Uplink Transmission Schemes for 5G NR Unlicensed: Design Principles and Achievable Performance

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***Abstract*—In this paper, we address and analyze different uplink (UL) transmission schemes for the 5G New Radio (NR) deployments at unlicensed spectrum. Specific emphasis is on the new NR-unlicensed (NR-U) wideband physical random access channel (PRACH) under short preamble formats as well as on the base-station receiver sensitivity requirements for the fixed reference channels. In general, in order to comply with ETSI regulations, the UL waveform resource allocation has been revised in NR-U. On one hand, the bandwidth (BW) of the PRACH sequences has been increased according to numerology, which based on the performance analysis presented in this paper provides a substantially improved detection performance while fulfilling the coverage requirements of Rel-15 preambles. On the other hand, the physical uplink shared channel (PUSCH) resource allocation is based on block interlace frequency division multiple access (B-IDFMA). This design is characterized by the number of interlaces allocated within the transmission BW and it should be properly defined for the multiple physical layer numerologies supported in NR systems. The NR-U PUSCH performance results provided in this paper show that the B-IFDMA design yields the best performance for the case of one interlace allocation compared to contiguous resource allocation for all numerologies. Additionally, it is shown that the non-B-IFDMA PUSCH design outperforms the NR-U design for larger number of allocated interlaces. There is thus a trade-off between the frequency diversity gain achieved by the sparse PRB distribution in NR-U and the corresponding channel estimation challenges impacting the demodulation performance.**

Keywords*—5G New Radio (NR), NR-U, unlicensed spectrum, physical layer design, wideband PRACH, block interlaced waveform, channel estimation, PUSCH

I. Introduction

The fifth generation new radio (5G NR) mobile networks are expected to facilitate diverse use cases and services while supporting operation and deployments on various different types of frequency bands. Specifically, based on the latest 3rd generation partnership project (3GPP) specifications in Rel-16 [1], 5G NR mobile networks can operate also in unlicensed spectrum – referred to as NR-unlicensed, NR-U – allowing cellular networks to harness more spectrum from the unlicensed bands. The operation in unlicensed bands results in reduced cost compared to licensed bands while increasing the network capacity, especially in small cell deployments. The initial focus is on the sub-7GHz unlicensed bands as described in the 3GPP work item [2]. More specifically, NR-U deployments in the 5 GHz and 6 GHz unlicensed bands have been considered in Rel-16 discussions while the extension to the 60 GHz band is being considered in Rel-17. The agreements are in line with long term evolution (LTE) standards for unlicensed bands, the so-called licensed-assisted access (LAA). In the NR-U study item [1], several unlicensed bands (such as 2.4, 3.5, 5 and 6 GHz) have been considered with some bands being available globally while some others are restricted and only available in some specific regions [3]. Besides, sub-1GHz unlicensed bands are essentially out of the scope of the study item due to the lack of spectrum in the band to support efficient NR-U operation. The main difference between LTE-LAA and NR-U is that the latter supports three deployment modes. In addition to the carrier aggregation, which is similar to LTE-LAA, NR-U supports dual connectivity and standalone modes introduced in later releases, namely, extended LAA (eLAA) and MulteFire [4]. To this end, standalone NR-U deployment does not require anchor to any licensed carrier and opens up the possibility to operate private networks in Industry 4.0 applications such as factory automation or mission-critical services [5], [6].

A. NR-U Basics and Regulatory Aspects

There are several technical challenges to be addressed and resolved in order to enable cellular networks to operate in unlicensed spectrum. On one hand, fair coexistance with other radio access technologies is required, such as Wi-Fi. For that purpose, the use of listen-before-talk (LBT) mechanisms allows multiple devices to sense the channel before accessing it and, therefore, be able to use the same channel without prior coordination. Coexistence performance studies have been performed in 3GPP as documented in [1], and the evaluations conclude that when the appropriate channel access schemes are defined, it is feasible for NR-U to achieve fair coexistence with Wi-Fi. On the other hand, the operation in unlicensed bands should fulfill regulatory requirements. In this context, LTE was designed to operate in licensed bands and extended afterwards to unlicensed bands with asynchronous operation. Different to LTE development, the ongoing NR-U standardization activities can take these requirements into account since the beginning. Hence, NR-U can be well designed for efficient operation in unlicensed bands, allowing efficient integration into 5G NR systems. This is the main technical scope of this paper, with specific focus on the involved physical channels and feasible physical layer enhancements and the corresponding achievable performance.

In general, the NR-U design principles [2] are not limited to a particular band, while from the physical layer perspective, the basic NR technology is serving as the baseline. Various potential design enhancements can then be considered and studied for the involved physical channels for improved support of the unlicensed operation. Based on the European Telecommunications Standards Institute (ETSI) regulations [7], the nominal channel bandwidth (NCB) is the widest band of frequencies (inclusive of guard bands) assigned to a single channel, while the occupied channel bandwidth (OCB) is the bandwidth containing 99% of the signal power. Furthermore, the OCB shall be between 80% and 100% of the NCB and therefore, the resource allocation should be redesigned for NR-U similar to LTE-LAA. In this regard, a block interlace frequency division multiple access (B-IFDMA) allocation for uplink (UL) resources was introduced in LTE-LAA to fulfill OCB requirements and it is taken also as the starting point for NR-U design [1]. This applies specifically to the UL waveform design for data, control or random access channels (PUSCH, PUCCH and PRACH, respectively). In this paper, we address different UL transmission schemes in NR-U context, focusing on the reference sensitivity requirements for B-IFDMA based PUSCH and the corresponding resource allocation as well as on the requirements and processing methods for wideband PRACH schemes.

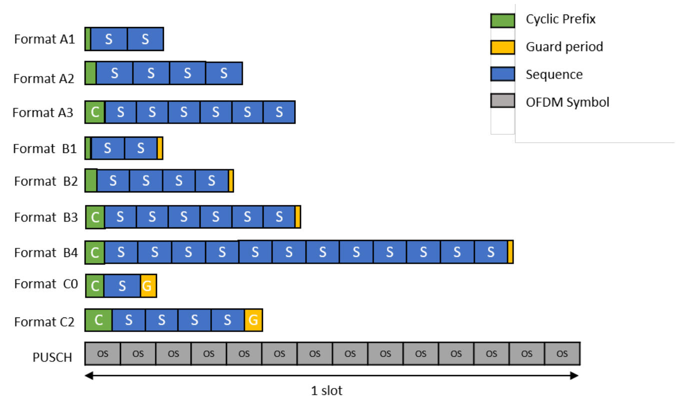


Fig. 1: Overview of the time domain structure for all short PRACH preamble formats within one slot (adapted from [12]).

B. Technical Scope and Contributions

The design of B-IFDMA resource allocation is characterized by the number of interlaces and the number of physical resource blocks (PRB) allocated within the channel bandwidth (BW). Unlike LTE, NR supports a large number of numerologies based on the transmission BW and subcarrier spacing (SCS), thus requiring a B-IFDMA design per numerology [8]. In order to satisfy the minimum 80% of OCB requirements, the larger the SCS, the more restrictive the interlace design. In particular, the transmission bandwidth configurations for different frequency ranges can be found in [9]. For example, the number of PRBs for a 20MHz channel bandwidth correspond to 106, 51 and 24 PRBs for SCS values of 15, 30 and 60kHz, respectively. Therefore, the maximum number of interlaces to satisfy the minimum OCB requirements will be 10, 5 and 2 for each SCSs, respectively. In addition, several bandwidth parts (BWPs) may be specified in NR as the carrier BW can go up to 400 MHz according to the specifications [9]. As described in [10], a UE could support multiple BWP operations and the size of the BWP can be used to define the exact interlace pattern according to the numerology. Under these premises, we address and analyse in this study the 5G NR-U UL receiver sensitivity performance considering different transmission BWs and PRB allocations sizes. In addition, the receiver processing framework to enable B-IFDMA design in NR-U is described and analysed as well as its impact on the demodulation performance with respect to normal NR operation. The obtained performance results indicate that there is a clear trade-off between the performance gain obtained from the frequency diversity and the corresponding channel estimation challenges impacting the demodulation performance.

Additionally, the NR PRACH formats have been also revised in order to comply with the minimum OCB requirements defined by ETSI regulations [1]. In this regard, there are two different sequence lengths supported in NR – a long sequence (L=839) that is designed for large cell deployments in FR1 (1.25 or 5 kHz SCS), and a short sequence (L=139) that is designed for small cell deployments in FR1 (15 or 30 kHz SCS) and generally for FR2 (60 or 120kHz SCS). As large cells are not expected to be common in NR-U deployments, it has been identified that the long PRACH sequences are not beneficial for NR-U operation. In regard to short PRACH sequences, there are several methodologies considered in 3GPP to increase the bandwidth. At first, uniform and non uniform block interlace mapping structures were proposed while in NR Rel-16, non-interlaced mapping has been selected for this purpose. To this end, the two new wideband PRACH transmission schemes are addressed and analysed in this paper, and the obtained improved detection performance results presented in the paper highlight the robustness of these sequences while providing similar coverage as legacy Rel-15 preambles. These are important technical findings and new insight for the first practical deployments and optimization of 5G networks operating at unlicensed bands.

The rest of the paper is organized as follows: Section II presents the random access transmission scheme in NR-U together with the system paramaterization and receiver detection aspects. Section III presents the PUSCH transmission design in NR-U, including also the considered reference channels for different scenarios. Additionally, the system paramaterization and the corresponding B-IFDMA physical channel design in NR-U are described. Then, in Section IV, the NR-U PRACH and PUSCH performance evaluation results are provided and analysed. Finally, in Section VII, the conclusions of this study are drawn.

II. NR-U Random Access Transmission Scheme

A. NR-U PRACH

The PRACH design for NR operation at licensed spectrum is described in [11]. The bandwidth of the short sequence is defined according to numerology, i.e., the bandwidth of the PRACH preamble corresponds to 2.08 MHz and 4.17 MHz for SCS values of 15kHz and 30kHz, respectively. In order to meet the OCB requirements at unlicensed spectrum, the sequence can be repeated in frequency domain – or as finally agreed and captured in [11], two new wideband PRACH preamble formats are used and supported in NR-U. The bandwidth of the new sequences is increased up to 17.27 MHz, which meets the OCB requirements for a 20MHz NCB for sequence lengths of 1151 and 571 with 15kHz and 30kHz SCS, respectively.

B. Operation and System Parameterization

Upon successful decoding of the system information transmitted by the base station (gNB), the user equipment (UE)

TABLE I: Considered 5G NR physical layer parameterization

General Parameters	
Carrier frequency [GHz]	5
Sub-carrier spacing [kHz]	15, 30
Channel model	TDL-A DS = 30ns, TDL-C DS = 300ns
Antenna configuration	1 Tx $\times$ 2 Rx
PUSCH Parameters	
Channel Bandwidth (MHz)	20, 40, 60
Slot duration [ms]	0.5, 1
UE velocity [kph]	3
Waveform	CP-OFDM
DMRS configuration	Type A
DMRS allocation density	2 per slot
MCS	QPSK, R=193/1024
Channel estimation	Realistic
PRACH Parameters	
Channel Bandwidth (MHz)	20
PRACH preamble format	[A1, A2, A3, A4, B1, B2, B3, B4, C2]
Zadoff-Chu sequence	L=1151, N_{cs}=164 (SCS = 15kHz) L=571, N_{cs}=190 (SCS = 30kHz)

performs the random access procedure to achieve UL synchronization. The UE transmits a RACH preamble to the gNB, which is randomly selected from a maximum of 64 available preambles [11]. There are multiple preamble formats comprising of one or more PRACH OFDM symbols. An overview of the time domain structure of the short PRACH formats (A1, A2, A3, B1, B2, B3, B4, C0, and C2) is shown in Figure 1, where the length of the cyclic prefix, the number of sequence repetitions and guard period duration (if any) are described and noted.

In this study, the performance requirements are analysed to support a wideband NR-U PRACH for all preamble formats. The random access preambles are generated from CAZAC codes known as Zadoff Chu (ZC) sequences. Therefore, they have a constant amplitude and their autocorrelation with a cyclically shifted version of itself with N_{cs} samples is zero. A ZC sequence that has not been shifted is known as a root sequence. Hence, different preambles are generated from one or several root sequences by applying cyclic shifts. The detailed base sequence generation algorithm is summarized in [11]. In this study, the number of N_{cs} samples of the cyclic shift are chosen to keep an equivalent cell size and coverage to baseline NR Rel-15 PRACH preambles, i.e., N_{cs}=164 and N_{cs}=190 are chosen for SCS values of 15kHz and 30kHz, respectively. Table I summarizes the exact link level assumptions used in the upcoming evaluations and performance assessments.

C. Detection

The basic processing approach of the detection algorithm is to exploit the correlation properties of the ZC sequences based on a window-based detection algorithm, after a sequence correlation in the frequency domain against a local replica of the preamble sequence. The window length is defined according to the number of N_{cs} samples of the cyclic shift used to generate one preamble from each root sequence. Utilizing empirically chosen thresholds, the transmitted preamble index is decided based on the index of the detection window exceeding the detection threshold and the position of the correlation peak is used to estimate the uplink timing advance (TA).

It should be highlighted that the wider NR-U PRACH sequences allow for more precise TA estimation. In this context, the time error tolerance requirements for Rel-15 PRACH are defined in [9]. To this end, time error tolerances of 0.48us and 0.24us can be obtained for $\kappa = 64$, and $T_c = 0.509$ ns under AWGN channel conditions, when considering 15kHz ($\mu = 0$) and 30kHz ($\mu = 1$) SCS values, respectively. However, the tolerance is indicated in multiples of the TA command resolution as $16 \cdot \kappa \cdot T_c/2^{\mu}$ [13], which implies that time error tolerances of 0.52us and 0.26us are eventually defined for 15kHz and 30kHz, respectively. Increasing the sequence length from 139 to 1151 or 571 for different SCS values could result in an increase of the TA accuracy with a time error tolerance of 0.06 us (i.e., 8 and 4 times smaller for each SCS, respectively). However, this will result in a time error tolerance requirements below the TA command resolution and therefore, the time error tolerance requirements for NR Rel-15 PRACH are taken as the baseline in this study.

III. NR-U Data Channel Transmission Scheme

A. NR-U PUSCH

The UL resource allocation in NR-U PUSCH is based on B-IDFMA design to comply with ETSI regulations. The interlace design is defined based on the transmission BW and SCSs. As described in [11], multiple interlaces indexed with $m \in \{0, 1, ..., M-1\}$ can be defined, where the number of interlaces M is defined per numerology. In particular, the separation between two consecutive resources is defined for 15 and 30 kHz SCS, where the separation between consecutive PRBs for the same interlace corresponds to $M = 5$ and $M = 10$, respectively. Each interlace is therefore composed of a subset of N allocated PRBs within the defined bandwidth, indexed as $N \in \{m, M+m, 2M+m, 3M+m, \dots\}$. The extension to FR2 has not been standardized, yet, as the larger the SCS, the more restrictive the interlace design. However, the interlaced-based design can be scaled according to the numerology following the same described design principles [14].

It should also be noted that the number of available PRBs per transmission BW can not always be divided by the number of interlaces M. Therefore, the remaining PRBs could be used in the first interlaces to avoid wasting resources. For example, for a 15kHz SCS ($M = 10$), the number of PRBs within 20 MHz BW is 106. Therefore, the first interlaces could occupy $N = 11$ PRBs while the rest could occupy $N = 10$ PRBs within the transmission BW. In this study, for simplicity, all interlaces are considered to have same number of PRBs. Additionally, three configurations are considered and evaluated corresponding to one ($m = 0$), two ($m \in \{0, 1\}$) and four consecutive interlaces ($m \in \{0, 1, 2, 3\}$) allocated for a single UE, respectively.

B. NR-U Fixed Reference Channels

The fundamental radio receiver characteristics, such as dynamic range and the reference sensitivity requirements for the wanted signal are defined in [15]. In this study, we focus on the reference sensitivity requirements to analyse the achievable demodulation performance and the corresponding impacts of the NR-U physical channel design. To this end, the reference

TABLE II: Fixed reference channels (FRCs) for receiver sensitivity requirement assessment. The allocated RBs are uniformly spaced over the channel bandwidth at RB indeces of $\{m, M+m, 2M+m, 3M+m, \dots\}$.

Transmission configuration (BW / PRBs / SCS)	Interlace allocation (M, m, N)
20MHz / 106 PRBs / 15kHz	10 / [0,...,9] / 10 PRBs
20MHz / 51 PRBs / 30kHz	5 / [0,...,4] / 10 PRBs
40MHz / 216 PRBs / 15kHz	10 / [0,...,9] / 21 PRBs
40MHz / 106 PRBs / 30kHz	5 / [0,...,4] / 21 PRBs
60MHz / 162 PRBs / 30kHz	5 / [0,...,4] / 32 PRBs

sensitivity requirements are defined 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:

$$\mathrm{P_S} = -174\mathrm{dBm} + 10\log_{10}(\mathrm{BW}) + \mathrm{N_F} + \mathrm{I_M} + \mathrm{SNR} \quad (1)$$

where $\mathrm{N_F}$ is the base station noise figure, assume to be 5 dB, 10 dB or 13 dB for Wide Area BS, Medium Range BS, or Local Area BS, respectively, $\mathrm{I_M}$ is the implementation margin equal to 2 dB, and SNR is the value for which 95% of the maximum throughput is reached [15]. We focus our performance analysis on few representative, so-called fixed reference channels (FRCs) according to 3GPP specifications [9], see Annex A1 and A2, where a transmission scheme using QPSK is chosen. We then analyse the performance difference considering different transmission BWs and therefore, different PRB allocation sizes. The PRBs are uniformly spaced over the channel bandwidth and exact RB indexes are described in Table II. Additionally, the B-IDFMA design in NR-U can impact the demodulation performance compared to contiguous data allocation on PUSCH. Therefore, in addition to the FRCs described in Table II, the performance difference between interlaced and contiguous allocation is presented in this study, aiming to assess and verify the potential gains obtained from the increased frequency diversity of the NR-U PUSCH design and the possible negative impacts due to the associated channel estimation challenges.

C. System Parameterization and Assumptions

Normal slot transmission is considered, containing 14 OFDM symbols per slot for all SCSs. The slot configuration contains two OFDM symbols to allocate the demodulation reference signal (DMRS) pilots. The DMRS occupies 6 resource elements (REs) per PRB where the pilots are allocated every second RE while the rest of the REs are reserved with no data allocated. In the performance assessments, a practical Wiener filter [16] is used to estimate the channel response based on the DMRS pilots. In this case, a minimum mean-squared error (MMSE) estimator is first utilized at the individual DMRS symbols and the corresponding pilot subcarriers. Then, a Wiener filter is used across subcarriers as well as across DMRS symbols to exploit the correlation of the channel in frequency and time directions. In addition, we consider several tapped-delay-line (TDL) fading channel models, specifically, the non-line-of-sight (NLOS) models, TDL-A and TDL-C, with 30 ns and 300 ns root-mean-squared (RMS) delay spread, respectively. The first refers to an indoor hotspot scenario and the second refers to a large rural deployment scenario. The distance between allocated PRBs can be larger than the coherence BW of these channels and therefore the frequency diversity will play an important role in the achievable performance. Table I summarizes the exact link level assumptions used in the upcoming performance assessments.

D. Channel Estimation for PUSCH Demodulation

As described in previous sections, a practical Wiener filter is used to estimate the channel response. At first, the channel response is estimated in the frequency direction for the OFDM symbols carrying the DMRS. Then, interpolation in the time direction is performed to obtain the channel estimate for the rest of the subframe. To lay the basics, the received signal vector $\mathbf{y}$ can be first defined as follows:

$$\mathbf{y} = \mathbf{Hs} + \mathbf{n} \quad (2)$$

where $\mathbf{H}$ is the channel matrix, $\mathbf{s}$ is the transmitted signal, and $\mathbf{n}$ is the noise vector with variance σ^2, respectively. In order to minimise the MMSE for each sample in the Wiener filter estimator, i.e $\mathbf{e} = \mathbf{y} - \hat{\mathbf{y}}$, the linear estimator can be defined as:

$$\hat{\mathbf{y}} = \mathbf{Bx} \quad (3)$$

where the samples $\hat{\mathbf{y}}$ are estimated based on the pilot channel measurements $\mathbf{x}$. The Wiener equation can be defined as:

$$E\{\mathbf{yx^H}\} = E\{\mathbf{Bxx^H}\} \rightarrow \mathbf{R_{yx}} = \mathbf{BR_{xx}} \quad (4)$$

and the estimation matrix solved as:

$$\mathbf{B} = \mathbf{R_{yx}}\mathbf{R_{xx}^{-1}} \quad (5)$$

Focusing on the channel estimation in frequency direction per OFDM symbol, every second RE is a pilot according to the DMRS pattern. Therefore, the channel at other positions has to be interpolated from the pilot measurements. The basic processing approach is to use several consecutive PRBs. Based on previous studies analyzing the receiver reference sensitivity requirements for contiguous PRB allocation in NR bands [17], a filter bandwidth of 5-PRB is chosen for the Wiener estimator. The channel measurements are given at frequency positions f for the 30 pilots and hence, the auto-correlation matrix can be defined as follows:

$$\mathbf{R_{xx}^{(5PRB)}} = \begin{bmatrix} R_H(0)+\sigma^2 & R_H(-2\Delta f) & ... & R_H(-58\Delta f) \\ R_H(2\Delta f) & R_H(0)+\sigma^2 & ... & R_H(-56\Delta f) \\ ... & ... & ... & ... \\ R_H(58\Delta f) & R_H(56\Delta f) & ... & R_H(0)+\sigma^2 \end{bmatrix} \quad (6)$$

where $R_H(f)$ is the frequency auto-correlation of the channel transfer function and Δf is the OFDM carrier spacing as defined in [16].

Based on the assumed filter BW, the number of interpolated samples in the Wiener estimator is defined by a 5-PRB pilot window shift. An example of this process is illustrated in Fig. 2 for a 20 MHz BW. However, due to the B-IFDMA design in NR-U, there is a limitation on the filter BW for the Wiener estimator. The amount of pilots available within the coherence BW of the channel may be impacted and the attenuation and phase shift can be different between pilots from different PRBs. Therefore, a filter BW of 1-PRB is chosen for the Wiener estimator to perform channel estimation over a single PRB at a time in the NR-U scenarios. In this case,

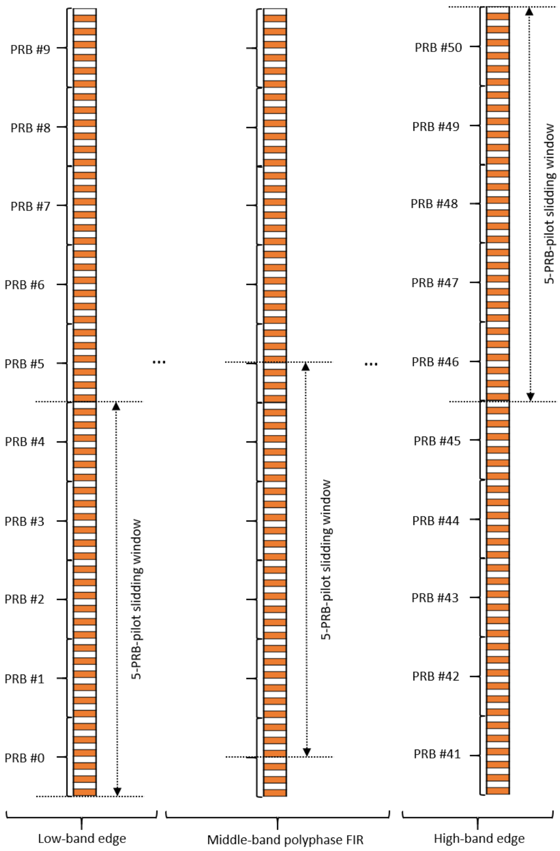


Fig. 2: Frequency domain Wiener estimator interpolation for a 5-PRB pilot window in an example 20MHz bandwidth case. Processing illustrated for the low band edge, middle-band polyphase FIR filtering and high-band edge.

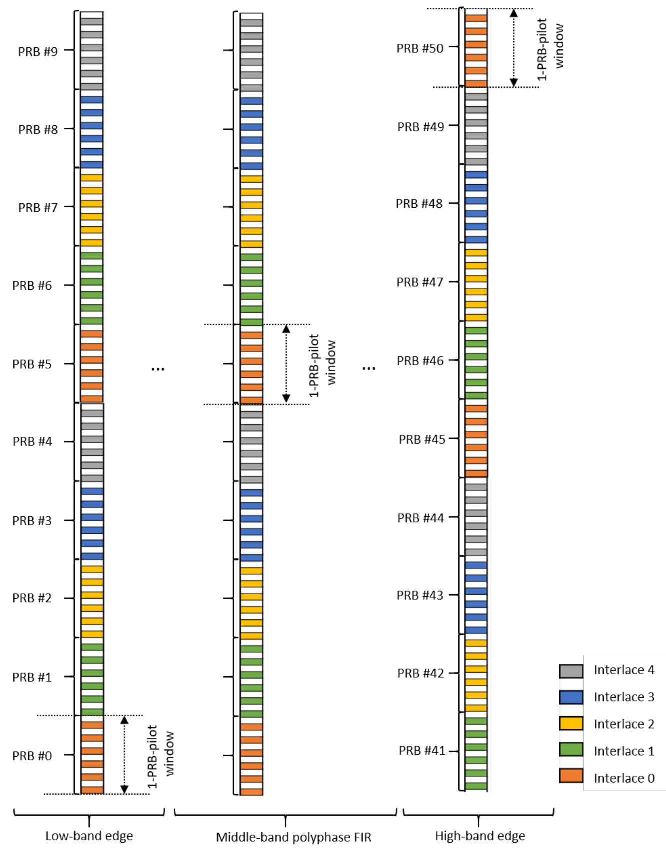


Fig. 3: Frequency domain Wiener estimator interpolation for one interlace resource allocation per UE in NR-U in an example case with 20MHz bandwidth and 30KHz SCS. Processing illustrated for the low band edge, middle-band polyphase FIR filtering and high-band edge.

there are 6 pilots for a 1-PRB Wiener estimator. The channel measurements are given at frequency positions for the 6 pilots and, therefore, the auto-correlation matrix can be defined as:

$$\mathbf{R}_{\mathbf{xx}}^{(\mathbf{1PRB})} = \begin{bmatrix} R_H(0)+\sigma^2 & R_H(-2\Delta f) & \dots & R_H(-10\Delta f) \\ R_H(2\Delta f) & R_H(0)+\sigma^2 & \dots & R_H(-4\Delta f) \\ \dots & \dots & \dots & \dots \\ R_H(10\Delta f) & R_H(4\Delta f) & \dots & R_H(0)+\sigma^2 \end{bmatrix} \tag{7}$$

A graphical illustration of the Wiener estimation defined by a 1-PRB pilot window shift is illustrated in Fig. 3 for an example case of 20 MHz BW and 30kHz SCS. Therefore, there are 51 PRBs available within the transmission BW and the separation between consecutive PRBs for the same interlace corresponds to $M = 5$. The same logic can be applied for the rest of FRCs considered and analysed in this study.

IV. Performance Results and Analysis

In this section, large collections of performance evaluation results are provided and analysed. The results focus on the SNR requirements to achieve a target miss-detection probability of 1% under a given false alarm target of 0.1% for the new wideband PRACH preambles, on one side, and on the receiver sensitivity requirements for the UL data channel (PUSCH) at the gNB, on the other side. All evaluations are performed using a 3GPP 5G NR standardization compliant radio link simulator based on the agreed simulation assumptions in Rel-16 study items.

A. PRACH Results

In order to fulfil the minimum of 80% OCB requirements and aiming to allow larger transmit power, the two new enhanced PRACH sequences with an increased BW transmission have been evaluated considering only short preamble formats. The corresponding SNR requirements to achieve a target detection probability of 99% (or miss-detection probability of 1%) are provided in Table III for the wideband PRACH preambles considered in NR-U (L=1151 or 571 for 15kHz and 30kHz, respectively). In addition, the SNR requirements for NR Rel-15 short PRACH preambles (L=139) are captured for comparison purposes. In this case, the detection probability is defined as the probability of detecting a transmitted preamble with the correct timing estimate while the false alarm probability is defined by the ratio of detecting a non-transmitted preamble (e.g incorrect preamble or wrong timing estimation) and the total number of possible detection occurrences. Besides, there is a trade-off between the achievable performance and the detection threshold. Therefore, an empirical detection threshold was defined to keep the false alarm rate below the target of 1% for all cases evaluated.

The results presented in this study for the legacy Rel-15 PRACH sequences in terms of SNR values are comparable to

TABLE III: Link performance results for the new wideband PRACH preamble designs for NR-U operation (L=1151 or 571 for 15kHz and 30kHz, respectively) compared to legacy Rel-15 preambles (L=139). The listed values represent the SNR values (dB) required to reach 99% detection probability (under 1% false alarm rate) under different channel conditions (AWGN, TDL-A DS = 30ns and TDL-C DS = 300ns).

PRACH Format	SCS	AWGN		TDL-A		TDL-C	
		Wideband	Rel-15	Wideband	Rel-15	Wideband	Rel-15
Format A1	15 kHz	-21.10	-12.74	-16.03	-6.49	-14.93	-5.39
	30 kHz	-18.12	-12.57	-12.56	-6.81	-11.67	-5.92
Format A2	15 kHz	-23.96	-15.71	-18.87	-9.51	-17.61	-8.26
	30 kHz	-21.20	-15.55	-15.60	-9.79	-14.63	-8.82
Format A3	15 kHz	-25.61	-17.06	-20.39	-10.79	-19.22	-9.62
	30 kHz	-22.92	-16.88	-17.21	-11.24	-16.32	-10.35
Format B1	15 kHz	-21.09	-12.69	-16.09	-6.64	-14.79	-5.35
	30 kHz	-18.26	-12.56	-12.66	-7.01	-11.71	-6.06
Format B2	15 kHz	-23.95	-15.59	-19.09	-9.42	-17.81	-8.14
	30 kHz	-21.23	-15.58	-15.52	-9.79	-14.68	-8.95
Format B3	15 kHz	-25.55	-17.00	-20.50	-11.06	-19.21	-9.77
	30 kHz	-22.90	-16.86	-17.22	-11.19	-16.38	-10.35
Format B4	15 kHz	-27.38	-19.77	-22.33	-13.64	-21.06	-12.37
	30 kHz	-25.63	-19.62	-19.92	-13.85	-19.07	-13.01
Format C0	15 kHz	-24.40	-16.02	-18.38	-9.03	-18.01	-8.66
	30 kHz	-21.62	-16.00	-14.51	-10.01	-15.08	-9.58

TABLE IV: Link performance results with non-B-IFDMA design for NR bands and B-IFDMA design for NR-U operation for a 5- and 1-PRB pilot window shift (w) in the Wiener channel estimator. The listed values represent the SNR values (dB) required to reach 95% of the maximum throughput under different channel conditions (TDL-A DS = 30ns, TDL-C DS = 300ns).

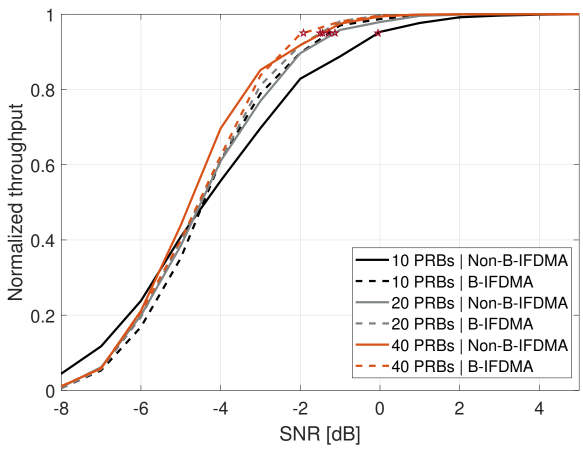
			TDL-A DS = 30ns			TDL-C DS = 300ns		
			Non-B-IFDMA		B-IFDMA	Non-B-IFDMA		B-IFDMA
BW	SCS	Alloc.	w = 1	w = 5	w = 1	w = 1	w = 5	w = 1
20 MHz	15 kHz	10 PRB	2.4	1.2	0.5	0.8	-0.3	-1.3
		20 PRB	2.1	0.9	0.1	-0.4	-1.4	-1.5
		40 PRB	1.2	-0.2	0.4	-1.4	-2.5	-1.6
	30 kHz	10 PRB	2.2	1.4	0.4	0	-0.8	-1.3
		20 PRB	1.6	0.2	0.4	-1.1	-2.1	-1.5
		40 PRB	0.2	-0.6	0.2	-1.4	-2.6	-1.9
40 MHz	15 kHz	21 PRB	2.0	1.0	0	-0.4	-1.5	-1.7
		42 PRB	1.1	-0.3	0.2	-1.4	-2.6	-1.8
		84 PRB	0.7	-0.7	0.1	-1.7	-3.0	-1.7
	30 kHz	21 PRB	1.5	0	-0.5	-1.1	-2.1	-1.7
		42 PRB	0.5	-0.6	-0.2	-1.5	-2.5	-1.6
		84 PRB	-0.3	-1.3	-0.4	-1.7	-2.7	-1.7
60 MHz	30 kHz	32 PRB	0.7	-0.2	-1.0	-1.5	-2.3	-2.1
		64 PRB	-0.1	-1.0	-0.9	-1.8	-2.7	-2.0
		128 PRB	-0.4	-1.6	-0.8	-1.9	-3.0	-1.9

the minimum SNR requirements captured in [9] for AWGN and TDL channel profile in NR operation together with the time error tolerance requirements. Therefore, they are taken as baseline and compared to the new PRACH sequences considered for NR-U operation. To this end, based on the results in Table III, it can be clearly noted that the enhanced Rel-16 NR-U wideband PRACH sequences provide systematically a better performance for all the evaluated cases compared to the legacy Rel-15 PRACH sequences. In particular, a performance gain of up to 9 and 6 dB can be observed for 15kHz and 30 kHz, respectively, for the different channel profiles evaluated. Such differences are really substantial, and thus the obtained results highlight the robustness of the NR-U sequences compared to NR operation, which can fulfill the coverage requirements of Rel-15 preambles while complying with ETSI regulations and achieving accurate uplink synchronization.

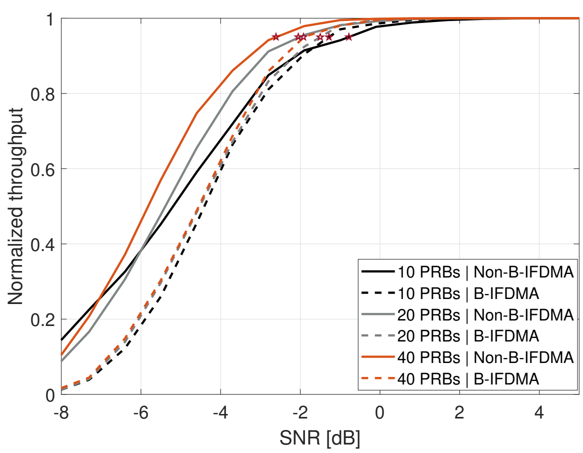
B. PUSCH Results

We begin by first analysing the impact of the filter BW, used in the practical channel estimator for non-B-IFDMA design, on the achievable PUSCH performance. As described in Section III, a filter BW of 5-PRB can be commonly assumed in NR bands. These results are presented and compared with the case where the channel estimation is performed over a single PRB at a time for a contiguous PRB allocation within the transmission BW. In particular, the evaluations are performed considering the same number of PRBs allocated for the case of one, two or four interlaces within each transmission BW for a B-IFDMA design as described in Table II. The corresponding link performance results are shown in Table IV, in terms of the SNR requirements to reach 95% of the maximum throughput under different channel conditions. There is systematically a performance improvement of approximately 1dB for all numerologies evaluated when increasing the filter BW from 1 to 5 PRBs for a non-B-IFDMA design under high frequency selective channel conditions such as TDL-C 300ns RMS delay spread channel. Similar observations can be made for TDL-A 30ns RMS delay spread channel, where the performance differences go up to 1.5dB for the highest allocation cases. Therefore, we take these results as baseline and analyse next the potential performance gains obtained due to the frequency diversity in NR-U PUSCH design, while also comparing to the above-noted performance loss of 1 dB observed due to the channel estimation challenges.

In order to comply with ETSI regulations, it has been hihglighted that the B-IFDMA design in NR-U benefits from a sparse distribution within the transmission BW and lower overhead. In this study, we next compare the performance obtained for the case of non-B-IFDMA design and B-IFDMA design assuming a 1 PRB window size in the channel estimation filter for both cases and the same number of PRBs allocated per considered FRC case. Example throughput performance results are shown in Fig 4 (a) for both designs, 20MHz BW, 30kHz SCS and TDL-D 300 ns LOS channel. It can be observed that the B-IFDMA design provides always the best performance in comparison to the non-B-IFDMA with the same number of allocated PRBs. The results in Table IV indicate that the best performance is obtained for 10 and 20 PRBs allocation compared to contiguous PRB allocation due to the benefit from the frequency diversity of the channel for both considered SCS values. Besides, similar performance is observed for both designs and 30 kHz SCS for the higher BWs evaluated when increasing the number of PRBs allocated for a single transmission BW, i.e., allocations corresponding to 40, 84 or 128 PRBs for 20, 40 and 60 MHz, respectively. The performance of the B-IFDMA design outperforms the non-B-IFDMA design for a 15 kHz SCS even for large PRB allocations due to the higher separation between consecutive PRBs for the same interlace, especially in TDL-A 30ns RMS delay spread channel case. In general, a contiguous PRB allocation can be severely attenuated by a frequency notch in the radio channel and therefore, significant frequency diversity improvement can be observed by a sparse PRB distribution.



(a)



(b)

Fig. 4: Throughput performance comparison for non-B-IFDMA and B-IFDMA designs using (a) the same channel estimation parameterization and Wiener filter BW of 1-PRB, (b) different channel estimation parameterizations with Wiener filter BWs of 5-PRBs and 1-PRB, respectively. A 20MHz channel BW and 30 kHz SCS with 10, 20 and 40 PRBs in TDL-C 300 ns LOS channel.

Finally, the performance between both designs is compared for the case of a filter BW of 5-PRB in the channel estimator filter for the non-B-IFDMA compared to the B-IFDMA design with a fixed filter BW of 1-PRB. Example throughput performance results are shown in Fig 4 (b) for both designs, 20MHz BW, 30kHz SCS and TDL-D 300 ns LOS channel. Based on results collected in Table IV, the NR-U design systematically outperforms the non-B-IFDMA design for the case of one interlace allocation per UE for different numerologies. However, as the number of allocated PRBs is increased up to two and four interlaces for the target UE in NR-U, the gain from the frequency diversity is diminished. In this case, the performance of the non-B-IFDMA design exceeds the B-IFDMA design for the same number of PRBs allocated for each FRC. In particular, we benefit from the larger filter BW in the frequency domain interpolation for the practical channel estimation due to the contigous PRB allocation. Therefore, there is a trade-off between the frequency diversity gain achieved by the sparse PRB allocation in NR-U based on the B-IFDMA design and the corresponding degrading impact due to the practical channel estimation challenges.

V. Conclusions

In this paper, the physical-layer design enhancements for the UL transmission schemes in NR-U were presented, with particular focus on the new wideband PRACH sequences and the B-IFDMA PUSCH design. The new PRACH sequences are introduced for NR-U in order to comply with ETSI OCB regulations. In addition to that, our results show that these NR-U PRACH sequences provide several dBs of detection gain in comparison to the legacy Rel 15 PRACH sequences. Furthermore, the B-IFDMA PUSCH design is robust against frequency selective channels and complies with ETSI regulations. The corresponding performance assessments in this paper focused on the achievable reference sensitivity requirement enhancements in NR-U. The results show that the B-IFDMA design provides the best performance for different numerologies with one interlace allocation, while the non-B-IFDMA design outperforms the NR-U design for higher allocations due to the channel estimation gain achieved by contigous resource allocation. There is thus a trade-off between the frequency diversity gain achieved by the B-IFDMA based sparse PRB allocation in NR-U and the corresponding negative impact in the channel estimation accuracy.

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