1 and FR2. While the baseline CBW assumptions are 20 MHz for FR1 and 100 MHz for FR2, the table shows the considered exact allocation bandwidths (ABWs). In addition to parameterizations stemming from [3], we have included also a few additional narrow allocations to provide further insight on UL CP-OFDM coverage performance. In FR1 the evaluations concentrate on 30 kHz SCS, which is seen to be the dominant operating mode of 5G NR. For FR2, we consider narrow allocations with 60 kHz and 120 kHz SCSs to address the UL coverage performance while also address full-band allocations to evaluate maximum throughput. The main reason for including similar bandwidth allocations with two SCSs in FR2 is to evaluate the effect of user mobility on the link performance with different DM-RS patterns.

TABLE I: Considered fixed reference channels for receiver sensitivity requirement evaluations at FR1 and FR2. ABW refers to the allocation bandwidth.

FR1 (ABW / number of PRBs / SCS)	FR2 (ABW / number of PRBs / SCS)
19.08 MHz / 106 PRBs / 15 kHz	8.64 MHz / 12 PRBs / 60 kHz
360 kHz / 1 PRB / 30 kHz	97.2 MHz / 135 PRBs / 60 kHz
2.16 MHz / 6 PRBs / 30 kHz	8.64 MHz / 6 PRBs / 120 kHz
18.36 MHz / 51 PRBs / 30 kHz	95.04 MHz / 66 PRBs / 120 kHz

In the performance evaluations, representative MCS index 4 with 5G NR LDPC channel code is assumed [7], which corresponds to QPSK modulation and target code rate $R = 308/1024$. The reference performance values obtained for LTE turbo codes are with QPSK modulation and target code rate $R = 1/3$ reflecting a fair comparison. It should be noted that the target code rates and transport block size definitions based on the number of layers and the total number of PRBs are different for each channel code as presented in [2] for 5G NR LDPC code and in [4] for LTE turbo code, respectively. A rate matching stage associates the encoded bits to the transport block and for each modulation order an effective code rate is calculated. Therefore, based on [2] and [4], the effective coding rate in the case of LDPC code is slightly lower than turbo code and it should be considered in the final performance comparisons. In general, two decoding algorithms are commonly considered for LDPC codes, namely, accurate believe-propagation algorithm building on the calculation of the marginal distributions which reflects the best performing LDPC decoder [9], and the min-sum iterative decoder algorithm widely accepted as a well performing, simpler LDPC decoder [10]. In 3GPP technical reports, e.g. [11], the LDPC min-sum decoder is typically defined as the feasible channel decoder for 5G NR and is thus used also in this work.

B. System Parameterization

The supported CP-OFDM numerologies in 5G NR [2] are based on scalable SCS according to 15×2^n kHz, where the scaling factor ensures aligned slots in the time domain. For FR1, 15 kHz, 30 kHz, and 60 kHz SCSs are currently supported while for FR2, 60 kHz and 120 kHz SCSs are currently endorsed as specified in [3] for FRCs. In this paper, 15 kHz and 30 kHz SCSs are assumed for 3.5 GHz carrier

TABLE II: Physical layer parameterizations for FR1 and FR2

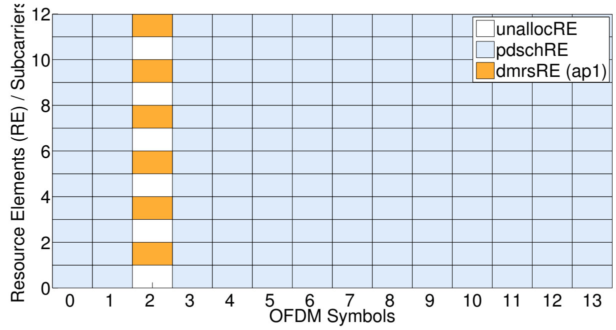
Parameter	FR1	FR2
Carrier frequency [GHz]	3.5	30
Channel model	TDL-C 300 and 1000	TDL-D 100 and 300
User equipment mobility [km/h]	3, 30, and 120	3, 30, and 60
Sub-carrier spacing [kHz]	15 / 30	60 / 120
Slot duration [ms]	1 / 0.5	0.25 / 0.125
FFT size	2048 / 1024	
CP length	144 / 72	
Modulation	QPSK	
Channel code	LDPC (5G NR) [2] Turbo code (LTE) [4]	
Antenna configuration	1 Tx $\times$ 1 Rx	
Waveform	CP-OFDM	
OFDM symbols per slot	14	
SCs per PRB	12	
DM-RS allocation density	1 or 2 per slot	
Channel estimation	Perfect or Practical	

frequency (modeling FR1 operation) with up to 20 MHz bandwidth, while 60 kHz and 120 kHz SCSs are considered for 30 GHz carrier frequency (modeling FR2 operation) with up to 100 MHz bandwidth. Normal slot transmission is evaluated, containing 14 OFDM symbols per slot for all SCSs. This indicates that the slot duration increases as SCS decreases, making higher SCSs more robust against time variations induced by high user velocities. Table II summarizes the exact link level characteristics and parameters assumed in this study.

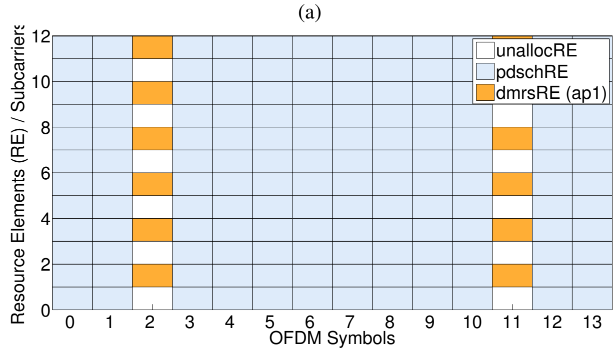
The normal slot can be parameterized to contain from 1 up to 4 OFDM symbols to allocate the DM-RS(s). In a recent RAN4 agreement [12], it was agreed to allocate two DM-RS symbols per slot boosted by 3dB for FRCs REFSENS evaluations, with no data allocated in the DM-RS symbols. In this paper, in addition to the agreed two DM-RS symbol pattern, a purely front-loaded pattern with only one DM-RS is also considered to evaluate the achievable radio link performance in several mobility scenarios. These two different DM-RS patterns are illustrated in Figure 1. We have also evaluated the performance with three and four DM-RS symbols, but using more than two DM-RS symbols did not provide any additional performance gain. Therefore, we focus in this paper on one and two DM-RS pattern configurations.

In the evaluations, we also assess the ideal channel knowledge (perfect CE) cases, for reference. In DM-RS based channel estimation, a minimum mean-squared error (MMSE) estimator is first utilized at the individual DM-RS symbols and the corresponding pilot subcarriers. Then, an additional Wiener filter is used across subcarriers as well as across DM-RS symbols (in case of two DM-RS design) which exploits the correlation of the channel in both frequency and time directions to improve the CE performance [13].

The exact REFSENS related radio link performance aspects are defined in 3GPP for plain AWGN channels. In this paper, we include such plain AWGN cases as baseline while also extend the evaluations by including several tapped-delay-line (TDL) fading channel models with varying user mobility. The used line-of-sight (LOS) model, TDL-D, and the non-line-of-sight (NLOS) model, TDL-C, are described in [14], and they can be used for both FR1 and FR2 and for user equipment (UE) speeds up to 500 km/h. In our evaluations, TDL-C channel



(a)



(b)

Fig. 1: Slot structures assumed for 5G NR evaluations illustrating front loaded reference symbol patterns with (a) 1 DM-RS symbol or (b) 2 DM-RS symbols.

model is assumed for FR1 with 300 ns and 1000 ns root-mean-squared (RMS) delay spreads. To have similar relative change in channel delay spread as in FR1, TDL-D channel model with RMS delay spreads of 100 ns and 300 ns are selected for FR2 concentrating on LOS evaluation.

III. 5G NR Reference Sensitivity Performance

In this section, the obtained 5G NR radio link performance results and the corresponding gNB Rx REFSENS results are presented and analyzed. All evaluations are performed using a 3GPP standardization compliant radio link simulator based on the agreed simulation assumptions in Release 15 [12]. Results are provided and analyzed with diverse OFDM numerologies, propagation channel models, coding schemes, DM-RS allocation densities and varying mobility conditions as described in the previous section. The obtained results are collected in Tables III and IV for FR1 and FR2 scenarios, respectively, showing SNR requirements for the 95^{th} percentile of the UL relative throughput performance. In addition, radio link block error rate (BLER) and maximum throughput performance in terms of SNR are addressed and discussed for selected scenarios. We note that also in plain AWGN cases, channel estimation is still carried out, i.e., the receiver does not know by default that it is operating in AWGN conditions.

A. FR1 Deployment Scenarios

In this section, the obtained link level performance results for sub-6 GHz band (FR1) presented in Table III are analyzed. Based on the results in Table III, we can observe for the LDPC based results that the 3GPP SNR target of -1 dB [7] in AWGN channel is achieved with 30 kHz SCS when using two DM-RS symbols, whereas with 15 kHz SCS there is a very minor

TABLE III: 5G NR link performance results with practical channel estimation for FR1 scenarios with one and two DM-RS symbols and both LDPC and turbo codes under different mobility conditions. The listed values represent the SNR values required to reach 95% of the maximum throughput in AWGN and fading channels (TDL-C). Ideal channel estimation results are shown in brackets.

			1 PRB, 30 kHz		6 PRBs, 30 kHz		51 PRB, 30 kHz		106 PRBs, 15 kHz	
			1 DM-RS	2 DM-RS	1 DM-RS	2 DM-RS	1 DM-RS	2 DM-RS	1 DM-RS	2 DM-RS
LDPC	AWGN		0,17 (-0,35)	0,12 (-0,31)	-0,04 (-1,37)	-0,56 (-1,39)	-0,42 (-2,00)	-1,01 (-2,01)	-0,34 (-1,91)	-0,92 (-1,91)
	TDL-C 300 ns	3 km/h	11,56 (10,23)	11,22 (10,54)	7,52 (6,57)	7,18 (6,62)	4,00 (3,19)	3,72 (3,24)	3,88 (3,19)	3,62 (3,10)
		30 km/h	11,55 (10,13)	11,29 (10,28)	7,74 (6,49)	7,02 (6,49)	4,17 (3,05)	3,76 (3,08)	4,76 (3,43)	4,05 (3,40)
		120 km/h	* (8,94)	10,33 (9,02)	* (5,95)	6,96 (5,90)	6,36 (2,91)	3,88 (2,85)	* (3,38)	4,48 (3,35)
	TDL-C 1000 ns	3 km/h	12,04 (8,53)	11,07 (8,67)	6,32 (4,20)	6,05 (4,22)	4,42 (2,70)	3,99 (2,67)	4.25 (2.75)	3.88 (2.69)
		30 km/h	11,69 (8,55)	11,45 (8,54)	6,62 (4,28)	5,95 (4,19)	4,55 (2,71)	4,01 (2,67)	5.09 (2.92)	4.42 (2.88)
		120 km/h	* (7,61)	10,84 (7,71)	* (3,95)	6,11 (3,90)	6,93 (2,5)	4,30 (2,43)	* (2.92)	4.75 (2.89)
Turbo	AWGN		-0,11 (-0,62)	-0,06 (-0,31)	-0,53 (-0,84)	-0,24 (-0,37)	-0,52 (-0,81)	-1,32 (-1,48)	-1,13 (-1,43)	-0,97 (-1,12)
	TDL-C 300 ns	3 km/h	10,56 (9,70)	10,79 (10,04)	7,88 (7,06)	8,33 (7,70)	5,12 (4,60)	4,06 (3,70)	4,33 (3,74)	4,59 (4,24)
		30 km/h	11,05 (9,66)	11,11 (10,19)	8,13 (7,11)	8,39 (7,61)	5,33 (4,59)	4,18 (3,69)	5,44 (3,99)	5.00 (4,47)
		120 km/h	* (8,21)	10,15 (8,71)	* (6,31)	8,13 (6,88)	8,27 (4,21)	4,36 (3,37)	* (3,90)	5,32 (4,40)
	TDL-C 1000 ns	3 km/h	11,28 (8.04)	11,12 (8.62)	7,07 (4,96)	7,27 (5,55)	5,72 (4,04)	4,59 (3,25)	4.53 (3.19)	4.71 (3.67)
		30 km/h	10,99 (8.05)	11,34 (8.54)	7,10 (4,85)	7,54 (5,50)	5,87 (4,03)	4,63 (3,16)	5.63 (3.41)	5.28 (3.79)
		120 km/h	* (6.99)	10,62 (7.58)	* (4,51)	7,44 (5,01)	8,9 (3,81)	4,82 (2,93)	* (3.39)	5.57 (3.76)

(*) Maximum theoretical throughput has not been reached for these channel conditions.

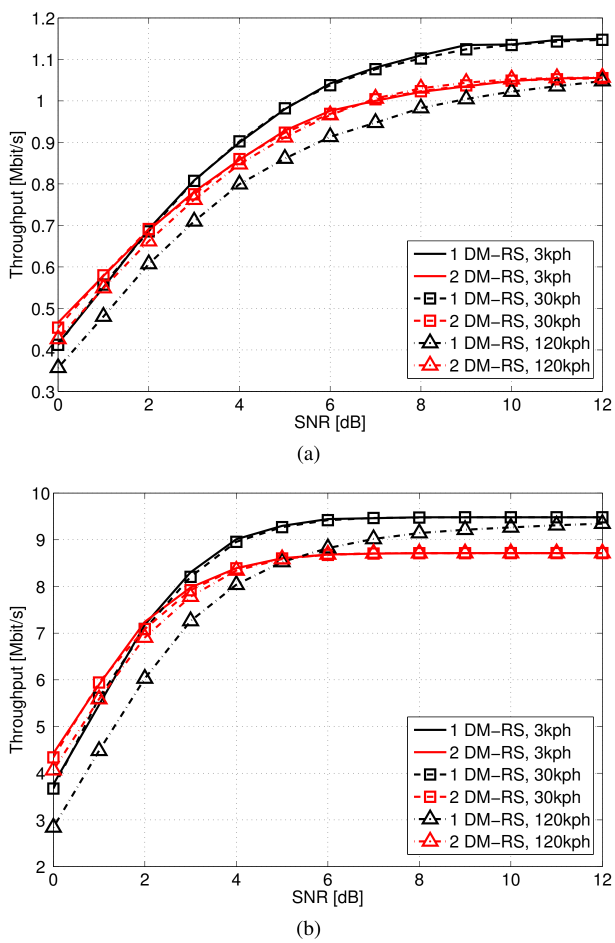


Fig. 2: 5G NR throughput performance at FR1 using LDPC coding scheme with practical CE and TDL-C NLOS 300 ns channel for 30 kHz SCS with (a) 6 PRBs and (b) 51 PRBs allocations.

gap as the observed SNR requirement is -0.92 dB. Narrow allocations (1 and 6 PRBs) require clearly higher SNRs to reach the 95^{th} percentile of the maximum throughput. In the frequency-selective channels, narrow allocations also do not achieve the maximum throughput in the case of 120 km/h with one DM-RS symbol, indicating that two DM-RS pattern is required for the coverage optimization. In addition, it is observed that the 6 PRBs allocation performs clearly better than 1 PRB case as it can benefit from the frequency-selective nature of the channel, implying that either 6 PRBs allocation should be used or frequency hopping for 1 PRB allocation with hop-distance corresponding to at least 6 PRBs should be used. With 51 PRBs allocation when using 30 kHz SCS, a front-loaded design with one DM-RS symbol is performing relatively well, emphasizing the wide range of velocities supported. On the other hand, with 15 kHz SCS, a clear performance degradation is observed already at 30 km/h, which is further accentuated at 120 km/h where at least two DM-RS symbols need to be used. This analysis thus shows that 30 kHz SCS can operate in wider range of mobility conditions, providing better performance in higher velocities with one or two DM-RS symbols compared to 15 kHz SCS. This is an important finding for practical deployments of 5G NR networks at FR1.

It can also be observed that the required SNR values in frequency-selective channels presented in Table III for LDPC coding scheme are consistently better than for turbo reference scheme, with significant differences especially in 6 PRBs allocation case and in high velocity (120 km/h) scenarios with 51 PRBs and 106 PRBs allocations, using 15 kHz SCS and 30 kHz SCS, respectively. Regarding the parameterization of the frequency-selective channel, different UE mobilities, and number of DM-RS symbols, similar trends are observed for turbo coded system as for LDPC coded system.

In general, it is important to note that the given 95^{th} percentile of the relative throughput results does not always correspond to the highest feasible throughput, and therefore directly comparing one and two DM-RS results is not trivial. In real networks, in general, link adaptation is used to determine the proper MCSs to provide the optimal throughput under different channel conditions. For the considered MCS index 4, the link performance for varying SNR with practical CE is shown in Figure 2 for 30 kHz SCS and in the cases of 6 and 51 PRBs. It can be observed that one DM-RS symbol provides the best actual throughput in TDL-C 300 ns RMS delay spread channel up to 30 km/h, while similar observations

TABLE IV: 5G NR link performance results with practical channel estimation for FR2 scenarios with one and two DM-RS symbols and both LDPC and turbo codes under different mobility conditions. The listed values represent the SNR values required to reach 95% of the maximum throughput in AWGN and fading channels (TDL-D). Ideal channel estimation results are shown in brackets.

			12 PRBs, 60 kHz		135 PRBs, 60 kHz		6 PRBs, 120 kHz		66 PRBs, 120 kHz	
			1DM-RS	2DM-RS	1DM-RS	2DM-RS	1DM-RS	2DM-RS	1DM-RS	2DM-RS
LDPC	AWGN		-0,2 (-1,74)	-0,80 (-1,77)	-0,40 (-1,92)	-0,83 (-1,94)	-0,05 (-1,40)	-0,55 (-1,40)	-0,40(-2,01)	-1,00(-2,11)
	TDL-D 100 ns	3 km/h	2,39 (1,00)	1,84 (0,95)	2,39 (0.89)	1,85 (0.92)	2,87(1,32)	2,22 (1,17)	2,63 (0,82)	1,87 (0,72)
		30 km/h	2,54 (0,90)	1,83 (0,87)	2,59 (1,15)	1,91 (1,12)	2,83 (1,29)	2,25 (1,22)	2,55 (0,85)	1,87 (0,75)
		60 km/h	2,87 (0,70)	1,81 (0,68)	2,85 (1,23)	1,82 (1,23)	2,93 (1,15)	2,22 (1,14)	2,49 (0,68)	1,84 (0,70)
	TDL-D 300 ns	3 km/h	2,4 (0,93)	1.86 (0,90)	2,00 (0,68)	1,60 (0,62)	2,82 (1,33)	2,26 (1,23)	2,28 (0,67)	1,71 (0,50)
		30 km/h	2,55 (0.84)	1.83 (0,62)	2,31 (0,80)	1,74 (0,78)	2,85 (1,27)	2,27 (1,19)	2,29 (0,59)	1,68 (0,47)
		60 km/h	2,85 (0.65)	1,79 (0,62)	3,12 (0,85)	1,92 (0,84)	2,91 (1,11)	2,23 (1,06)	2,38 (0,54)	1,68 (0,4)
Turbo	AWGN		-0,27 (-0,99)	-0,76 (-1,21)	-0,51 (-1,14)	-1,02 (-1,43)	-0,04 (-0,71)	-0,52(-1,27)	-0,02 (-0,85)	-1,00 (-1,61)
	TDL-D 100 ns	3 km/h	2,54 (1,8)	1,96 (1,64)	2,39 (1,77)	1,85 (1,42)	2.93 (1.95)	1.98 (1.38)	2.93 (1.99)	1.84 (1.13)
		30 km/h	2,59 (1,75)	1,91 (1,49)	2,8 (1,97)	2,02 (1,69)	2,98 (1,93)	1.98 (1.38)	3.03 (1.99)	1.85 (1.21)
		60km/h	2,85 (1,47)	1,82 (1,13)	3,73 (2,23)	2,32 (1,76)	3.04 (1,88)	1.95 (1.28)	3.32 (2.20)	1.82 (1.01)
	TDL-D 300 ns	3 km/h	2.54 (1.78)	1.94 (1.51)	2.11 (1.44)	1.65 (0.99)	2.94 (1.93)	1.93 (1.35)	2.78 (1.79)	1.72 (0.94)
		30 km/h	2,58 (1.68)	1.90 (1.42)	2,52 (1.69)	1.80 (1.28)	2.99 (1.9)	1.93 (1.28)	2.84 (1.81)	1.61 (0.90)
		60 km/h	2.82 (1,39)	1.82 (1.05)	3,26 (1,81)	1.94 (1.38)	3,00 (1.85)	1.95 (1.19)	2.97 (1.87)	1.57 (0.85)

were made also for 1000 ns RMS delay spread channel but not shown due to space limitations. The one DM-RS design is not purely optimal for high-speed scenarios, but the performance difference between one and two DM-RS designs is relatively small implying robust operation with one DM-RS design over the whole evaluated range of UE velocities.

B. FR2 Deployment Scenarios

Next, the FR2 deployment results shown in Table IV under varying mobility conditions for TDL-D LOS channel model with 100 ns and 300 ns RMS delay spreads are analyzed. Based on the presented results, only 66 PRBs allocation case with 120 kHz SCS achieves the 3GPP SNR target of -1 dB [7] in the AWGN channel with practical CE and two DM-RS symbols. As in FR1, the improvement in the practical CE performance in the AWGN channel with two DM-RS symbols is due to the larger number of reference signal samples in the Rx, leading to improved averaging gain in the CE process. Similar trend as for FR1 is observed for LDPC related performance results which are in general better than those of the turbo coded reference system when operating under frequency-selective channels. At large, the differences between different scenarios presented in Table IV are smaller than the ones observed for FR1 in Table III. This is due to the LOS channel model used in the FR2 evaluations. In addition, the difference between narrow and full CBW allocations are now smaller since the narrow allocations use 6 PRBs and 12 PRBs for 120 kHz and 60 kHz SCSs, respectively, compared to the single PRB case evaluated in FR1.

In FR2, the one DM-RS design works well over all evaluated channel profiles and UE velocities, again high-lighting the wide range of applicability of a purely front-loaded 5G NR slot design. It can also be observed that the one DM-RS design is within approximately 1 dB SNR gap when compared to two DM-RS design results. From Table IV, the effect of increased mobility on the relative performance difference between 60 kHz and 120 kHz SCSs starts to increase in the 60 km/h case when comparing 135 PRBs and 66 PRBs cases, respectively. The same phenomenon is observed also with turbo coded results. Based on our practical experience, this performance difference between 60 kHz and 120 kHz SCSs only increases as the UE velocity is further increased. In addition, in the evaluated LOS channels, the differences between different mobilities and RMS delay spreads are relatively smaller than those in FR1, making the overall variance between obtained

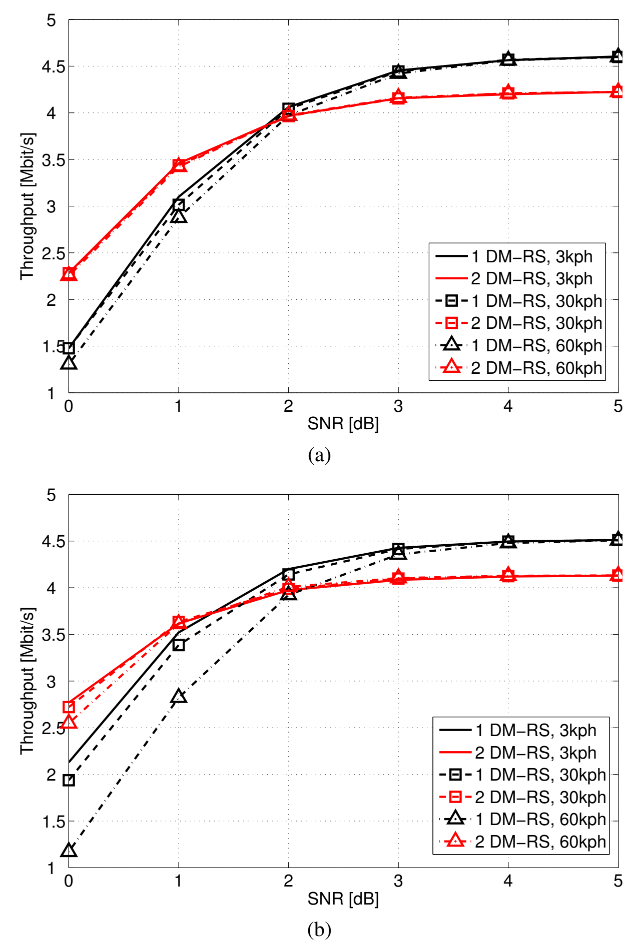


Fig. 3: 5G NR throughput performance at FR2 using LDPC coding scheme with practical channel estimation and TDL-D LOS 300 ns channel for (a) 120 kHz SCS with 6 PRBs allocation and for (b) 60 kHz SCS with 12 PRBs allocation.

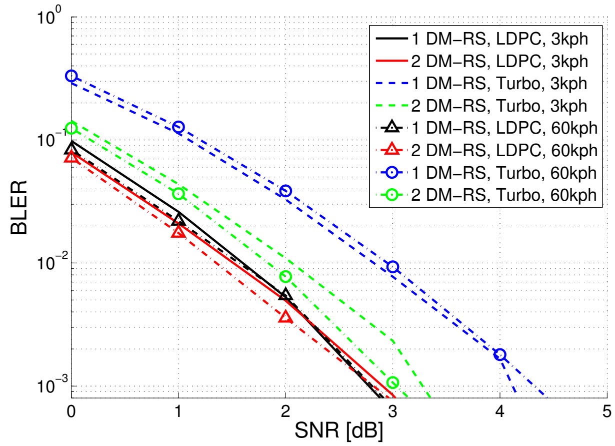


Fig. 4: 5G NR BLER performance at FR2 using LDPC and turbo codes with ideal channel estimation and TDL-D 300 ns LOS channel for 120 kHz SCS with 66 PRBs allocation.

SNR values smaller in FR2.

The FR2 link performance in terms of throughput vs. SNR with practical CE in TDL-D LOS 300 ns RMS delay spread channel is shown in Figure 3 for (a) 120 kHz SCS and 6 PRBs allocation case and (b) for 60 kHz SCS and 12 PRBs allocation case, with varying mobility conditions assuming LDPC channel code. The results indicate that one DM-RS design provides the best throughput performance up to 30 km/h with both SCSs, and with 120 kHz SCS the performance is similar even at 60 km/h UE velocity. With 60 kHz SCS, even though the actual throughput performance is degraded with one DM-RS design at 60 km/h UE velocity, the performance is still better than with two DM-RS design for SNR values above 2 dB. Thus despite the high center-frequency (30 GHz) and substantial UE velocity (60km/h), single DM-RS based system performs very well, especially with 120 kHz SCS.

Finally, example BLER results are shown for LDPC and turbo codes in Figure 4 for the case of 120 kHz SCS and 66 PRBs allocation case, assuming ideal CE in TDL-D 300 ns LOS channel. It can be observed that LDPC coding scheme gives consistent link BLER performance for both DM-RS densities and varying mobility conditions while turbo code performance varies more significantly, with a performance gap of approximately 0.8 dB between one and two DM-RS symbol designs. This is because the NR LDPC rate matching can provide more consistent code rate compared to the LTE turbo rate matching, for varying PRB and DM-RS allocations.

IV. Conclusion

In this paper, extensive uplink receiver reference sensitivity and radio link performance analysis for 3GPP 5G NR Release 15 was carried out. Several parameters affecting the UL radio link performance were considered, including different subcarrier spacings and allocation bandwidths, different DM-RS patterns, and user mobilities, covering both sub-6 GHz and millimeter-wave frequency ranges. The performance analysis focused on 5G NR LDPC coding scheme while for comparison purposes also LTE turbo coded results were presented.

The evaluations and comparison of NR reference sensitivity was mainly based on the SNR values required to achieve 95% of the relative throughput in different scenarios. It was shown that in frequency-selective channels, the required SNRs are consistently lower for LDPC coding scheme than for turbo coded cases. In addition, it was observed that LDPC provides more consistent link BLER performance for both evaluated DM-RS patterns and varying mobility conditions, while turbo coded performance varies considerable due to the differences in the rate matching.

It was also shown that while the reference sensitivity evaluations are defined at the 95^{th} percentile of the relative throughput, they do not necessarily correspond to the maximum achievable throughput. The results indicate that the best actual throughput performance is achieved with the front-loaded, single DM-RS design over a wide range of channel conditions and user velocities. This indicates that the front-loaded DM-RS design available in 5G NR is able to operate efficiently in wide range of scenarios for sub-6 GHz and millimeter-wave carrier frequencies while enabling low latency communications and highly efficient pipelined receiver processing.

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