5G New Radio UL Coverage with Peak Clipping

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***Abstract*—For the 5G new radio physical layer the CP-OFDM waveform has been chosen as the baseline for communications below 40 GHz. The requirement for multicarrier waveforms used for uplink is to achieve similar coverage as achieved by SC-FDMA in LTE uplink. In this paper, multiple candidate waveforms with enhanced CP-OFDM processing proposed for 5G incorporating realistic 3GPP compliant power amplifier model and peak clipping are evaluated in uplink transmission, and compared against SC-FDMA in terms of maximum average power amplifier output power and coded block error rate. It is shown that multicarrier waveforms have minor disadvantage in single-PRB transmission, but as the allocation size increases to encounter frequency selective fading the multicarrier waveforms provide similar or even improved link budget compared to SC-FDMA uplink. This implies that given the expected cell edge throughput requirements for 5G mobile broadband services and expected power amplifier development, enhanced CP-OFDM waveforms can achieve the uplink coverage requirement.**

***Keywords*—5G new radio, PHY layer, CP-OFDM, SC-FDMA, f-OFDM, UFMC, WOLA, PAPR, power amplifier, peak clipping, coverage, link budget**

I. Introduction

In the recent technical report [1], describing the 5G new radio (NR) physical layer, it is defined that cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) is the baseline waveform for below 40 GHz communications. It also defines that bandwidth utilization efficiency higher than the current 90% in LTE [2] and mixing different numerologies and services inside one channel should be enabled by the 5G NR. In 5G NR, also the single carrier frequency division multiple access (SC-FDMA) waveform is supported in uplink (UL) in coverage limited scenarios. The SC-FDMA waveform is used only in single layer transmission and with low modulation and coding schemes.

For 5G NR, where time domain duplexing (TDD) is assumed to be the dominant duplexing scheme, it is preferable to use multicarrier waveform in both UL and downlink (DL). This simplifies the UL and DL transceiver design, allows improved interference cancellation schemes, and aligns the control channel and reference symbol designs in UL and DL. Therefore, it is preferred to search for techniques to reduce PAPR in the multicarrier transmission to achieve the same UL coverage or link budget as is currently defined for LTE.

In this paper, the performance of a narrow band SC-FDMA transmission representing LTE UL performance is compared against different enhanced CP-OFDM waveform candidates discussed in 5G NR. A simple peak clipping scheme is adopted to reduce the backoff requirement with multicarrier waveforms. The evaluations concentrate on UL, which is typically the limiting direction in the link budget design. In this paper, a polynomial power amplifier (PA) model which was recently accepted in 3GPP TSG-RAN WG1 for 5G NR evaluations is used [3]. PA output power and link performance comparisons are performed for 1, 4, and 12 physical resource block (PRB) allocations, from which 1 PRB allocation provides the maximum power spectral density (PSD) and 12 PRB allocation is the largest allocation defined in LTE that can be used without maximum power reduction (MPR) [4] for a 10 MHz carrier bandwidth. Assuming a single tap linear minimum mean square error (LMMSE) equalizer in the receiver (Rx), it is shown that in the case of 1 PRB transmission SC-FDMA still provides link budget gain when compared to multicarrier waveforms with PAR clipping, whereas in the case of 4 PRB allocation all candidates provide similar performance, and for 12 PRB transmission multicarrier waveforms with PAR clipping provide better link budget. In addition, given the *User experienced data rate* target of 100 Mbit/s for enhanced mobile broadband operation (eMBB) defined in International Telecommunication Union recommendation [5][Fig. 3], the increased cell edge DL data rates require the effective pathloss in the link budget to be reduced. This further eases the use of enhanced CP-OFDM waveforms for UL connectivity in most scenarios. The role of SC-FDMA is still important to provide additional degree of reliability to the high throughput eMBB UL control channels and to allow implementation of low throughput, low complexity, and low power consumption terminals or devices designed for massive machine type communications. Furthermore, as the user equipment (UE) PA technology evolves to support higher order modulations, the linearity of the PAs improves and the difference in the PA output power with multicarrier and SC-FDMA waveforms decreases independently of the allocation size.

The rest of this paper is organized as follows. The evaluated system description, considering waveforms and peak clipping methods, as well as simulation parameters are described in Section II. Performance results are presented, analyzed, and discussed in Section III. Finally, conclusions are drawn in Section IV.

II. System Description

The evaluated system, conforming to 5G physical layer description in [1], follows an LTE like parameterization for a 10 MHz channel bandwidth, as described in Table I. The transmitted subframe used to evaluate the PSD after PA contains only data symbols, and no control channel or reference symbols. The control channel design nor the reference symbol layout has not yet been decided, so the initial evaluations are performed based only on data symbols. In Fig. 1, a simplified block diagram of the Tx chains used with (a) SC-FDMA or

(b) CP-OFDM based waveforms are given. With CP-OFDM based waveforms, the channel filtering, subband filtering, or time domain windowing is illustrated as one generic processing block, which is an implementation specific selection as long as the Tx processing is transparent to the Rx [1].

A. Basic System Assumptions and Performance Measures

The UE is assumed to have either 1, 4, or 12 PRB allocation for transmitting in UL at the cell edge, so the PA is driven with maximum output power while fulfilling the error vector magnitude (EVM), out-of-band (OOB) emission mask, and adjacent channel leakage ratio (ACLR) requirements [4]. The LTE specification defines 17.5% EVM target for QPSK modulation. Here it is assumed that the peak clipping and PA can cause 12% EVM and the remaining error margin is used by other sources, e.g., I/Q imbalance, phase noise, etc. The allocated PRBs are located contiguously on the left hand side of the target channel, placing them as close to the channel edge as possible following the LTE specification [4]. This represents the most difficult scenario for the uplink signal. For multicarrier waveforms, by scheduling cell edge UEs to the center of the channel, lower backoff can be used as long as the inband emission requirements are fulfilled [4].

The EVM is evaluated by inserting a signal from the PA output to the waveform detector. No equalization is applied. For f-OFDM and UFMC (described in more details later), transmitter (Tx) side pre-equalization and Rx side compensation for Tx and Rx filters are applied. These measures are taken to compensate for the amplitude attenuation in the subband edges in the Tx and Rx side. In the evaluation of the EVM, the FFT window is located at the end of the CP-OFDM symbol. This measure allows maximal channel delay spread and also gives the strongest indication of possible intersymbol interference between transmitted symbols.

The PA model is a polynomial model of order nine accepted for 5G NR UL evaluations [3]. The model is based on a polynomial fit on the output of a commercial UE PA in such a manner that a fully populated 20 MHz LTE UL signal with QPSK modulation is able to achieve 26 dBm PA output power with 1 dB MPR, while still meeting the minimum ACLR requirement of 30 dB for E-UTRA. It is also assumed that there are 4 dB of losses after the PA, so the maximum allowed PA output power is 27 dBm leading to maximum radiated power of 23 dBm, corresponding to the UE power class 3 average value defined in [4][Table 6.2.2-1]. The polynomial model should be used only for input levels between -30 dBm and 9 dBm. The 1 dB input power based compression point is at $P_{1dB} = 3.4$ dBm.

B. 5G NR Waveform Candidates

In the following performance evaluations and comparisons several CP-OFDM based waveform candidates proposed for 5G NR are evaluated, including CP-OFDM with LTE like Tx filtering, windowed overlap-and-add processing with CP-OFDM (WOLA) [6], [7], and subband filtered OFDM. For subband filtered OFDM, two different candidates are evaluated: universal filtered multicarrier (UFMC) (recently known also as UF-OFDM) [8], [9] and filtered-OFDM (f-OFDM) [10]. The SC-FDMA uses a similar LTE like channel filter as is used

TABLE I: Baseline physical layer parameterization

Parameter	Value
Carrier frequency	4 GHz
Channel model	TDL-C 1000 ns
Number of Tx antennas (UE)	1
Number of Rx antennas (BS)	2
Carrier bandwidth	10 MHz
Sampling rate	15.36 MHz
FFT size	1024
CP length (N_{CP})	72
Guard period	72
Subcarrier spacing (ΔF)	15 kHz
Number of PRBs	50
Number of SCs per RB	12
Number of active SCs	600
Number of OFDM symbols per subframe	14
Modulation	QPSK
Coding rate	1/2
EVM target [%]	12
ACLR target [dB]	30

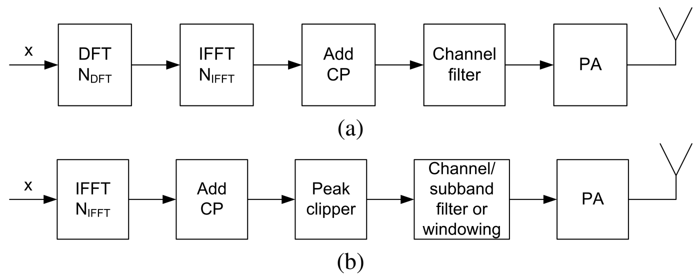


Fig. 1: Simplified Tx block diagrams for (a) SC-FDMA and (b) CP-OFDM waveforms.

for CP-OFDM. The Tx filter is designed to achieve the LTE emission mask and ACLR target with fully populated 10 MHz transmission.

Two different parameterizations are assumed for f-OFDM and UFMC per allocation size. In the case of f-OFDM [10], tone offset (TO) defines the extra passband width with respect to the allocated bandwidth and is given in multiples of subcarrier spacing ΔF. For example, given the parameterization in Table I, TO=4 corresponds to a 60 kHz wider passband than allocation bandwidth. TO is used to reduce the inband EVM with f-OFDM. The Tx and Rx filters with or without TO are designed for different allocation sizes separately.

For UFMC [8], [9], a Dolph-Chebyshev FIR filter is used with length $N_f = 37$ or $N_f = 73$ samples. The shorter filter causes transients that occupy half of the CP length and longer filter transients fully occupy the CP duration. With Dolph-Chebyshev filter the side lobe attenuation (SLA) defines the stopband attenuation and is used to tune the 3 dB bandwidth of the filter. For the 1 PRB allocation the short and long filters have a SLA of 20 dB. For the 4 and 12 PRB allocations the UFMC operates on 4 PRB subbands, filtering each subband separately. For the 4 PRB subband filter, the short and long filters have SLA of 37 dB or 75 dB, respectively. In the case of UFMC, a zero-prefix is used.

In the case of WOLA [6], [7], window slope length of $N_{ws} = 72$ is used, corresponding to full CP length,

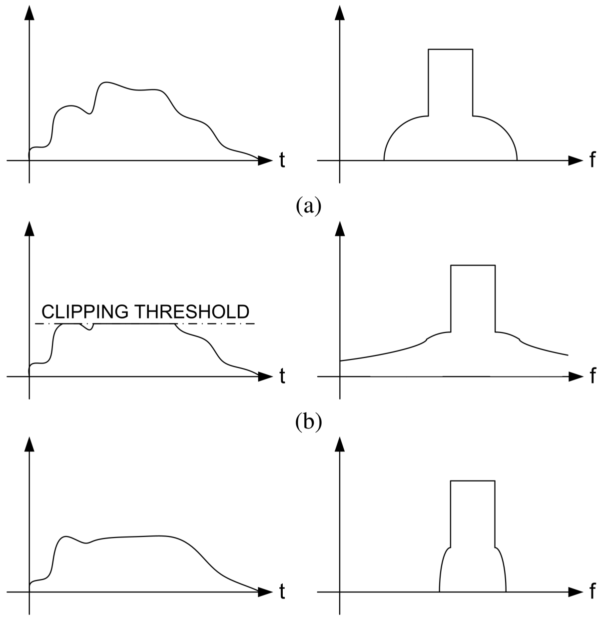


Fig. 2: Illustration of the peak clipping effect. Signal response in time and frequency (a) before clipping, (b) after clipping, and (c) after clipping and subband filtering.

respectively. The window slope length defines the length of the rising or falling slope. The total window length is $N_{win,Tx} = N_{FFT} + N_{CP} + N_{ws}$ and preceding symbols overlap by N_{ws} samples. On the receiver side, $N_{win,Rx} = N_{FFT} + N_{ws}$ long window is used to operate within the CP-OFDM symbol. After the overlap-and-add processing the FFT window is located in the middle of the WOLA processed symbol. The used window is a raised cosine window defined, e.g., in [11].

C. Peak Clipping

The peak clipping function to reduce the PAPR of the PA input signal is applied to the subband wise time domain signal after adding the CP or zero prefix. After this the signal is either filtered or windowed. In Fig. 2, a facile example of the peak clipping and its effects on time and frequency domain is given. In Fig. 2 (a), the original example signal is given. Then, in Fig. 2 (b), the signal is clipped in the time domain by a given clipping threshold. This leads to signal spreading in the frequency domain. Finally, in Fig. 2 (c), the signal is subband filtered to reduce the spectral regrowth. Due to the filtering, the PAPR of the clipped signal typically slightly increases. In 1 PRB and 4 PRB cases the processing is similar for all waveforms, but in the case of 12 PRB transmission the processing differs for UFMC. This is because UFMC is filtered in subbands of 4 PRBs, so each subband is first separately clipped and then combined after subband wise filtering. Also, because WOLA is based on time domain windowing, it can not reduce the spectral spreading in similar manner as filtering and therefore the use of peak clipping is more limited.

The peak clipping is performed in the baseband and is of minimal complexity. Peak clipping could also be performed after the upsampling required to model the PA induced spectral spreading. Both schemes have been evaluated and baseband peak clipping provides similar performance in the case of 1 PRB and better performance in the case of 4 and 12 PRB allocation. In the 12 PRB allocation case, if the peak clipping is performed after the subband filtering, the spectral spreading caused by clipping starts to dominate the OOB emissions and reduces the achievable PA output power.

TABLE II: Achieved PA output power gains with peak clipping

Waveform	PA output power gain [dB]		
	1 PRB	4 PRB	12 PRB
CP-OFDM	0.4	0.7	1.1
UFMC,$N_f = 37$	0.4	0.4	0.2
UFMC,$N_f = 73$	0.3	0.2	0.1
f-OFDM, TO=0	0.3	0.1	0.5
f-OFDM, TO=4	0.1	0.3	0.6
WOLA,$N_{ws} = 72$	0.3	0.3	0.1

The peak clipping function is defined as

$$G\left(x(n)\right) = \begin{cases} x(n) & , |x(n)| \leq A_{sat} \\ A_{sat} \cdot e^{j \arg(x(n))} & , |x(n)| > A_{sat} \end{cases} \quad (1)$$

where $x(n)$ is the discrete-time time-domain baseband input signal and A_{sat} is the clipping amplitude defined based on the given PAPR target $PAPR_{target}$, as

$$A_{sat} = \sqrt{PAPR_{target} + E[|x(n)|^2] - E[|x(n)|]^2}. \quad (2)$$

The $PAPR_{target}$ is an evaluation parameter approximating the PAPR after peak clipping. It should be noted that A_{sat} is now defined based on the mean power of the input signal, so the actual PAPR level after the amplitude clipper varies with the subframe realization. More complex schemes targeting a fixed PAPR in the clipper output or more advanced PAPR reduction schemes, e.g. windowed clipping [12], are left for future studies.

Different companding techniques were discussed in [13] and a well known iterative clipping-and-filtering technique is discussed in [14]. The peak clipping was chosen in this work because it is simpler to implement than companding or iterative clipping-and-filtering, and because the subband wise filters can efficiently remove the increased out-of-subband emissions caused by clipping.

The achieved PA output gains obtained through peak clipping are shown in Table II and are generally in line with the results shown in [13]. There are a few interesting outcomes regarding the PA output gain improvement shown in Table II. First, the channel filtered CP-OFDM is able to benefit most from the clipping process. This is related to the minimal inband distortion caused by the channel filter and to the bandwidth of the used filter, which allows to retain lower PAPR after filtering. Second observation relates to UFMC and f-OFDM parameterizations which have larger inband attenuation leading to lower gains. These are TO=0 case for f-OFDM, and $N_f = 73$ case for UFMC. This effect is related to the required inband pre-equalization done in the transmitter to remove the inband attenuation caused by the subband filter. Finally, WOLA is able to gain from peak clipping, although the related signal processing is not able to suppress the leakage power caused by peak clipping. The gain is achieved by clipping the highest peaks which then allows a modest reduction in power backoff before significant spectral regrowth occurs.

III. Performance Results and Analysis

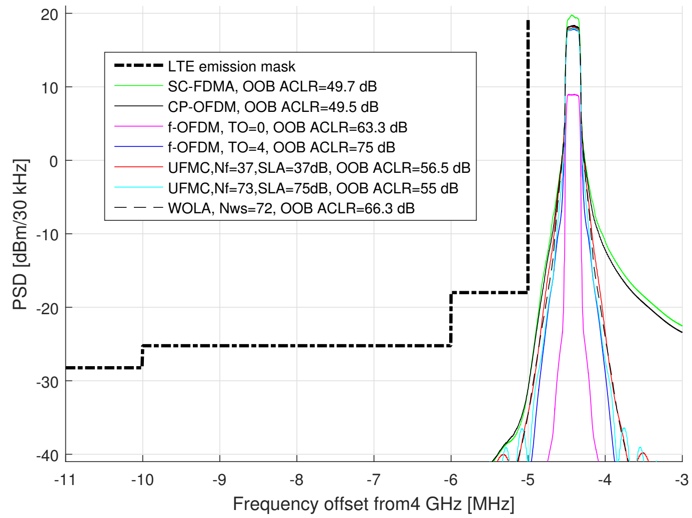
In this section, the achievable maximum PA output power and coded link performance in terms of required SNR for BLER targets 1% and 10% are evaluated. BLER target 1% can be considered for control channels, and BLER target 10% is typically assumed for channel coded wireless communications together with hybrid automatic repeat-request (HARQ) support. The presented BLER results are without HARQ. The PSD results were averaged over 100 independent subframe realizations and BLER results over 30000 subframe realizations. The optimal PA output power and PAPR target pairs were searched in a brute force manner through different input backoff values and PAPR targets with resolution of 0.1 dB.

A. Maximum PA Output Power

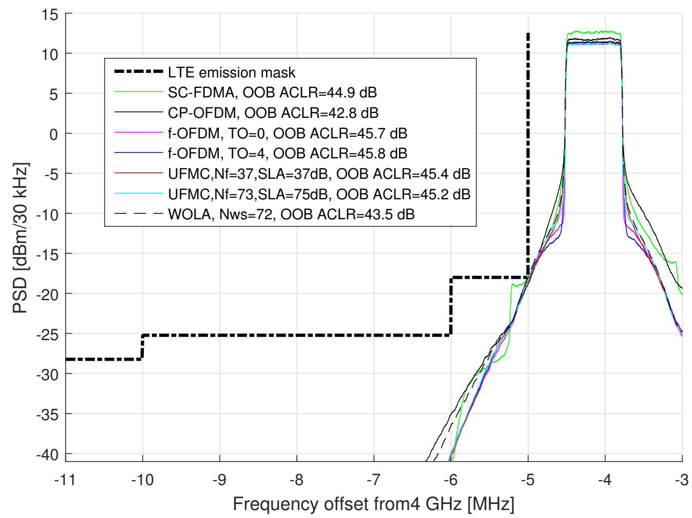
In Fig. 3 the simulated PSD curves at PA output for the case of 1 PRB, 4 PRB, and 12 PRB transmission are shown for all waveforms. In the figures also the LTE UL OOB emission mask is drawn. The PSDs are evaluated with 30 kHz measurement bandwidth and the LTE emission mask is scaled correspondingly for the whole frequency range. The OOB ACLR obtained by each waveform is defined as the ratio of average power of the desired channel over the leakage power in the neighboring channel.

From Fig. 3 (a) three observations can be made for 1 PRB transmission. First, the OOB emissions in terms of fulfilling LTE emission mask or OOB ACLR target are not an issue and multicarrier waveforms are limited by the EVM requirement. There are significant variations in OOB ACLR between different waveforms, but these are meaningless because all waveforms are well below the 30 dB target value. Second observation is that CP-OFDM and SC-FDMA using an LTE like channel filtering are unable to suppress the inband power leakage. All other waveforms are designed to suppress leakage power on a subband level and therefore achieve clearly lower inband leakage power levels. Third observation is the very low power density achieved for f-OFDM with TO=0. This is caused by the high inband EVM inherent to f-OFDM in narrow band transmission if TO is not used. This forces us to limit the error caused by the PA to be marginal and leads to significant radiated power reduction, as is seen from Table III. This result is also affected by the Rx side FFT window location, which in the used parameterization emphasizes the filter induced inter-symbol-interference.

In the 4 PRB case, shown in Fig. 3 (b), the shape of the PSD response is clearly different from the 1 PRB case. The PA spectral regrowth is now the dominant factor limiting the PA output power because all waveforms are limited by the LTE emission mask. Although not clearly visible from Figures 3 (b) and 3 (c), there is a similar clear difference in the inband leakage power between channel filtered waveforms and subband processed waveforms as shown in Fig. 3 (a).



(a)



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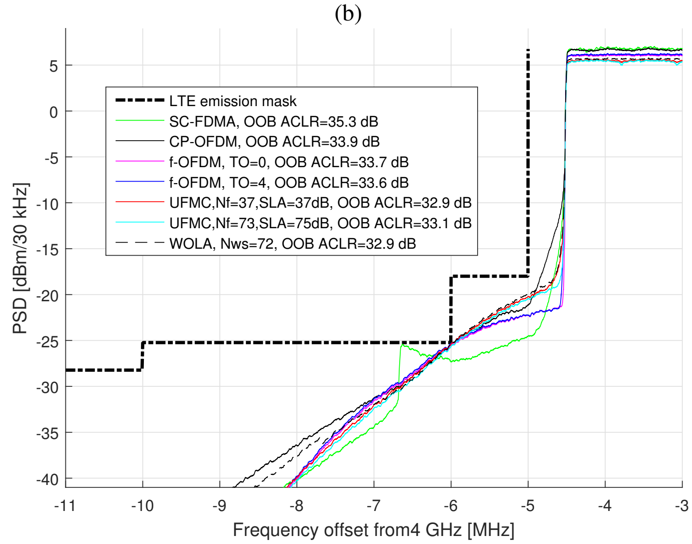


(c)

Fig. 3: PSD comparison of the different waveforms with peak clipping and polynomial PA model with (a) 1 PRB, (b) 4 PRB, and (c) 12 PRB allocation

In Fig. 3 (c), the PSD responses of different waveforms are shown for the 12 PRB transmission case. The waveforms seem to have similar behavior as in 4 PRB case, but through careful inspection it can be observed that the CP-OFDM and SC-FDMA provide approximately 5 dB worse spectral containment in the inband region. Other waveforms are on similar level on the inband side of the allocation.

In Table III the achievable PA output power in dBm, EVM percentage, and the used PAPR target value in dB are provided. For 1 PRB allocation, the different multicarrier waveforms provide similar PA output power, except for f-OFDM with TO=0. All multicarrier waveforms are limited by the 12% EVM target. Typically, the share of distortion caused by PAPR clipping and PA is roughly 6% each, so they contribute evenly on the inband error with the used peak clipping and polynomial PA model. SC-FDMA is limited by the assumed maximum of 27 dBm. SC-FDMA can facilitate on average 1.5 dB higher PA output power if the very low performing f-OFDM with TO=0 is excluded from the multicarrier waveform average in the 1 PRB allocation case.

Considering the achieved PA output powers with 4 PRB allocation, the first observation is that now the average inband EVM of the f-OFDM with TO=0 is not dominated by the few bad subcarriers in allocation edges, and provides similar PA output power as the rest of the multicarrier waveforms. Next observation is that waveforms with largest inband pre-equalization coefficients requirements require also largest PAPR target, as is seen for f-OFDM with TO=0 and UFMC with $N_f = 73$. Last observation is that from here on WOLA is not EVM limited unlike other multicarrier waveform candidates. Instead, it is limited by the emission mask because it can not suppress the spectral regrowth caused by the peak clipping. Still, the performance of WOLA is comparable to filtered waveform candidates.

In the case of 12 PRB allocation, the differences between the maximum PA output powers of the different waveforms are now smaller as the allocation size is increased. For WOLA, the relative PA output power when compared to other multicarrier waveforms is reduced but is still on a comparable level, where as the PAPR target is already clearly larger and the inband EVM clearly smaller. In this case, the average PA output power gain in benefit of SC-FDMA is only 0.8 dB on average, and only 0.1 dB when compared to channel filtered CP-OFDM.

While the performance was limited only by the inband EVM in the 1 PRB case, also the emission mask limits the achievable PA output power with 4 PRB and 12 PRB allocation. Interestingly, the difficult region is the emission mask corner at 1 MHz distance from the channel edge. The spreading at this point is dominated by the PA model and it is very difficult to improve the PA output power with simple amplitude clipping. In addition, it should be noted that in these evaluations the PSD measurement bandwidth is 30 kHz for the full frequency range and the LTE emission mask is scaled accordingly. In the LTE specification [4], the measurement bandwidth is switched to 1 MHz at 1 MHz distance, which can lead to more relaxed comparison compared to the one used in this paper. The 30 kHz measurement band was chosen because in NR one can expect narrowband services to co-exist with eMBB and therefore it is important to evaluate the emissions with finer measurement bandwidth than 1 MHz also in the OOB emission evaluations.

TABLE III: Maximum PA output power

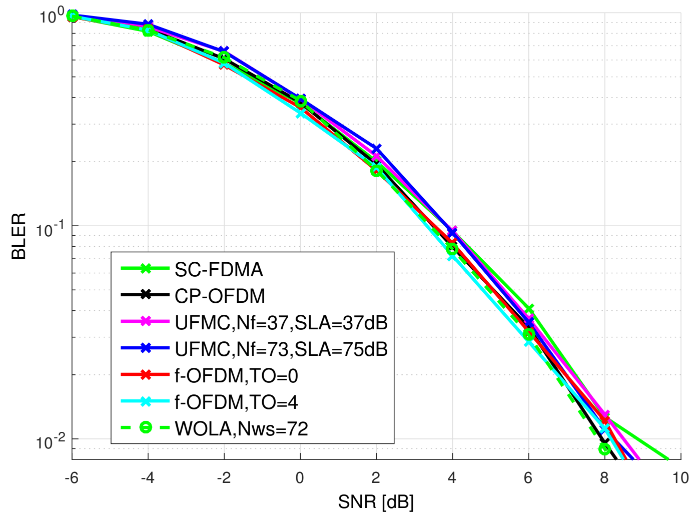
Waveform	PA power [dBm]	EVM [%]	PAPR target [dB]
	1 PRB allocation		
SC-FDMA	27.0	8.5	-
CP-OFDM	25.8	12.0	4.2
UFMC, $N_f = 37$	25.5	12.0	4.3
UFMC, $N_f = 73$	25.4	12.0	4.8
f-OFDM, TO=0	16.4	12.0	6.6
f-OFDM, TO=4	25.3	11.8	4.5
WOLA, $N_{ws} = 72$	25.7	12.0	4.8
	4 PRB allocation		
SC-FDMA	26.3	7.6	-
CP-OFDM	25.5	12.0	4.3
UFMC, $N_f = 37$	25.0	12.0	5.2
UFMC, $N_f = 73$	24.9	12.0	6.0
f-OFDM, TO=0	24.9	12.0	6.4
f-OFDM, TO=4	25.1	12.0	4.8
WOLA, $N_{ws} = 72$	25.1	10.5	4.6
	12 PRB allocation		
SC-FDMA	25.3	8.3	-
CP-OFDM	25.2	11.9	4.0
UFMC, $N_f = 37$	24.1	11.9	4.1
UFMC, $N_f = 73$	24.0	12.0	4.4
f-OFDM, TO=0	24.6	12.0	4.3
f-OFDM, TO=4	24.7	12.0	4.1
WOLA, $N_{ws} = 72$	24.2	8.6	5.5

B. Link Performance with Maximum PA Output Power

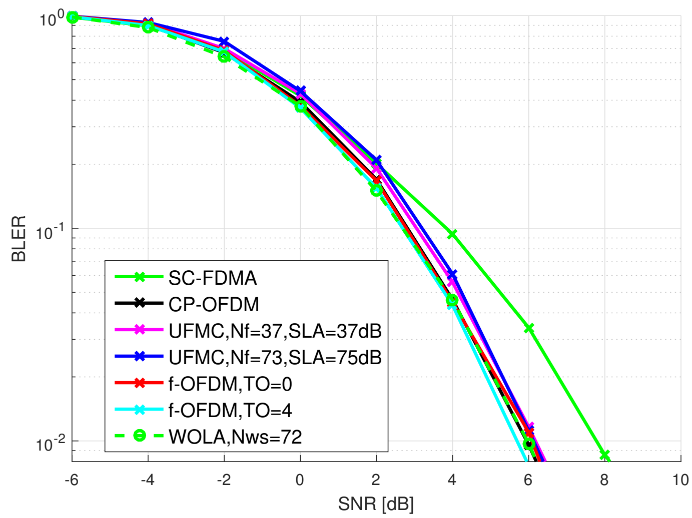
With all allocation sizes, the BLER performance with or without PA and clipping is the same for each waveform candidate, indicating that fullfilling the 12% EVM target does not affect the performance with QPSK and coding rate $R = 1/2$. All waveforms go through a similar Rx processing including a single tap LMMSE channel equalizer. The single tap LMMSE assumption for all waveform candidates allows to share the same equalizer solution between CP-OFDM and SC-FDMA waveforms, thus simplifying the BS Rx design for 5G NR. Ideal channel estimates are assumed in the simulations. The channel codec is an LTE compliant turbo codec [2] with 8 max-log-MAP decoding iterations. The PSD and link performance results are obtained from the highly sophisticated Nokia Bell Labs link simulator.

In Fig. 4 (a), the coded link performance of the different waveforms with 1 PRB allocation and using the average PA output powers given in Table III are shown. The SNR is not affected by the PA power, because it is normalized in the link performance simulations, thus only the inband distortion affects the performance. In the case of 1 PRB, there is no significant difference between the BLER performance of SC-FDMA and multicarrier waveforms. This is because the used channel model, TDL-C 1000 ns [15] where the 1000 ns defines the RMS delay spread, results essentially to a flat channel inside 1 PRB allocation. Because there is no meaningfull difference between SC-FDMA and the multicarrier waveform candidates, the SNR gain for SC-FDMA is on average 0 dB.

In Fig. 4 (b), the link performance with 4 PRB allocation is shown for different waveform candidates. In the case of 4 PRB and with larger allocations, the frequency selectivity of the



(a)



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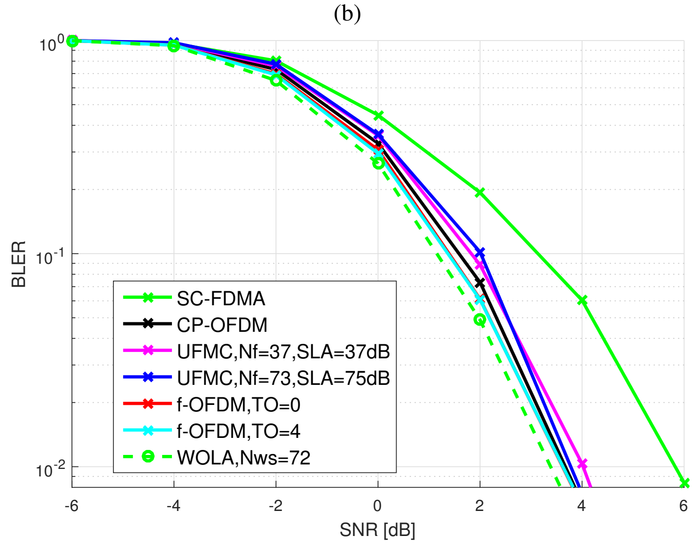

(c)

Fig. 4: Link performance in TDL-C 1000ns channel with (a) 1 PRB, (b) 4 PRB, (c) 12 PRB allocation

TABLE IV: Average link budget gain for SC-FDMA compared to peak clipped multicarrier waveforms

BLER target	Allocation size		
	1 PRB	4 PRBs	12 PRBs
10 %	1.5 dB	0.35 dB	-0.7 dB
1 %	1.5 dB	-0.75 dB	-1.3 dB

selected channel model starts to affect the relative performance between SC-FDMA and multicarrier waveforms. The SNR loss for SC-FDMA is from 0.6 dB to 1.1 dB at BLER target 10% and from 1.8 dB to 2.1 dB at BLER target 1%.

In Fig. 4 (c), the coded link performance using the PA output powers of Table III is shown for 12 PRB allocation. Now the channel is already strongly frequency selective inside the allocation and a clear difference in the performance between SC-FDMA and other waveform candidates is observed. All waveforms are processed by the same LMMSE channel equalizer and channel decoder, which indicates that the SC-FDMA performance loss is due to the noise spreading in the inverse DFT after frequency domain equalization. The SNR loss for SC-FDMA is from 1.1 dB to 1.9 dB at BLER target 10% and from 1.8 dB to 2.4 dB at BLER target 1%.

The average link budget gains for SC-FDMA signal with different allocation sizes are given in Table IV. The gain in the achievable PA output power and the gain or loss in the link performance SNR are added together to obtain the total link budget gain of SC-FDMA versus multicarrier waveform candidates. The average link budget gain is defined as the difference between average PA output power gain and average SNR gain or loss. Average PA output power gain is defined as the difference between SC-FDMA PA output power and average PA output power over multicarrier waveforms. Similarly, average SNR gain is the difference between SC-FDMA SNR requirement and average SNR requirement for different multicarrier waveforms. These results show that with 4 PRB allocation the SC-FDMA and multicarrier waveforms provide similar coverage and with 12 PRB allocation multicarrier waveform candidates are already better, especially if considering the control channel performance where the BLER target of 1% is can be assumed. The special case of 1 PRB transmission in UL providing the maximum power spectral density for the transmitted signal can still benefit from the SC-FDMA waveform to achieve the LTE like coverage.

IV. Conclusions and Discussion

In this paper, the maximum achievable uplink PA output power and link performance of several 5G new radio enhanced CP-OFDM waveform candidates were evaluated and compared against the SC-FDMA, which is used also in LTE uplink. Simple subband wise peak clipping scheme was adopted to obtain realistic results for the maximum PA output power of the new multicarrier waveform candidates. The evaluated waveform candidates include channel filtered CP-OFDM, subband filtered schemes f-OFDM and UFMC, and time domain windowed scheme WOLA.

The PA model used in the evaluations was a realistic polynomial model agreed on 3GPP TSG-RAN WG1 for uplink waveform evaluations, introducing a significant nonlinear distortion on the transmitted signal. The maximum PA output powers for different waveforms were obtained by evaluating the maximum PA output power per waveform with given allocation size at the edge of a 10 MHz channel with maximum allocation of 50 PRBs. Link performance was evaluated by including the peak clipping and PA induced distortion into simulations and evaluating the required SNR for multicarrier waveforms and SC-FDMA when targeting 10% or 1% BLER. Average link budget gain for SC-FDMA was defined as the sum of average PA output power gains and the average coded link SNR gain or loss.

It was shown that in 1 PRB transmission the SC-FDMA based radio access is able to provide 1.5 dB link budget gain, whereas in the 4 PRB case the average link budget gain is 0.35 dB at 10% BLER target and the average link budget loss is 0.75 at 1% BLER target. For 12 PRB transmission the SC-FDMA average link budget loss is 0.7 dB at BLER target 10% and 1.3 dB at BLER target 1%. This indicates that multicarrier waveforms using simple peak clipping to reduce PAPR provide similar link budget already with 4 PRB allocation and better link budget with 12 PRB allocation. Therefore, for 1 PRB transmission in uplink to obtain the maximum power spectral density, SC-FDMA based waveform should be used to achieve the LTE coverage in 5G NR while already with 4 PRB allocations, and beyond, better performance can be obtained through true multicarrier uplink radio access. Together with the cell edge target of 100 Mbit/s for eMBB, the increased cell edge DL data rate requires the effective pathloss in the link budget to be reduced which allows to use enhanced CP-OFDM waveforms for UL connectivity in most scenarios. The role of SC-FDMA is still important to provide additional degree of reliability to the high throughput eMBB UL control channels and to allow implementation of low throughput, low complexity, and low power consumption devices for massive machine type communications. Furthermore, as the user equipment PA technology evolves to support higher order modulations, the linearity of the PAs improves and the difference in the PA output power with multicarrier and SC-FDMA waveforms decreases independently of the allocation size.

In this paper, the performance between SC-FDMA and multicarrier waveforms was compared in the more traditional 4 GHz carrier frequency with LTE like numerology. The decision made in 3GPP TSG-RAN WG1 defines that the CP-OFDM and SC-FDMA based waveforms are used up to 40 GHz carrier frequency. Beyond 6 GHz carrier frequency the radiation environment, waveform parameterization, antenna array sizes, and RF distortion change significantly. This requires future studies on the comparison of these waveform variants in the new carrier frequencies to fully optimize the performance of the 5G new radio physical layer.

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