Filtered OFDM Based URLLC in 5G New Radio: Principles and Performance

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***Abstract*—In this paper, the principles and performance of 5G new radio (NR) based ultra-reliable low-latency communications (URLLC) building on subband filtered cyclic-prefix orthogonal-frequency-division-multiplexing (CP-OFDM) are provided and analyzed. We will demonstrate that subband filtered URLLC allows to achieve highly reliable link performance, which is not affected by interference induced by a mobile broadband service using a different numerology. In addition, we analyze and demonstrate asynchronous URLLC uplink performance with relaxed power control requirements to show that significant receiving power differences in the 5G NR base station (gNB) receiver can be tolerated, especially if highly selective subband filtering is applied in both the URLLC devices transmitters and the gNB's receiver. We also demonstrate how the mobile broadband users may be interfered by the URLLC users in mixed numerology scenario, unless sufficient guard bands and sophisticated waveform signal processing solutions improving spectral localization in transmitter and receiver side are applied. Overall, the results show that by using subband filtering on top of basic CP-OFDM processing, frequency multiplexing URLLC and enhanced mobile broadband (eMBB) services within one 5G NR carrier is feasible.**

Keywords*—5G, enhanced mobile broadband (eMBB), link performance, new radio (NR), PHY layer, power control, synchronization, ultra-reliable low latency communications (URLLC)

I. Introduction

Ultra-reliable low-latency-communications (URLLC) is one of the most exciting new features of 5G new radio (NR) [1], [2], which enables novel use cases and applications for different verticals. For example, URLLC can be envisioned to push forward the development of factory automation and logistics, autonomous or tele-operated vehicles and robots, and provide completely new kinds of immersive entertainment services for end-users [3], [4]. Even under URLLC context, different services have highly different requirements regarding radio layer latency, application layer latency, reliability, and medium-access-control (MAC) layer throughput [5, Table 7.2.2-1].

To enable flexible use of scarce spectral resources, it is assumed that different services will be multiplexed within the same carrier bandwidth in the future [6]. This is the basic assumption for the network slicing concept [1] to operate in the physical layer. Noting the different requirements for enhanced mobile broadband (eMBB), which aims to maximize the end user throughput, and URLLC communications aiming to minimize latency and packet error probability, it can be assumed that they use different subcarrier spacing (SCS). In this article we assume as a concrete example that eMBB service would be based on 30 kHz SCS to provide improved latency compared to 15 kHz SCS used in LTE, and URLLC service is based on 60 kHz SCS to provide minimal physical layer latency in carrier frequencies below 6 GHz.

In the process to maximize the link reliability for URLLC, we apply a novel fast-convolution (FC) based subband filtering on top of CP-OFDM [7] in the transmitter (Tx) and receiver (Rx) side. We compare the performance of the fast-convolution based filtered CP-OFDM (FC-F-OFDM) processing [7] with windowed overlap-and-add (WOLA) processing [8], and show that using highly selective subband filtering allows to improve the reliability of URLLC radio links in the case of mixed numerology and asynchronous interference with relaxed power control requirements. In addition, we demonstrate the benefits of FC-F-OFDM on the reliability of the eMBB radio links in the case of coexistence with URLLC within the same carrier bandwidth.

In this paper, the first results for DL and UL mixed numerology and UL asynchronous interference effects on the reliability of a 5G NR URLLC link, including possible power control error in the URLLC signal, are presented. In addition, the link performance of the eMBB service in mixed numerology interference scenario is analyzed in DL and UL, where in UL the power control error of URLLC service is included. It is shown that to maximize the 5G NR spectral efficiency through minimized guard bands (GBs) and to ensure reliable operation of URLLC and eMBB services, a highly selective subband filtering solution should be adopted. Especially in the case where additional power headroom is allowed for URLLC radio communication links, or where the ultra-low latency requirements hinder the accuracy of the URLLC power control loop, highly selective subband filtering can provide significant performance gains. These results also indicate that asynchronous URLLC operation with significant Rx power level variations is feasible when highly selective subband filtering is deployed.

The rest of this paper is organized as follows. In Section II, the basic principles of subband filtered URLLC are discussed and the description of the used example scenarios is provided. In Section III, the physical layer parameterization for URLLC and eMBB communication links is defined and the performance results are provided and discussed. Finally, in Section IV, conclusions are drawn.

II. Processing Principles and Scenarios

A. Subband Filtered OFDM Based URLLC

The basic principle of subband filtered OFDM processing is illustrated in Fig. 1. Compared to traditional channel filtering, which is used to reduce out-of-band emissions to allow smooth operation between different operators on neighbouring frequency channels, subband filtering is used to also reduce the interference between subbands or bandwidth parts (BWPs) [2] within the operator channel. The need for subband filtering arises from the highly

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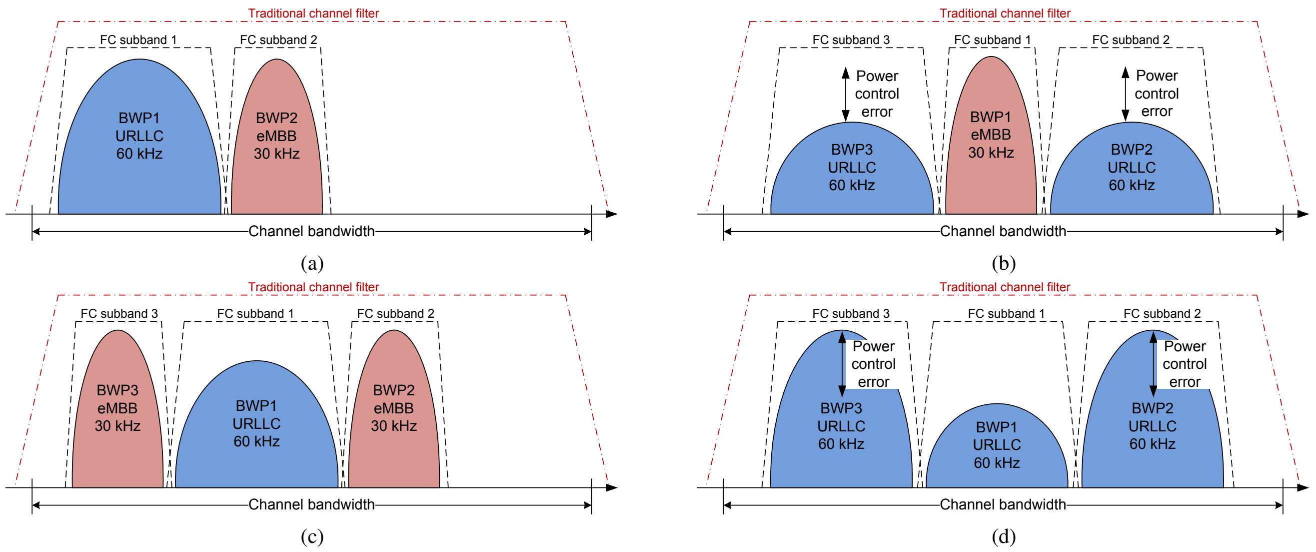

Fig. 1: Illustration of the considered mixed numerology scenarios in (a)-(c), and in (d) the UL asynchronous interference scenario for URLLC with power control error. Mixed numerology scenarios include (a) DL scenario common for URLLC and eMBB, (b) eMBB UL mixed numerology scenario, and (c) URLLC UL mixed numerology scenario.

flexible design of the 5G NR physical layer [1]. As the 5G NR base station (commonly denoted as gNB) may be simultaneously transmitting or receiving in downlink (DL) or uplink (UL), respectively, several BWPs dedicated to different services and using different numerologies, the different signals are not orthogonal and cause inter-service-interference. Therefore, different BWPs need to be highly spectrally contained to minimize the required GBs and to maximize the reliability of different services.

Introducing highly-selective subband filtering to gNBs and user equipments (UEs) Tx and Rx processing provides several additional benefits. For example, it provides increased robustness against timing error, frequency offset, and power control error [6]. In general, in the context of URLLC communications, the accuracy of power control loop and synchronization can be questioned to certain extent. As the target is to minimize the processing and channel access latency, it would be beneficial to avoid timely processes to obtain accurate Tx power level and UL timing synchronization. Firstly, regarding the accurate Tx power level, the traditional approach has been to adapt the Tx power to such a level that the nominal Rx power is sufficient to detect the used modulation and coding scheme (MCS). On the other hand, in URLLC communications, we want to maximize the link reliability and for this reason allowing URLLC devices to transmit with power headroom, or deliberate power control error (PCE), would allow to improve reliability in fading channels. In the extreme case, URLLC devices could always transmit with maximum power to maximize the power headroom in the Rx in order to minimize the link error probability. This could possibly completely remove the need for closed-loop power control [1] in URLLC services, thus simplifying the system design and minimizing access latencies.

If all the devices are transmitting with full power, the signals are received in the gNB based on the large scale fading properties of the operation environment, and again significant differences in URLLC device wise Rx power will be observed. For example, in industrial environments, the standard deviation of the normally distributed logarithmic shadowing coefficients, with fixed intercept pathloss model assuming a free-space pathloss up to a distance of 15 m, can be approximately 6.09 dB at 5.2 GHz carrier frequency [9]. Therefore, it is not unexpected to see power differences in the order of 20 dB in the gNB Rx in scenarios where, e.g., one device is blocked by clutter and other simultaneously transmitting devices have a line-of-sight connection.

Secondly, the requirement for accurate UL synchronization is a time consuming task, as it requires signaling between URLLC device and the gNB [1]. Although the URLLC device is constantly following the DL control channel, and is thus DL synchronized, the transmitted UL signal may not be synchronized with the gNB Rx timing. This may lead to significant interference between URLLC device's UL signals, unless highly selective subband filtering is applied in each URLLC device. It should be also noted that the UL synchronization accuracy requirements increase as we increase the SCS, as in 5G NR the cyclic prefix (CP) length is scaled respectively [2]. Furthermore, the UL synchronization accuracy becomes even more critical if also the power control loop accuracy is relaxed. However, as shown in this paper, adopting sub-band or BWP wise filtering is one technical enabler to allow for relaxed power control and UL timing accuracy, while still facilitating high reliability in the radio link.

B. Evaluated Interference Scenarios

The different mixed numerology and asynchronous interference scenarios considered in this paper, as concrete examples, are shown in Fig. 1, while the assumed exact system parameterization is given in Section III. The DL mixed numerology scenario shown in Fig. 1 (a) is common for URLLC and eMBB, where one service is interfered from one side by another service. In the DL mixed numerology scenarios the power spectral densities of the transmitted signals are assumed to be on equal level, which is a common assumption in multiplexing different services in the gNB transmitter. In the following UL mixed numerology and asynchronous interference scenarios the assumed MCS indices affect the nominal power differences listed below, whereas the exact definitions of the used MCS indices are provided in Section III-A.

In the mixed numerology eMBB UL link performance evaluations following the scenario shown in Fig. 1 (b), it is assumed that the eMBB signal is received with 11.5 dB or 20.5 dB higher power with MCS 16 or MCS 25, respectively, compared to the nominal power level required by the MCS 0, which is the assumed modulation scheme for the URLLC signal. We evaluate a scenario where the power level of the received URLLC signal is increased with 20 dB. This corresponds to the case where there is PCE with respect to the nominal required URLLC Rx signal level, and this can be intentional in the case of power headroom or unintentional in the case of relaxed power control loop accuracy. In general, we are interested in the cases when URLLC signal is received with a larger power than required, as the closed-loop power control might not be possible in latency-critical communications and the URLLC devices could transmit with larger power than indicated by the open-loop power control. The effect of PCE is modeled also in the asynchronous URLLC case shown in Fig. 1 (d), and discussed in more detail below.

In Fig. 1 (c), the URLLC mixed numerology scenario is shown where the desired URLLC UL signal is neighbored from both sides by an eMBB interferer. In this case the URLLC signal and eMBB signals are received with nominal powers. Thus, in the case of using MCS 0 or MCS 10 in the URLLC link, the eMBB signal is received with 20.5 dB or 8 dB larger power, respectively, when using MCS 25 for the eMBB transmission. This models the worst case scenario for the URLLC signal which is received with nominal Rx power.

Finally, in Fig. 1 (d), the asynchronous URLLC scenario is depicted, where the effect of PCE on the URLLC link is evaluated by setting the neighboring URLLC signals using the same MCS as the desired signal to have 10 dB or 20 dB larger average power in the Rx. The asynchronous interference is achieved by shifting the neighboring signals by 144 samples, corresponding to twice the assumed CP length. This scenario models how the gNB Rx could observe simultaneously received URLLC UL signals from spatially distributed devices whose Tx is following only DL synchronization (thus no timing advance), and including significant power level differences.

In all evaluated scenarios, the performance of the signal in BWP 1, and in DL mixed numerology scenario also BWP 2, is measured with or without a GB. The used GB is a single 15 kHz SCS physical resource block (PRB). In general, the different scenarios also follow the physical layer evaluation guidelines provided in the 5G NR technical report [10] for link level performance assessments.

III. Obtained 5G NR Link Performance and Analysis

A. System Parameterization

The baseline parameterization for the physical layer evaluations is provided in Table I. The evaluation setup follows the URLLC physical layer simulation assumptions provided in [10]. In all scenarios, a single-input multiple-output radio link is assumed, where the Tx uses one antenna and Rx uses two antennas for diversity reception. The block error rate (BLER) is used throughout the paper to measure the reliability of the communications link. For the URLLC and eMBB link evaluations 10^6 and 10^4 mini-slots are transmitted per SNR point, respectively. The supported CP-OFDM numerologies in 5G NR [2] are based on scalable SCS according to $15 \times 2^{\mu}$ kHz, where the scaling factor ensures time aligned slots for different numerologies. In this paper the link performance evaluations concentrate on FR 1, defined to cover frequencies from 450 MHz to 6 GHz, and where 15 kHz, 30 kHz, and 60 kHz SCSs are currently supported based on μ values 0, 1, and 2, respectively [1].

TABLE I: Considered 5G NR physical layer parameterization [10]

Parameter	Value
Carrier frequency	4 GHz
Channel bandwidth	50 MHz
Sampling rate	61.44 MHz
Subcarrier spacing	URLLC: 60 kHz / eMBB: 30 kHz
FFT size	URLLC: 1024 / eMBB: 2048
CP length (N_{CP})	URLLC: 72 / eMBB: 144
Mini-slot length	7 OFDM symbols
Channel model	TDL-C 300 ns
UE mobility	3 km/h
MCS index for URLLC	MCS Table 1 [11]; 0 and 10
MCS index for eMBB UL	MCS Table 1 [11]; 16 and 25
MCS index for eMBB DL	MCS Table 2 [11]; 19 and 24
Channel code	LDPC
BLER target for URLLC	0.1%
BLER target for eMBB	10%
Allocation size for URLLC	MCS 0: 20 PRBs / MCS 10: 4 PRBs
Allocation granularity for eMBB	12 PRBs
WOLA	
Window slope length	$N_{\mathrm{CP}}/8$
FC-F-OFDM	
Transition bandwidth	URLLC: 3 FFT bins / eMBB: 6 FFT bins
Stopband minimum attenuation	10 dB

In all cases, a mini-slot of length seven OFDM symbols is used. In 5G NR the normal slot length is defined to be 14 symbols while 1-13 symbol allocations are referred to as mini-slots [1], [2]. With the assumed 60 kHz SCS for URLLC this leads to a mini-slot duration of 0.125 ms which allows to achieve sub-millisecond end-to-end latency at the 5G NR physical layer, assuming the physical downlink shared channel (PDSCH) detection time of 20 OFDM symbols given in [11]. The mini-slot duration for eMBB is correspondingly 0.25 ms with SCS 30 kHz. For both systems, one control symbol is assumed as the first symbol of the mini-slot and the second symbol is a demodulation reference symbol (DM-RS) following the PDSCH DM-RS configuration type 1 [12]. The channel code is the 5G NR low-density parity-check (LDPC) code [1] for PDSCH and physical uplink shared channel. The evaluated channel model is selected to be TDL-C 300 ns [13] to include moderate frequency selectivity in the propagation environment.

For the URLLC radio link, this work concentrates on the reliability aspect of an ultra-low latency control link targeting to transmit a MAC protocol-data-unit (PDU) packet of size 32 bytes (256 bits) [5] within each mini-slot. For high reliability communications, robust MCS indices are selected from 5G NR MCS index Table 1 for PDSCH [11] corresponding to MCS 0 (QPSK,$R = 120/1024$, where R is the coding rate) and MCS 10 (16-QAM,$R = 340/1024$). With the selected MCSs and given MAC PDU packet size the required allocation is 20 PRBs or 4 PRBs with MCS 0 or MCS 10, respectively. The target reliability level for the URLLC link is set to 0.1% BLER level, and this is now the initial reliability level of the transmission as no retransmissions are assumed. With one retransmission, the reliability would drop already to 10^{-6} which is sufficient even

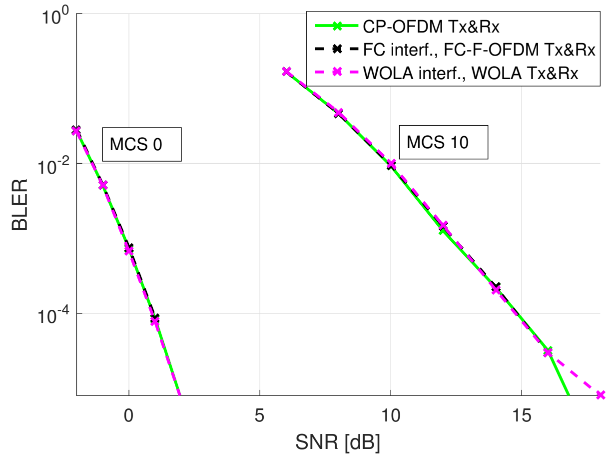

Fig. 2: URLLC downlink BLER performance with mixed numerology interference from a 30 kHz SCS eMBB service and without a guard band.

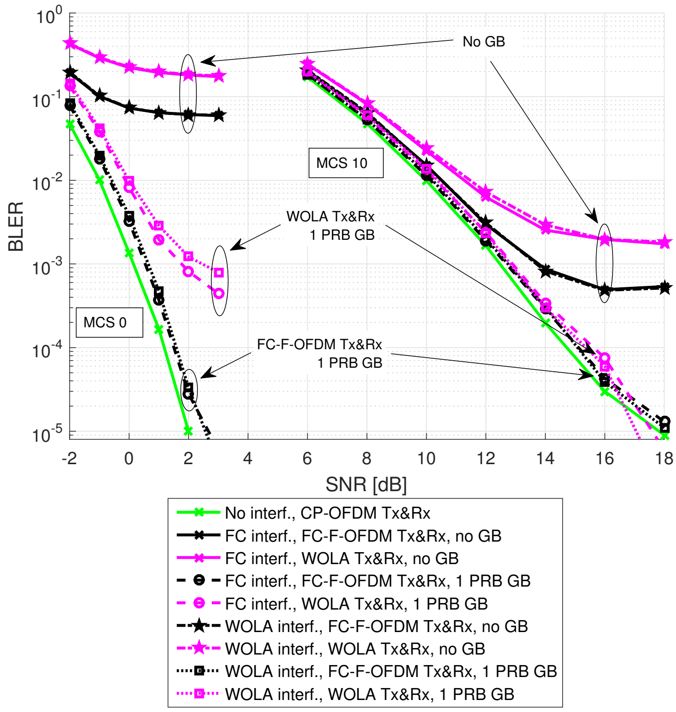

Fig. 3: URLLC uplink BLER performance with mixed numerology interference from a 30 kHz SCS eMBB service with either no guard band or 1 PRB guard band applied.

for the tightest 3GPP requirements [5]. Noting the extremely short mini-slot duration of 0.125 ms, advanced Rx processing capable to decode the received packet within a mini-slot would be able to support one retransmission while fulfilling the 1 ms physical layer end-to-end latency.

With eMBB service, high throughput is targeted leading to higher MCS selections. For UL, MCS indices are also selected from MCS index table 1 [11], corresponding to MCS 16 (16-QAM,$R = 658/1024$) and MCS 25 (64-QAM,$R = 822/1024$), while for DL MCS indices are selected from MCS index table 2 [11], corresponding to MCS 19 (64-QAM,$R = 873/1024$) and MCS 24 (256-QAM,$R = 841/1024$). The PRB allocation for eMBB radio link is fixed to 12 PRBs, which is selected as it corresponds to the primary and secondary synchronization-signal allocation size [1], [12], and it is also considered to be a good representative allocation size for UEs operating in a multi-access eMBB channel.

The enhanced waveform processing solutions considered in this paper are FC-F-OFDM [7] and WOLA [8]. The FC-F-OFDM is a novel subband filtering scheme relying on efficient frequency domain implementation. The subband filters are defined through frequency domain windows which can be optimized in terms of Tx signal quality, stop-band attenuation, and transition band width (number of frequency bins used to model the transition band of the filter) [7]. In this work, transition band width corresponding to 180 kHz (bandwidth of one PRB with 15 kHz SCS) is used, which maps to three frequency bins with 60 kHz SCS (URLLC case) and six frequency bins with 30 kHz SCS (eMBB case). The minimum attenuation target in the frequency domain window optimization was set to 10 dB. Note that this attenuation target is the minimum attenuation at the beginning of the stopband, and the effective attenuation at larger frequency distances is effectively larger.

WOLA, in turn, is a well known time-domain windowing based solution where the spectral containment of CP-OFDM symbols is improved by applying overlapping time domain windows at the OFDM symbol edges [8]. In this paper, we have assumed a raised cosine response for the time domain window and weighted $N_{\mathrm{CP}}/8$ samples in the raising and falling window parts, where N_{CP} corresponds to the CP length of the used service wise numerology.

All the presented results assume a demodulation reference signal based channel estimation and Rx signal-to-interference-and-noise (SINR) estimation. A constant CP length is assumed for simplicity. For the DL, a modified Rapp power amplifier (PA) model [14] is used while for UL a polynomial PA model of order nine [15] is adopted. These particular PA models are selected because they are used also by 3GPP and are publicly available. In UL, the power backoff used with the PA model is a design parameter, and we have used 4.7 dB and 6.2 dB power backoff with MCS 0 and MCS 10, respectively, in the case of URLLC, and 6.2 dB and 8.5 dB power backoff with MCS 16 and MCS 25, respectively, in the case of eMBB.

The interference free radio link performance of a plain CP-OFDM system without service multiplexing is shown as a reference in all cases. For DL mixed numerology interference scenarios, we assume that the gNB applies the same waveform processing on top of all subbands. Therefore, the interfering signal is always processed in similar manner as the desired signal. In UL mixed numerology or asynchronous interference scenarios, the mixing of different types of waveform processing on top of interfering signals and desired signal is allowed. This comparison is included because it is assumed that different device vendors or different device generations can be using different waveform processing on the Tx, thus leading to a mixture of performance figures in practical networks [16]. The provided results help to understand the performance trade-offs with different combinations of waveform processing solutions.

B. *URLLC Radio Link Performance*

1) Mixed Numerology Interference: First set of results correspond to the URLLC mixed numerology DL following the scenario presented in Fig. 1 (a). In Fig. 2, the URLLC DL performance in terms of BLER is shown, assuming eMBB transmission using MCS 24 based on 5G NR MCS table 2 [11]. With the

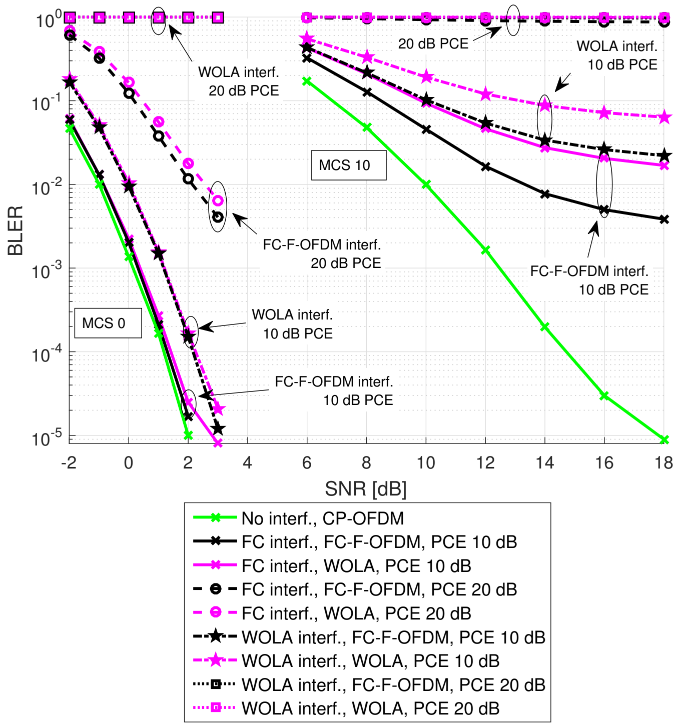

Fig. 4: URLLC uplink BLER performance with asynchronous interference, PCE values of 10 dB or 20 dB, and without a guard band.

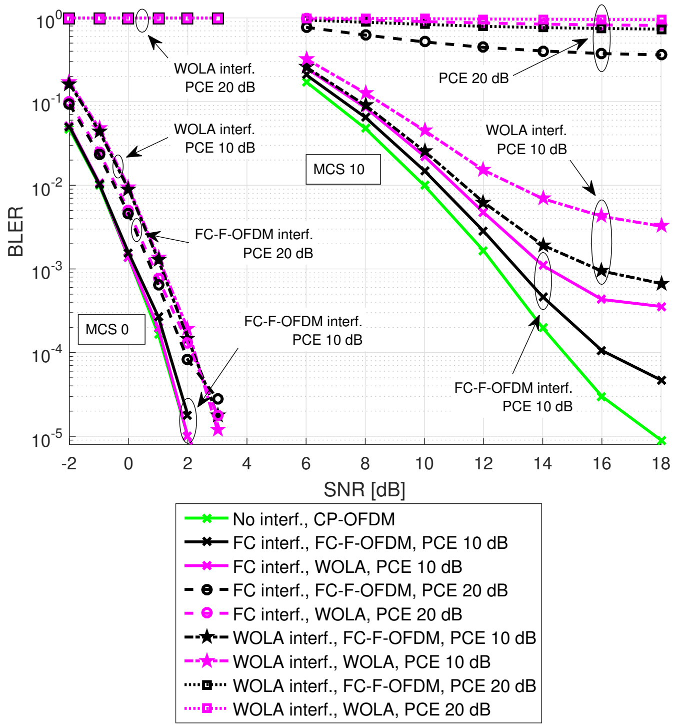

Fig. 5: URLLC uplink BLER performance with asynchronous interference, PCE values of 10 dB or 20 dB, and with 1 PRB guard band.

evaluated MCS options the URLLC DL radio link is very robust and does not suffer from the mixed numerology interference imposed by the eMBB channel. This is primarily because in DL both services have equal power, are time and frequency synchronized, and URLLC is using a robust MCS and larger SCS than eMBB service.

In Fig. 3, the URLLC UL performance with mixed numerology interference is shown. This corresponds to the scenario depicted in Fig. 1 (c). The eMBB signal using MCS 25 based on 5G NR MCS table 1 [11] is received with nominal power required for 10% BLER, as defined in Section II-B, to model the nominal power difference between the two different services. The power difference is obtained as the difference of required SNR where URLLC link achieves the target BLER of 0.1% and the eMBB link achieves 10% BLER in interference free scenario. It can be observed that 1 PRB GB is required to achieve the given reliability target of 0.1% with MCS 0. Furthermore, FC-F-OFDM based URLLC radio link is able to operate within 0.5 dB from the interference free reference. WOLA processing based desired radio links loses approximately 2 dB in the required SNR when compared to interference free scenario. With MCS 10 and without a GB, FC-F-OFDM based desired link is able to achieve the target BLER value 0.1% with 1.2 dB SNR degradation with respect to the interference free CP-OFDM, while WOLA has BLER values saturating above the 0.1% target. With 1 PRB GB both waveform processing candidates provide similar performance. This implies that in mixed numerology scenarios, URLLC services should aim to use higher MCS if power boosting is not enabled, as it allows to increase the received power spectral density in the gNB and alleviates the interference induced by the eMBB service.

These results indicate that especially for URLLC UL, 1 PRB GB combined with highly selective subband filtering in URLLC devices Tx's and gNB's Rx allow to achieve ultra-reliable operation with less than 0.5 dB degradation in the required SNR.

2) Asynchronous Interference: In Figures 4 and 5, the performance of asynchronous URLLC operation including PCE is demonstrated. This scenario now corresponds to Fig. 1 (d), where the PCE is assumed to increase the power of the interfering signals.

From Fig. 4, we can observe that with MCS 0 and no GB, if the interfering signals are spectrally well-contained with FC-F-OFDM in the respective Txs, 10 dB PCE has negligible effect on the link reliability while even 20 dB PCE can still be tolerated causing approximately 4 dB degradation in the required SNR at BLER level 0.1% . With WOLA processed interfering signals, 10 dB PCE is observed as 1 dB degradation in the required SNR, whereas in 20 dB PCE case the URLLC link does not work anymore. In Fig. 4, the performance with more sensitive URLLC radio link using MCS 10 is also shown. Without any GB, we can observe that the target BLER level is not achieved, although applying FC-F-OFDM to gNB Rx and to all UE Txs allows to reach close to the BLER target of 0.1%.

In Fig. 5, with MCS 0 and 1 PRB GB, it can be observed that if interfering UEs apply FC-F-OFDM processing in their Txs, 10 dB PCE has no effect on the desired link performance and 20 dB PCE is observed as a 0.6 dB degradation on the required SNR to achieve 0.1% BLER target. With WOLA interference and 10 dB PCE the corresponding SNR degradation is 1 dB. With WOLA interference and 20 dB PCE, the URLLC radio link does not work anymore. With MCS 10, 1 PRB GB, and assuming 10 dB PCE and FC-F-OFDM processed interfering signals, the target 0.1% BLER target can be achieved with 0.6 dB or 1.6 dB SNR degradation with FC-F-OFDM or WOLA Rx processing in the gNB, respectively. If the interfering UEs apply WOLA Tx processing, then FC-F-OFDM is required in the gNB Rx to achieve the BLER target with 3.3 dB

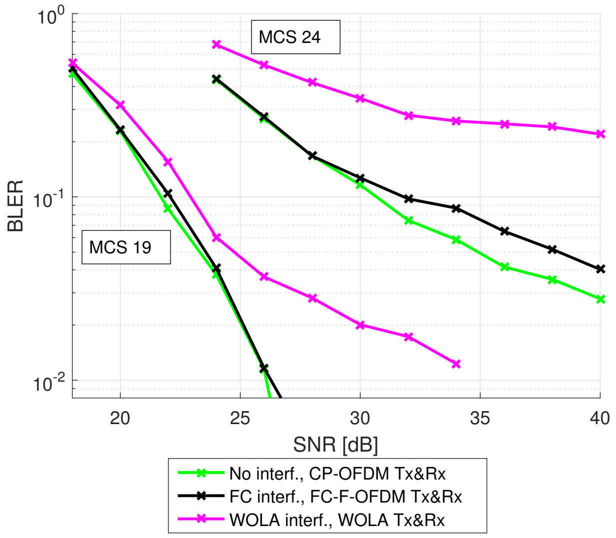

Fig. 6: Enhanced mobile broadband downlink BLER performance with mixed numerology interference from a 60 kHz SCS URLLC service and with 1 PRB guard band.

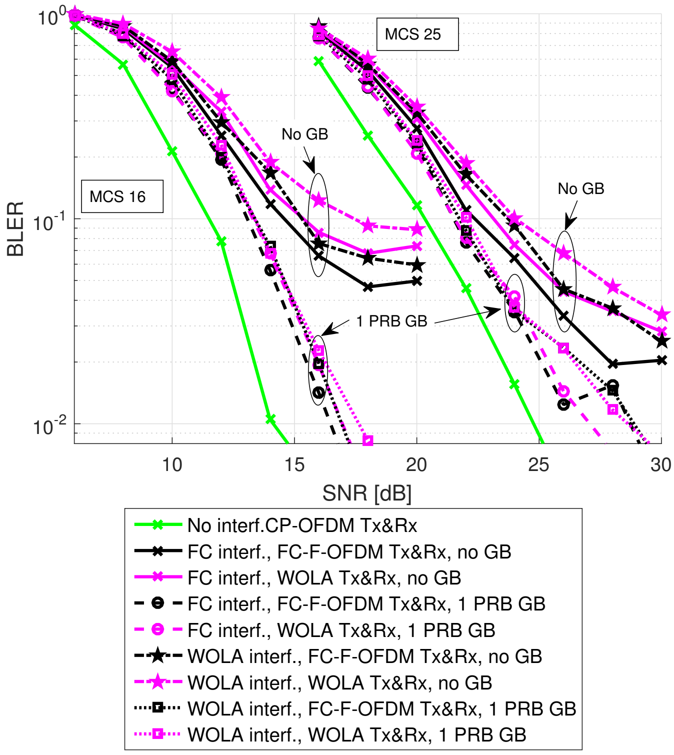

Fig. 7: Enhanced mobile broadband uplink BLER performance with mixed numerology interference from a 60 kHz SCS URLLC service and assuming 20 dB PCE. Both cases of no guard band and 1 PRB guard band are shown.

SNR degradation. With WOLA based interference and desired link waveform processing, the BLER target is not achieved anymore. Although one PRB GB is applied, 20 dB PCE is too aggressive for MCS 10 based URLLC link and the BLER performance is saturated close to unity value. For both evaluated MCS values, with or without GB, there was no link performance degradation observed in the asynchronous interference case if the desired and interfering signals were received with equal powers.

Overall, the presented results for URLLC UL indicate that clear performance gains can be achieved if highly selective sub-band filtering is applied in the URLLC devices Tx's and gNB's Rx. Furthermore, in the asynchronous interference scenario, FC-F-OFDM based waveform processing enables operation even with 20 dB PCE.

C. eMBB Radio Link Performance

In this section, we focus on the eMBB performance in coexistence with a URLLC service in the same carrier. In contrast to the URLLC link evaluations, eMBB users are assumed to target high throughput services and therefore high order modulations and high coding rates are evaluated, as discussed in Section III-A and defined in Table I. In the eMBB evaluations, an MCS limiting factor in the UL is the highly non-linear polynomial PA model which basically limits the maximum modulation order to 64-QAM, whereas in DL 256-QAM modulation is also evaluated.

First, the eMBB DL performance results following the DL mixed numerology scenario illustrated in Fig. 1 (a) are provided in Fig. 6, using either MCS 19 or MCS 24 based on 5G NR MCS table 2 [11]. Performance results without GB are not shown, as for both evaluated MCS the BLER is saturated close to value of 50%. The dramatic performance drop of eMBB service without a GB is due to the more sensitive high-order modulations used in communications. Unlike in the case of URLLC service, where robust MCSs were used, eMBB service is more vulnerable in the DL to the mixed numerology interference.

In the case of MCS 19, illustrated in Fig. 6, we note that 1 PRB GB can be considered as sufficient. In the case of WOLA based waveform processing in the transmitting gNB and receiving UE, the required SNR increases by 1.3 dB at the evaluated BLER target of 10%, and the link performance saturates approximately at BLER value of 1%. Applying FC-F-OFDM waveform processing in the gNB Tx and UE Rx allows to achieve the interference free performance. In the case of MCS 24, as shown in Fig. 6, and with 1 PRB GB, FC-F-OFDM based waveform processing is required to nearly achieve the interference free performance, with only 1.2 dB increase in the required SNR given the 10% BLER target. With WOLA based waveform processing the BLER target of 10% is not achieved.

In Fig. 7, the eMBB UL link performance is shown for MCS 16 and MCS 25 following 5G NR MCS table 1 [11], following the setup shown in Fig. 1 (b) and described in Section II-B. Here the URLLC signal is assumed to include a PCE causing it to be received with higher power than required by the URLLC MCS. In all cases we assume that the URLLC signal is using MCS 0 and is received with 20 dB higher power to model the effect of relaxed power control accuracy or power headroom required to further improve the URLLC link reliability. The same evaluations were repeated by assuming 0 dB and 10 dB power headroom for the URLLC link, but no degradation in the eMBB link performance were observed. Furthermore, with PCE equal to 20 dB, increasing the GB from 1 PRB to 2 PRBs did not provide clear benefits in any evaluated scenario. In high level, these results indicate that the high MCS based eMBB UL is robust against relatively large PCE values of URLLC service, and thus from the eMBB service point of view relaxed power control accuracy or deliberate power headroom for URLLC services can be accepted.

In Fig. 7, considering the eMBB link performance using MCS 16, we can observe that without a GB the required SNR is increased by 3 dB in the case of FC-F-OFDM based Tx and Rx processing combined with FC-F-OFDM based interferer, and 6 dB in the case of WOLA based Tx and Rx processing with WOLA based interferer. With 1 PRB GB, all different combinations are within 2 dB from the interference free reference SNR value. The difference between different waveform processing solutions is within 0.5 dB, including different waveform processing variants in desired link Tx and Rx and in interfering UEs' Txs.

Considering the eMBB link performance using MCS 25, as shown in Fig. 7, the performance trends are very similar as with MCS 16. Without a GB, FC-F-OFDM waveform processing based system provides approximately 2 dB better SNR for BLER target of 10%, when compared to WOLA waveform processing based system. With 1 PRB GB, all waveform processing and interference signal combinations are within 2 dB from the interference free reference SNR value.

These results indicate that especially for high throughput eMBB DL the use of highly selective subband filtering is required. For the eMBB UL, if significant PCE is expected for the URLLC service, highly selective subband filtering can provide additional performance improvements especially in the case when no GB is applied between services.

IV. Conclusion

This paper introduced the basic principles and benefits of subband filtered OFDM based URLLC link, and evaluated URLLC link performance with highly selective subband filtered CP-OFDM in mixed numerology and asynchronous interference scenarios including the PCE effect. The PCE is defined as the difference between the received power and the nominal received power required to achieve a given BLER target in an interference free scenario. The PCE can be deliberate, e.g., when targeting to provide power headroom for the URLLC service to increase its robustness against large scale fading, or it can be induced by relaxed power control loop requirements imposed on URLLC service in order to minimize the access latencies. In addition to URLLC link evaluations, the effect of URLLC link on the co-existing eMBB radio link was evaluated.

Based on the presented results, we can conclude that highly selective subband filtering, e.g., FC-F-OFDM, is required in DL and UL, stemming from the requirements of the two different services evaluated. In mixed numerology DL, the eMBB link can be considered as the victim service, as it requires guard band and enhanced waveform processing solutions in gNB Tx and device Rx to achieve the considered BLER target of 10%. In the case of eMBB service, one PRB GB is required to achieve good performance in DL whereas URLLC DL does not require any GB.

On the contrary, in mixed numerology UL, the eMBB performance is less dependent on the applied waveform processing solutions in different network nodes than the URLLC service, as long as 1 PRB GB is applied between services. In URLLC link it is important to apply highly selective subband filtering on all URLLC devices' Txs and on gNB's Rx. Especially, to support minimized Tx latency though inaccurate time synchronization and power control in the URLLC UL, a highly selective subband filtering is required. On the other hand, these results can also be interpreted in such a manner that *applying a highly selective subband filtering allows to relax the power control and the time synchronization requirements with URLLC services, enabling simpler operation and reduced channel access latencies*.

It was also shown that WOLA waveform processing allows to support URLLC service in mixed numerology and asynchronous interference scenario, if sufficient guard bands are applied. Using FC-F-OFDM allowed to achieve the best performance among evaluated waveform processing solutions, and also allows interesting new possibilities for relaxed time synchronization and power control in the URLLC context. Therefore, for smooth coexistence it is reasonable to strive for efficient and highly selective waveform signal processing in all 5G devices to minimize required guard bands maximizing the 5G NR spectral efficiency and to ensure reliable and stable communication links for all co-existing services.

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