5G New Radio Uplink Performance: Noise, Interference and Emission Constraints

Toni Levanen*, Karri Ranta-Aho†, Jorma Kaikkonen†, Sari Nielsen†, Kari Pajukoski†,
Markku Renfors*, Mikko Valkama*
*Laboratory of Electronics and Communications Engineering, Tampere University of Technology, Finland
†Nokia Bell Labs, Finland
Email: toni.levanen@tut.fi

***Abstract*—This paper investigates the 5G new radio (NR) uplink (UL) performance with CP-OFDM and DFT-s-OFDM based waveforms. The effects of highly non-linear PA behavior, inter-allocation interference, and UL multi-user MIMO on the relative performance of these waveforms are addressed. It is shown that with relaxed EVM and inband emission requirements for CP-OFDM, the coverage limited operation can be improved to achieve better link budget than DFT-s-OFDM based UL without performance penalty in the multi-user uplink. For high-throughput user equipment, the assumed highly non-linear PA behavior restricts the CP-OFDM based transmit power, which may limit the coverage compared to DFT-s-OFDM based waveform in UL without multi-user MIMO support. In UL multi-user MIMO scenario the CP-OFDM based waveform provides clearly better link performance and achieves better link budget than DFT-s-OFDM based waveform. Within the multi-user MIMO UL scenario, the requirement for substantially better PA linearity in high-throughput cases is also observed.**

Keywords*—5G new radio, uplink coverage, CP-OFDM, DFT-s-OFDM, link budget, peak clipping, PHY layer, power amplifier, WOLA

I. Introduction

There is now an agreement on the first standard for fifth generation (5G) mobile communications system's physical layer, entitled as 5G new radio (NR) [1], and the main working assumptions are summarized in the technical report [2]. For 5G NR it has been decided that CP-OFDM based waveform is the baseline for downlink (DL) and uplink (UL) transmissions. DFT-s-OFDM is also to be supported by user equipment (UE) for UL transmissions, but it's use is limited to single stream transmissions in coverage limited cases.

In this article we concentrate on the CP-OFDM based UL and compare it to DFT-s-OFDM based UL. The CP-OFDM based UL brings several benefits, e.g., simplified Tx and Rx chains, enhanced capabilities for interference cancellation, and aligned reference symbol (RS) designs in DL and UL [3]. We show that even with highly non-linear UE power amplifier (PA), the CP-OFDM provides as good UL coverage as DFT-s-OFDM. In addition to coverage limited UEs, the performance of high-throughput UEs is addressed and evaluated with or without PA model or interfering signals in adjacent subbands. In case of highly non-linear PA behavior, the high-throughput UEs need higher backoff with CP-OFDM waveform, which is seen as increased maximum power reduction (MPR) requirement.

Given the high cell edge spectral efficiency requirements [4], [5], multi-user multiple input multiple output (MU-MIMO) transmissions are in dominant role in 5G NR. UL MU-MIMO is beneficial due to its inherent capability to improve cell throughput without sacrificing user fairness in UL [6]. For this reason, we also address the UL link performance in case of two-UE MU-MIMO where each UE is transmitting a single layer. The evaluation is based on two UEs per allocation operating in MU-MIMO assuming that the inter-allocation interference is generated by similar two-UE MU-MIMO links. This scenario is highly relevant in the 5G NR context and increases the novelty of this paper since such results have not been reported earlier.

The presented single-user UL performance results with realistic interference sources, including adjacent subband single-user single-stream or two-user MU-MIMO interference, are novel and first of their kind in the 5G NR context. The link performance evaluations include a realistic polynomial PA model defined by 3GPP for UEs [7]. The achievable PA output power is evaluated by following the emission requirements set for LTE UL signal [8], because the final emission requirements for 5G NR are still under preparation in 3GPP.

This paper is organized as follows. In Section II the evaluated system parameterization and the considered interference scenarios are explained. Then, in Section III the link performance comparison without interference and with or without a nonlinear PA model are given. These are followed by link performance results with synchronous inter-allocation interference in Section IV. The conclusions are drawn in Section V.

II. System Parameterization

The baseline physical layer definition and numerology follow the one defined for LTE operating in a 10 MHz channel, as defined in Table I. The UL link performance is evaluated in TDL-C channels [9] with 1000 ns and 300 ns RMS delay spreads with QPSK and 64-QAM modulations, respectively. In TDL-C channels the root-mean-squared (RMS) delay spread is defined by a scaling factor indicated in the name. In addition, link performance with synchronous inter-allocation interference in UL is evaluated, which can be considered as the dominant operation mode in enhanced mobile broadband (eMBB).

The UL link performance with different 5G NR waveform candidates combined with peak clipping based peak-to-

TABLE I: Physical layer parameterization

Parameter	Value
Carrier frequency	4 GHz
Channel bandwidth	10 MHz
Sampling rate	15.36 MHz
Channel model [9]	TDL-C 300 ns (64-QAM) TDL-C 1000 ns (QPSK)
UE mobility	3 km/h
Modulation	QPSK or 64-QAM
Channel code [10]	turbo code
Coding rate	$1/3$ (QPSK) $3/4$ (64-QAM)
FFT size	1024
CP length (N_{CP})	72
Subcarrier spacing	15 kHz
Number of SCs per PRB	12
Allocation granularity	4 PRBs
Number of Rx antennas (BS)	2
Number of Tx antennas (UE)	1
5G NR DFT-s-OFDM	
Tx Waveform processing	WOLA-based DFT-s-OFDM
Rx Waveform processing	channel filtered DFT-s-OFDM
5G NR CP-OFDM	
Tx Waveform processing	WOLA-based CP-OFDM with channel filter
Rx Waveform processing	channel filtered CP-OFDM
Window slope length (N_{WS})	$N_{\text{CP}}/8 = 9$

TABLE II: PA related parameterization and performance

	Value			
	DFT-s-OFDM		CP-OFDM	
Parameter	QPSK	64-QAM	QPSK	64-QAM
PAPR target in peak clipping [dB]	-	-	1.8	6.5
input backoff [dB]	3.2	5.4	2.6	6.4
PA output power [dBm]	27.0	25.0	27.0	24.0
Tx EVM [%]	7.3	4.5	19.5	6.2
out-of-band 30 kHz margin [dB]	0	4.2	0.1	8.1
out-of-band 1 MHz margin [dB]	19.0	23.0	13.1	27.3
inband margin [dB]	3.8	2.6	-2.4	0.4

average-power (PAPR) reduction method was evaluated earlier in [11]. In this paper the same simple PAPR reduction method is used with CP-OFDM based 5G NR UL signal. This allows to achieve higher PA output power with CP-OFDM without essentially degrading the error vector magnitude (EVM). Due to the used peak clipping, channel filter is added to the 5G NR UE Tx chain to limit the effect of peak clipping induced spectral spreading on the out-of-band emissions.

Windowed overlap-and-add (WOLA) is a well known, low complexity technique to reduce OOB emissions of a CP-OFDM or DFT-s-OFDM signal [12]. With WOLA, a window slope length $N_{ws} = 9$ samples is used which corresponds to approximately 1% rolloff. The window slope length defines the length of the rising or falling slope. The total window length in Tx is $N_{win,Tx} = N_{FFT} + N_{CP} + N_{ws}$ and preceding symbols overlap by N_{ws} samples.

All presented results assume an ideal channel knowledge in the Rx and each simulated subframe contains only data symbols. A constant CP length is assumed for simplicity. For UL a polynomial model of order nine is used [7]. The PA model was selected because it is used also by 3GPP and is publicly available. The Rx uses a single tap MMSE equalizer in all evaluated scenarios.

In Table II, the PA related parameters and achieved performance are given. The out-of-band 30 kHz and 1 MHz margins refer to minimum difference between evaluated power spectral density (PSD) of the Tx signal at the PA output and the LTE requirements for 10 MHz channel with 30 kHz and 1 MHz measurement bandwidths, respectively [8]. For coverage limited UEs, the main design target is to achieve the PA output power of 27 dBm. Typically an insertion loss of 4 dB is assumed after PA so this corresponds to the radiated power of 23 dBm. From Table II we can observe that the CP-OFDM based signal does not exactly achieve the LTE EVM target 17.5% or inband emission requirements (indicated by a negative value in Table II) defined in [8]. We will shown in the following sections that this does not compromise the link performance for coverage limited UEs nor for high-throughput UEs interfered by coverage limited UEs (see case (c) in Fig. 1). With high-throughput UEs the LTE EVM requirements have the highest weight as we do not want to compromise the link performance. Therefore, with 64-QAM modulation and CP-OFDM waveform, we have to use 1 dB larger MPR than defined for DFT-s-OFDM in LTE [8] to achieve the EVM requirement. This MPR increase is seen as 1 dB smaller PA output power for 64-QAM modulated CP-OFDM signal in Table II.

In Fig. 1, the different evaluated inter-allocation interference cases are illustrated. In all interference cases the desired signal is located in the middle and is neighbored on both sides by an interfering signal. In cases (a) or (b), the desired signal is QPSK modulated and the interfering signal uses either QPSK or 64-QAM modulation, respectively. These cases correspond to the coverage limited UE performance. In cases (c) and (d), the desired signal is a 64-QAM modulated signal modeling a high-throughput UE. The desired signal and the interfering signals are assumed to have a 4 PRB allocation each. Thus, the interference analyzed in this paper is inter-allocation interference while in case of MU-MIMO also the intra-allocation inter-user interference is included. It is also assumed that CP-OFDM signal is interfered by another CP-OFDM based signal and DFT-s-OFDM based signal is interfered by another DFT-s-OFDM signal. QPSK and 64-QAM modulated signals, desired and interfering ones, assume PA output powers as given in Table II. In the case of CP-OFDM based UL, the desired and interfering UE Txs are using peak clipping as described in [11]. The co-existence of the CP-OFDM and DFT-s-OFDM based UL signals and their inter-allocation interference effects are for future studies.

Throughout the paper, the link performance is evaluated at the 10% block error-rate (BLER) reference point, which is commonly assumed to be a proper operation point for a mobile communication system supporting hybrid automatic repeat request (HARQ) error control. The BLER results presented in this paper are those that are obtained in first transmission, i.e., do not include HARQ combining gain.

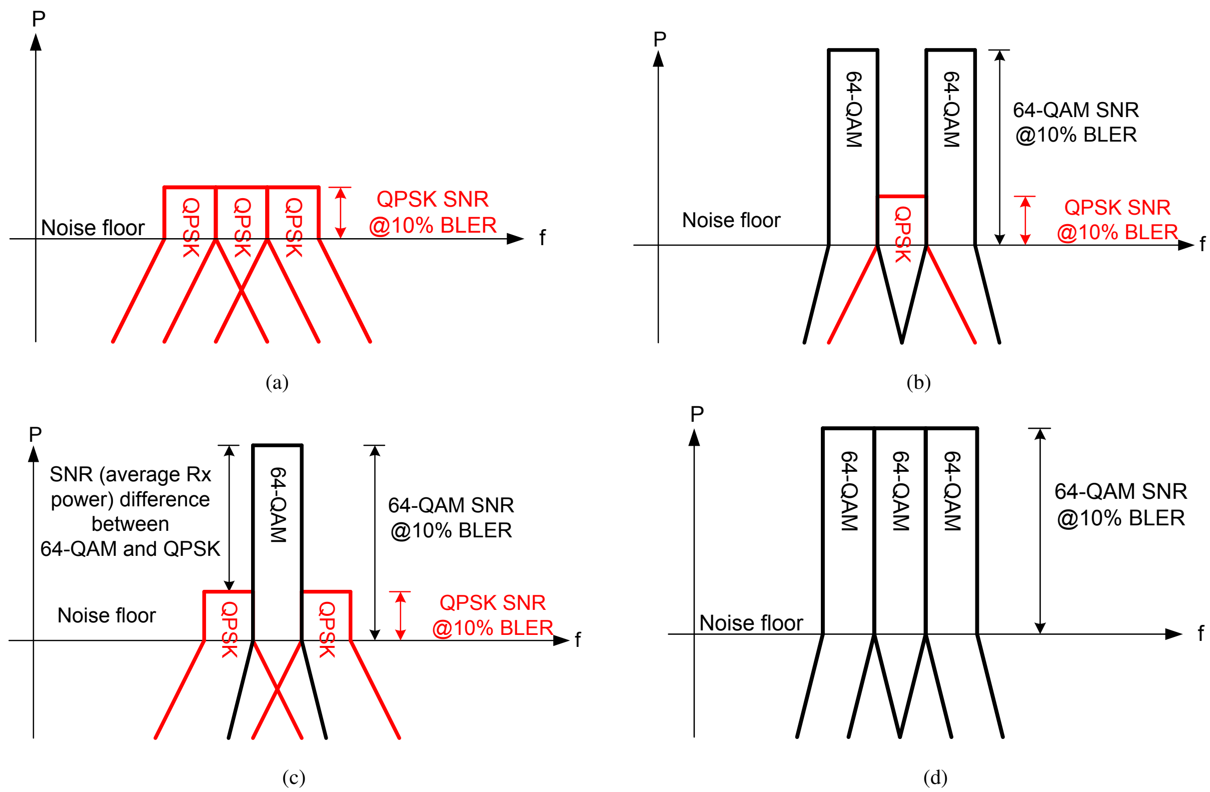


Fig. 1: Considered in-channel inter-allocation interference cases where different UL signals are frequency multiplexed to neighboring subbands (i.e., sets of 4 PRBs).

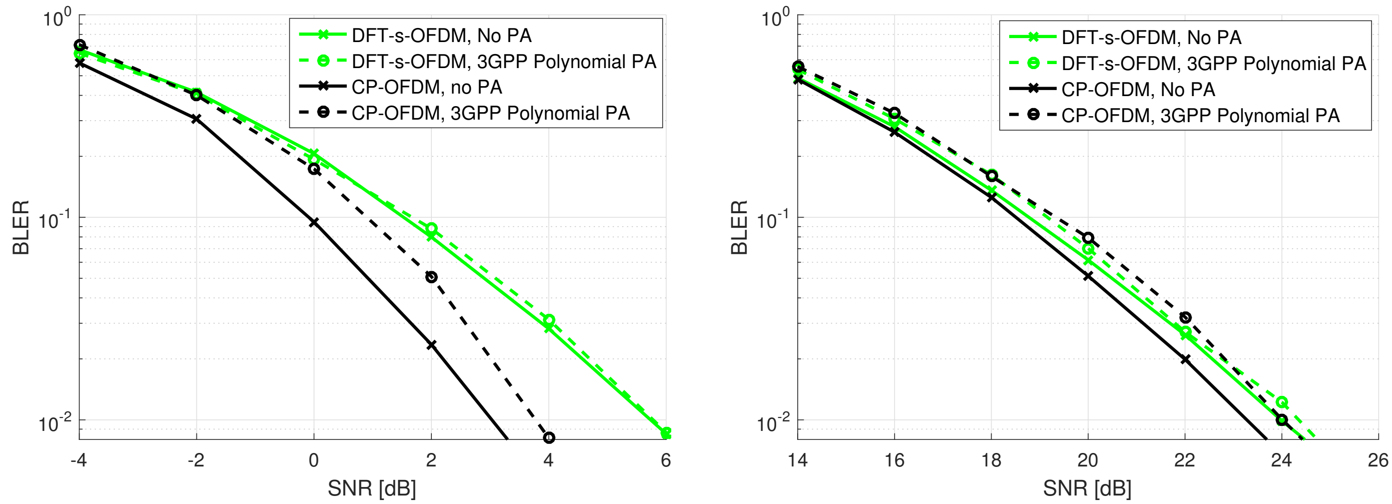
III. Performance Evaluation without Inter-Allocation Interference

In this section the achievable baseline link performance without inter-allocation interference is evaluated, in cases without and with a nonlinear PA. These results indicate how the PA nonlinearity affects the 5G NR UL performance with given waveform specific parameterization and also define the SNR differences used between victim and aggressors in different interference cases evaluated in Section IV.

In Fig. 2, the link performance for single user UL transmission using (a) QPSK or (b) 64-QAM modulation are given. From Fig. 2 (a), we can observe that even though the CP-OFDM signal with largely nonlinear polynomial PA model did violate the LTE EMV requirement (see Table II), the link performance is better than with DFT-s-OFDM, as was observed also in [11]. The EVM violation is observed as a clear degradation in the CP-OFDM link performance with the PA model when compared to performance without the PA model. With DFT-s-OFDM such a clear difference is not observed due to lower PAPR compared to CP-OFDM. At the 10% BLER target, the SNR requirement is 0.4 dB better for CP-OFDM based UL signal. Thus, CP-OFDM is able to achieve better link budget than DFT-s-OFDM while the PA output powers are the same.

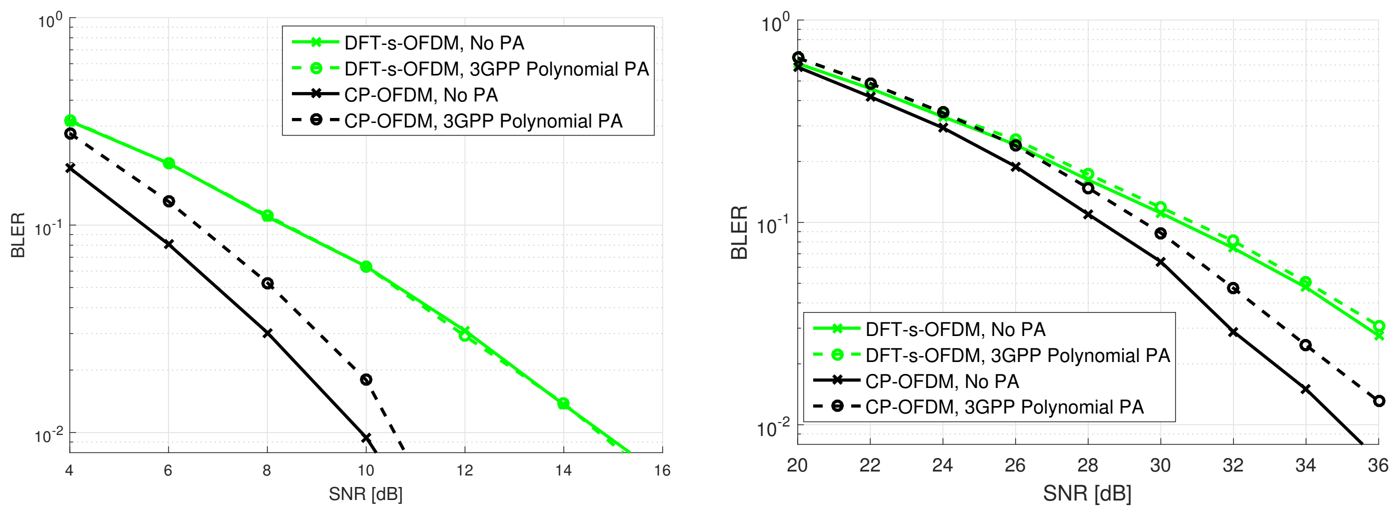
In Fig. 2 (b), the corresponding performance with 64-QAM modulation is given. Here the differences between waveforms and the PA distortion effects are smaller than with QPSK modulation due to larger power backoff needed to ensure sufficient Tx EVM performance. The required SNR at the 10% BLER target is 0.2 dB higher for the CP-OFDM based signal. Thus, in this case CP-OFDM loses 1.2 dB in the link budget performance to DFT-s-OFDM because CP-OFDM has to use 1 dB lower PA output power to achieve the EVM requirements. It should be noted, that in practice high-throughput UEs use larger bandwidths and also most often have discontinuous spectral allocations. Especially discontinuous spectral allocation in UL destroys the PAPR benefits of the DFT-s-OFDM signal and reduces the PA output gain compared to CP-OFDM. Furthermore, as the UE PAs become more linear to support 256-QAM and higher modulations in UL, the DFT-s-OFDM and CP-OFDM performance approach the corresponding linear PA performance and the benefits of CP-OFDM based UL become larger over the evolution of hardware in 5G NR.

In Fig. 3, the link performance for two-user MU-MIMO is given for (a) QPSK and (b) 64-QAM modulated signals. It is assumed that within each 4 PRB allocation there is independent MU-MIMO session ongoing, so within the three 4 PRB allocations, there are in total six UEs transmitting to the base station (BS). In this scenario the differences between CP-OFDM and DFT-s-OFDM increase further, indicating the importance of CP-OFDM based UL for 5G NR. In Fig. 3 (a), the CP-OFDM based UL requires 1.7 dB smaller SNR than DFT-s-OFDM at BLER target 10%. Especially notable is the 4 dB difference at 1% BLER level, which can be assumed for control channel and maybe for the future ultra reliable low latency communications (URLLC). This implies that in MU-MIMO, which is seen as the dominant UL scheme for 5G NR,



(a) (b)

Fig. 2: 5G NR UL link performance results for (a) QPSK data modulation and (b) 64-QAM data modulation assuming a single user transmission per allocation.



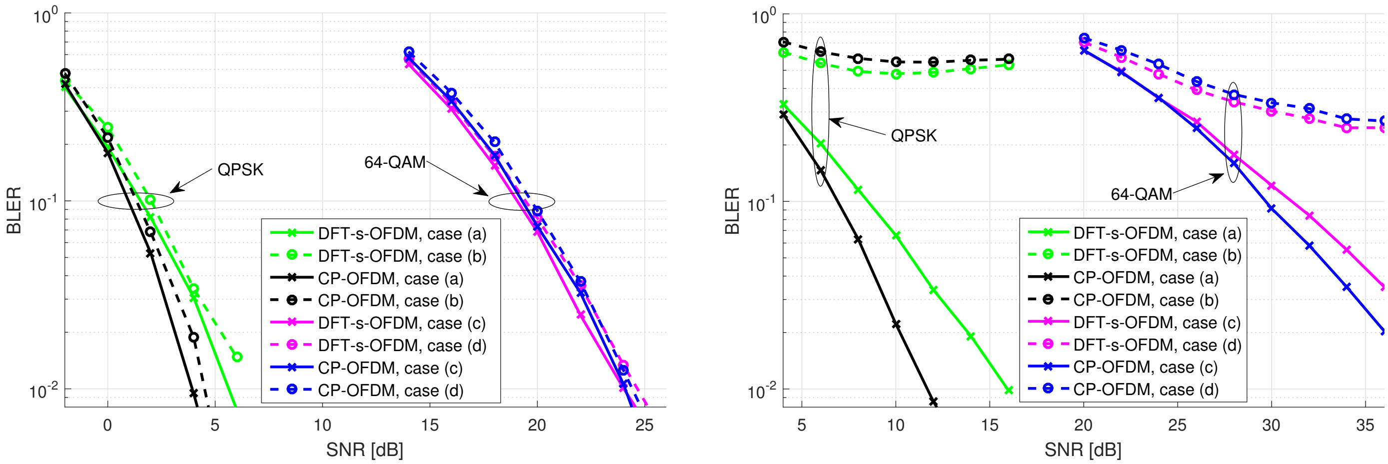
(a) (b)

Fig. 3: 5G NR UL link performance results for (a) QPSK modulated and (b) 64-QAM modulated UL signal assuming a multi-user MIMO transmission with two UEs transmitting a single layer per allocation.

CP-OFDM provides 1.7 dB improvement in the link budget for cell edge UEs and 4 dB link budget improvement for control channel signaling. These are substantial benefits in the mobile radio network context.

In Fig. 3 (b), the performance for 64-QAM modulated desired signal is illustrated for the two-user MU-MIMO scenario. Here, CP-OFDM requires 1.4 dB smaller SNR to achieve the BLER target of 10%. Noting the 1 dB higher MPR required with the highly non-linear polynomial PA model, CP-OFDM can still provide 0.4 dB improvement in the link budget. Again, noting the difference in required SNR between CP-OFDM signal with or without a PA model implies that there is a larger margin for performance improvement due to PA evolution than there is for DFT-s-OFDM. The differences in the performance between CP-OFDM and DFT-s-OFDM observed in Figures 2 and 3 are due to frequency selective channel within the allocation and CP-OFDM's better tolerance against multi-stream-interference.

In the following evaluations with inter-allocation interference, the average power level of interfering signals in the receiver is adjusted by the required SNR of each modulation in interference free scenario. From Figures 2 and 3 it is observed that in single user scenario the SNR difference between QPSK and 64-QAM is approximately 18 dB and in MU-MIMO scenario the difference is approximately 23 dB. These values are used in evaluations with inter-allocation interference. Thus, for example in single user scenario and case (b), the average power of the desired QPSK signal is 18 dBs smaller than for interfering 64-QAM signals. This corresponds to the case in practical Rx which has a certain noise floor and is receiving



(a) (b)

Fig. 4: 5G NR UL link performance with adjacent subband interfering signals for (a) single layer UEs and (b) two UE multi-user MIMO transmissions per allocation. Interference cases follow the ones presented in Fig. 1.

UL signals with different scheduled modulation and coding schemes in neighboring allocations of size 4 PRBs.

IV. Performance Evaluation with Inter-Allocation Interference

In Fig. 4, the UL link performance in different interference cases shown in Fig. 1 is given in (a) for single stream UEs and in (b) for two-user UL MU-MIMO transmissions per allocation. In Fig. 4 (a), the results are closely inline with the results shown in Fig. 2 having approximately 0.6 dB higher SNR requirements in all cases than in the earlier evaluations where no adjacent subband interference signals were present. The same observations drawn for performance without interference in previous section hold here and it is clear that CP-OFDM UL signal is well suited for coverage limited UEs but in narrow continuous allocations with 64-QAM modulation it loses 1 dB to DFT-s-OFDM due to higher MPR requirement. From case (a) and (c) results we can also observe that the QPSK modulated CP-OFDM signal that slightly violated the inband emission mask requirements does not significantly degrade the performance of other UL UEs in the network.

In Fig. 4 (b), showing the UL MU-MIMO performance with adjacent subband interference, we can observe that with QPSK modulated interfering signals, cases (a) and (c), the CP-OFDM based UL link performance provides 1.5 dB gain in required SNR at BLER target level 10%. Thus, in these cases CP-OFDM based UL signal provides improved link budget for QPSK and 64-QAM modulated desired signal. For cases (b) and (d), the interference from the neighboring 64-QAM modulated aggressors is too high for the error control coding to work properly and the link performance is largely degraded.

The poor performance in Fig. 4 (b) is due to the spectral spreading of the interfering signals on top of the desired one. In this case Rx subband wise filtering discussed for 5G NR in [13] can't remove interference within the desired signal allocation. To improve the MU-MIMO UL performance with neighboring high MCS MU-MIMO UL signals either the scheduler has to

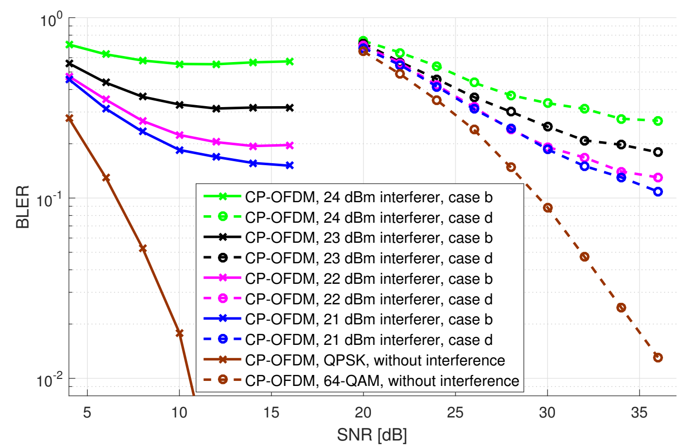


Fig. 5: Effect of increased backoff on interfering 64-QAM modulated MU-MIMO signal on the performance of the desired 5G NR UL MU-MIMO link.

provide guard band between UL signals, the PA linearity has to be improved or higher MPR has to be used. Improvement in the PA linearity throughout the 5G NR evolution is inevitable and will improve the performance compared to the current highly non-linear 3GPP polynomial UE PA model. Increasing the MPR for UL MU-MIMO signals using high order modulation reduces the range of operation. On the other hand, the inter-allocation interference degrades also SU-MIMO performance and not only MU-MIMO performance.

The results shown in Fig. 4 (b) also demonstrate the effectiveness of MU-MIMO for cell edge communications because the QPSK-based desired signal performs well with QPSK-based interference (case (a)) and the high rate UE link performance is not affected by the QPSK-based neighboring MU-MIMO inter-allocation interference (case (c)). Thus, MU-MIMO is an important tool to boost the cell-edge performance in 5G NR.

In Fig. 5, the effect of increased power backoff on the interfering signal is illustrated for CP-OFDM based UL. All the other parameters are kept as in Fig. 4 (b), and only the Tx power of the interfering signal is decreased to reduce the spectral spreading caused by the highly non-linear PA model. From Fig. 5, we can observe that the linearity of the PA model has a clear effect on the interference between allocations and also that significant power backoff is required with highly non-linear PAs to support frequency multiplexing of narrow MIMO allocations. These results clearly indicate that more linear PA implementations, than the one assumed by the 3GPP polynomial PA model, are required for 5G NR to truly unleash the high capacity UL which is promised by the physical layer design.

V. Conclusion

In this paper, the 5G NR UL link performance with CP-OFDM and DFT-s-OFDM based waveforms were compared, first in a scenario without inter-allocation interference and with or without a highly nonlinear polynomial PA model, followed by a synchronous inter-allocation interference evaluations with multiple different interference cases. In addition, the performance in traditional single stream UL and two layer, two-user multi-user MIMO UL were evaluated. The UL multi-user MIMO is, in general, seen as the dominant UL operation mode for 5G NR due to the high spectral efficiency requirements [5].

It was shown that CP-OFDM based UL access can achieve the same PA output power as DFT-s-OFDM signal with QPSK modulation, reflecting coverage limited UEs assuming relaxed EVM and inband emission requirements, and that these relaxations do not affect the UL link performance. With the presented link performance results it can be concluded that CP-OFDM based waveform allows to achieve the same or better link budget for coverage limited UEs. In UL MU-MIMO scenario, CP-OFDM based UL provided 1.7 dB improvement in coverage limited data connection measured at 10% BLER target and up to 4 dB improvement at BLER target 1%, which can be assumed for control channel and for future ultra reliable low latency communications.

With high-throughput parameterization assuming a 64-QAM modulation for the desired signal, the CP-OFDM based signal needs 1 dB higher MPR with the used highly non-linear PA model and this is seen as approximately 1 dB worse link budget in traditional single stream UL transmissions. In the multi-user MIMO case, it was shown that the CP-OFDM provides clear link performance gain over DFT-s-OFDM based signal and also improved link budget.

For UL-MIMO with high modulation order UEs the requirement for more linear PAs was noted as the link performance was shown to be clearly degraded in inter-allocation interference cases with 64-QAM based MU-MIMO interference signals. This observation holds also for high order SU-MIMO UEs causing inter-allocation interference.

In addition, CP-OFDM based UL access provides higher performance improvement potential with evolving PA technology and linearity than DFT-s-OFDM, thus driving the PA development to fully capitalize the high-throughput performance of 5G NR and to push the CP-OFDM based UL coverage and throughput beyond what was achieved in LTE with DFT-s-OFDM.

Acknowledgment

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