Influence of Transceiver Imperfections to Digital Pre-distortion Linearization - Application to 5G waveforms

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Abstract—In this paper, we present the quantitative study of the effects of the selected most important transceiver imperfections on the performance of digital baseband pre-distortion linearizers. Starting from the power amplifier model identification based on the measured data captured using the low-cost software defined radio platform (USRP), we evaluate the performance in term of out-of-band signal emissions at the power amplifier output for the case of typical representative of signals envisaged for fifth generation (5G) of mobile communication systems - filtered OFDM. The results are presented for the values of imperfections (IQ imbalances, DC offset) swept within the range of values corresponding to simple, commercially available wireless front-ends. We highlight the fact that the front-end imperfections can significantly affect the influence of pre-distorters.

Index Terms—filtered OFDM, FBMC, 5G systems, amplifier linearization, pre-distortion

I. Introduction

The future mobile communication systems with services like virtual reality, video streaming and cloud storage are related to high data rate transmission. This increasing demands on data transmission force network providers to increase their capacity and efficient use of spectrum. So called post-Orthogonal Division Multiplex (OFDM) modulation schemes are pre-determined waveforms in 5G mobile communication systems, because of their clear spectral mask. From the point of view of the Radio-Frequency (RF) transmitter front-end, to achieve high transmitter efficiency it is desirable to operate the power amplifiers (PA) close to their saturation point. These circumstances effects to transmitted waveforms by non-linear distortion which result both into adjacent channel as well as in the in-band signal distortion manifesting in increased Error Vector Magnitude (EVM).

There are several modulation schemes which have been proposed as the candidates for use in 5G systems. The Filter Bank Multi Carrier (FBMC) is a technique where the spectrum is divided into multiple orthogonal sub-bands [1], [2]. Each sub-band is filtered by a prototype filter. The first effect of the prototype filter is attenuation of side-lobes and decrease of inter-carrier interferences more than in the OFDM case. Due to this effect neither the Guard Interval (GI) nor the Cyclic Prefix (CP) is not needed [3]–[5] and the spectral efficiency is improved. Second effect is that the carriers may not be orthogonal because of the filtering which allow us to control bandwidth and the degree of overlap between sub-carriers. The third effect is that the FBMC sub-bands have not to be synchronized between themselves this fact can solve problems of possible synchronization and dispersion [6], [7].

The Generalized Frequency Division Multiplex (GFDM) is based on the circular-shifted prototype filter in time and frequency domain. Hence the Out Of Band (OOB) emissions are significantly suppressed. This fact allows that the modulation scheme is well suited for transmission on non-contiguous frequency bands with strict spectral mask constraints [8].

The filtered OFDM (F-OFDM) is a conventional OFDM signal passed through an appropriately designed spectrum shaping filter [9].

To preserve the advantages of such post-OFDM signals in presence of strongly nonlinear front-end devices (power amplifiers), it will be necessary to include pre-distortion processing into the 5G systems. The Digital Pre-Distortion (DPD) is the one of the most used techniques to reduce the effect of the non-linearities. Its main principle is to find an inverse characteristic of the PA. Although some non-traditional approaches, such as the neural network method were published [10], the most conventional methods arise from the use of Volterra Series (VS) and their derivatives. VS-based model is the most general model, due to its computational complexity the simplified forms have been presented in [11]–[14].

VS-based models are not able to capture all impairments of a transmitter such a in-phase to quadrature (IQ) imbalances and DC offset. This fact has significant effect on the DPD linearization process [15].

The paper is structured into several parts. The section II compares 5G candidates in point of view complementary

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cumulative distributive function (CCDF) of the Peak to Average Power Ratio (PAPR) and also discusses the PA model extraction. The part III discusses the used method of the DPD and PA model specification. The simulation results are introduced in the part IV. Finally the part V rounds up this paper.

II. Model extraction

Prior the investigation of the effects of the imperfections to DPD performance, we have been working on the estimation of model parameters of the real class AB in-house fabricated PA and on the measurement of practical values of individual imperfections. We made use of the commercially available software defined radio USRP N210. Simplified scheme of the measurement system is depicted in Fig. 1. The USRP N210 is intended for demanding communications applications and suitable for rapid development. The software radio is equipped with the modified WBX front-end with synchronous receiver and transmitter part which provides up to 100 mW of output power and a noise figure of 5 dB [16]. The WBX provides up to 40 MHz of bandwidth in range from 50 MHz to 2.2 GHz. Transmitted signal is amplified by PA and then attenuated and received by the WBX input and corresponding USRP processing chain.

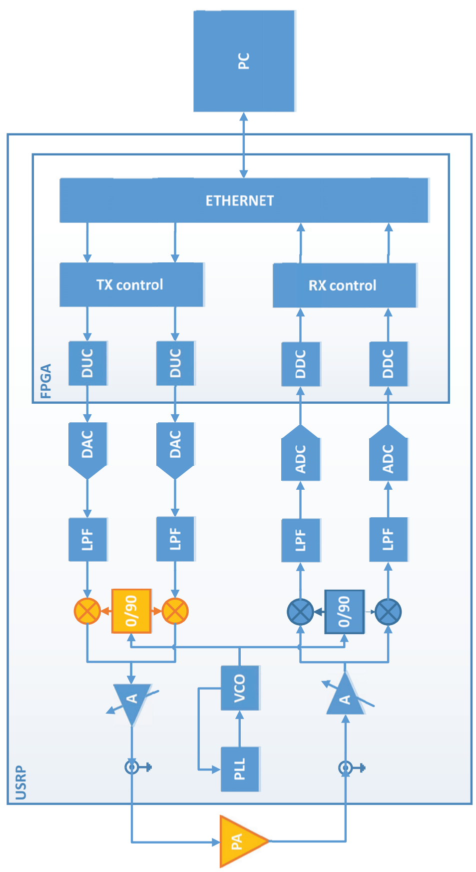

Fig. 1: Simplified system scheme (90 degrees rotated).

In the experiment the sampling frequency was 6.25 MHz and the carrier frequency was 800 MHz. The motivation for the choice of such frequency lies in the prospective use of bands below 1 GHz (especially 700 MHz) for 5G machine-type and ultra reliable low latency communications (URLLC). On the contrary, for the high bitrate-type communications, rather the spectrum in 1-6 GHz bands or even in millimeter-waves will be allocated.

Although the FBMC signal was initially used to extract the PA model coefficients, the same model can be used for experiments with DPD also for other 5G candidate waveforms, due to the almost identical statistics - Complementary Cumulative Distribution Function (CCDF) of Peak to Average Power Ratio of these signals. Please see the PAPR CCDF's on Fig. 2, with the main parameters of the considered 5G waveforms shown in Table. I.

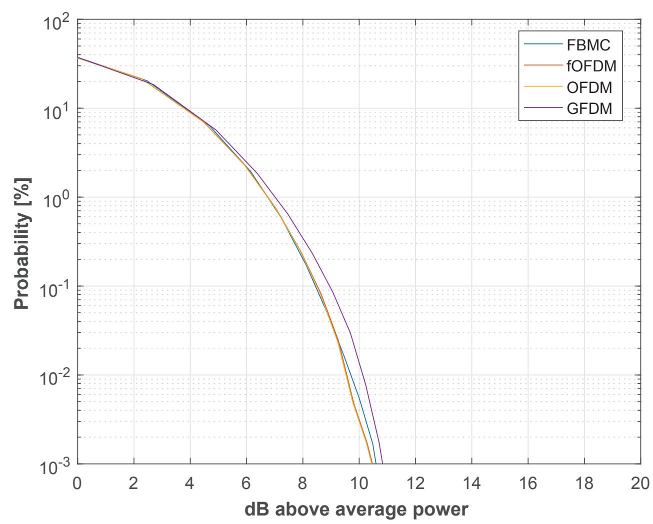

Fig. 2: CCDF of PAPR of examined 5G waveforms and OFDM

TABLE I: Filters and their setting for examined 5G waveforms

waveform	filter
f-OFDM	rectangular (0 tone offset)
FBMC	Phydyas [17] ($K = 4$)
GFDM	RRC [18] ($\alpha = 0.5$)

For further experiments, we decided to use F-OFDM signal, because this particular scheme, or some of its very close alternatives, has been recommended as the most perspective waveform for 5G system, [19].

Based on the experimentally obtained data, we have extracted the PA model in form of Orthogonal Polynomial

Series with Memory (OPSM), described in [12], [20] :

$$y(t) = \sum_{k=1}^{K}\sum_{q=0}^{Q} b_{k,q} \sum_{l=1}^{k} (-1)^{l+k} \frac{(k+l)!}{(l-1)!\,(l+1)!\,(k-l)!} |x\,(t-q)|^{k-l} x\,(t-q) \tag{1}$$

taken from [21]. The model has been identified for varying polynomial (K) and memory (Q) orders. Signal transmitted through the model is compared with the original signal transmitted through HW setup by Normalised Mean Square Error (NMSE)

$$NMSE[dB] = 10\log_{10}\left(\frac{\sum\limits_{n=1}^{N}|x-\hat{x}|^2}{\sum\limits_{n=1}^{N}|x|^2}\right) \tag{2}$$

where x is the original signal and $\hat{x}$ is the signal at the PA model output. The results are shown in Fig. 3. It is clear from the results that for a given amplifier model, it is not worth considering higher order polynomials, because they bring only a slight reduction at the cost of a large computational cost. Thus for the further experiments we have chosen K=3 ad Q=1.

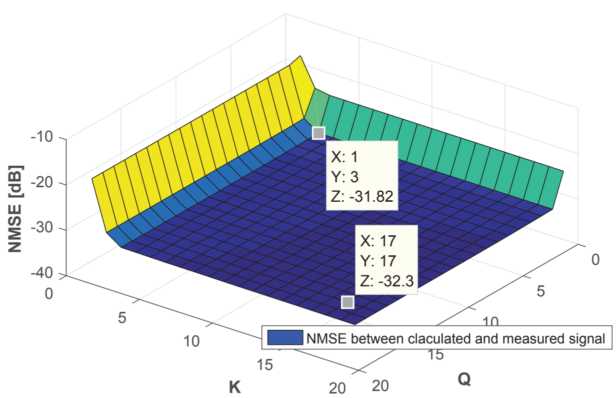

Fig. 3: NMSE function for PA model extraction as function of polynomial order K and memory order Q.

The extraction of IQ imbalances is performed by spectrum analyzer Rohde-Schwarz FSVR 13 on QAM signal with same bandwidth as used FBMC/F-OFDM signal. The reason for that is that the FSVR 13 is equipped with VSA analysis option, allowing to measure the IQ imbalances and DC offsets of the RF front-end on the basic digital communication signals. Such approach is not contradictory, as the front-end imperfections are signal-independent. The DC offset extraction is performed by digitally frequency shifting of the FBMC signal which allows to directly measure the DC offset. Measured result for DC offset is $0.00569 - j0.00569$ (result is normalized to full-scale of the signal equal to value of $1 + 1j$), the phase imbalance is -0.390 degrees and the gain imbalance 0.01 dB.

III. DPD method and model specification

To obtain less-complex models than Volterra series, various approaches can be used, including a dynamic deviation reduction (DDR) method. This method is based on removing high dynamic effect which has tendency to decrease with increasing non-linearity order [13]. Removing these higher-order terms leads to a significant simplification of complexity of the system. It is important to notice that such truncation is not directly equivalent to the non-linearity or memory truncation. A simplified equation of the second order DDR model can be written as:

$$\begin{aligned} y(t) &= \sum_{k=0}^{\frac{K-1}{2}}\sum_{i=0}^{Q} g_{2k+1,1}(i)|x(t)|^{2k}x(t-i) \\ &+ \sum_{k=0}^{\frac{K-1}{2}}\sum_{i=0}^{Q} g_{2k+1,2}(i)|x(t)|^{2(k-1)}x^2(t)x^*(t-i) \\ &+ \sum_{k=0}^{\frac{K-1}{2}}\sum_{i=0}^{Q} g_{2k+1,3}(i)|x(t)|^{2(k-1)}x(t)|x(t-i)|^2 \\ &+ \sum_{k=0}^{\frac{K-1}{2}}\sum_{i=0}^{Q} g_{2k+1,4}(i)|x(t)|^{2(k-1)}x^*(t)x^2(t-i) \end{aligned} \tag{3}$$

where $x(n)$ is discrete input signal and K is the non-linearity order and Q is the memory length. The total number of coefficients is $2QK + [(K+1)/2] - Q$. Such DDR model has been used for DPD coefficients extraction and performance evaluation with polynomial order varied from 3 to 11 and memory length varied from 0 to 1. We have considered the indirect learning architecture for DPD adaptation [21]. The imperfections of a quadrature modulator include gain and phase imbalance is modeled by the baseband signal model presented in [22] described by equation:

$$y = (\cos\Delta\phi - j\epsilon sin\Delta\phi)\,x + (\epsilon\cos\Delta\phi + j\sin\Delta\phi)\,x^* \tag{4}$$

The effect of the DC offset is simulated by adding a DC component after the variable gain pre-amplifier with ideal linear characteristic.

IV. Results

The results have been obtained by numerical system simulation in MATLAB which observation is in relationship with real system. The main investigated metric was the Adjacent Channel Power Ratio (ACPR) defined as the ratio of the power into adjacent (out-of-band) to the power in the main (in-band) channel, expressed in the logarithmic scale. We considered the bandwidths of main and adjacent channels being 0.25 and the frequency offset between the main and adjacent channels equal to 0.3 where all these values are relative to sample frequency.

The results have been plotted either as a function of the individual front-end imperfections, or as a function of the

PA operation point, expressed in term of Peak Back-Off (PBO), with PBO=0 corresponding to PA saturation.

A. Influence of front-end imperfections to DPD adaptation

In the first step, we decided to isolate each imperfection and to carry out simulations of ACPR as a function of DC offset and IQ imbalances separately. In the Fig. 4 we may see that for ideal transmitter (without imperfections) the DPD with higher number of coefficients has better performance than DPD with low orders. With increasing front-end imperfections the performance of high order polynomials is not suitable. The Fig. 5 shows similar, yet less dominant influence.

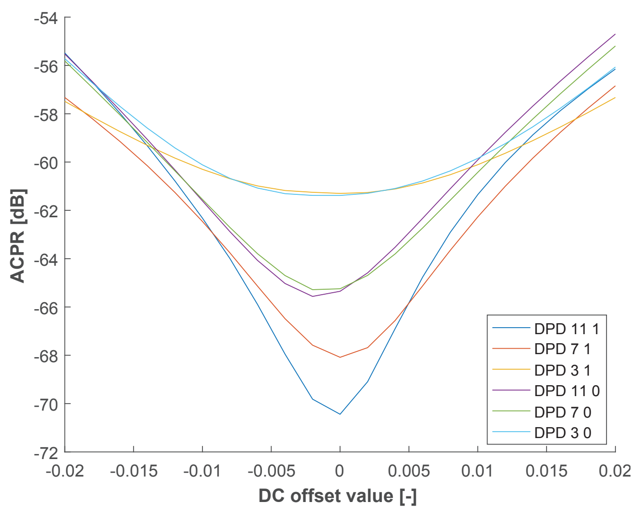

Fig. 4: ACPR as a function of the DC offset

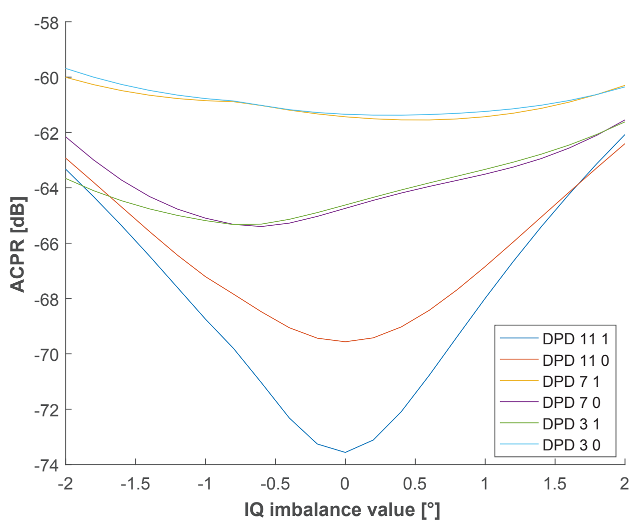

Fig. 5: ACPR as a function of the phase imbalance

B. Comparison between ideal and real system

Even considering the typical values obtained from the real hardware, we may compare ACPR for different DPD polynomials as a function of PBO. Results for ideal transmitter are shown in Fig. 6. It is evident that for such a case, for all PBO values the ACPR performance improves with increasing polynomial and memory order of DPD. The Fig. 7 shows that, especially for attenuated signal, lower ACPR performance is obtained which is caused by more dominant effect of imperfections with respect to the signal far from the PA saturation. This follows that, for lower power levels, the polynomials with lower number of coefficients provides less sensitive solution.

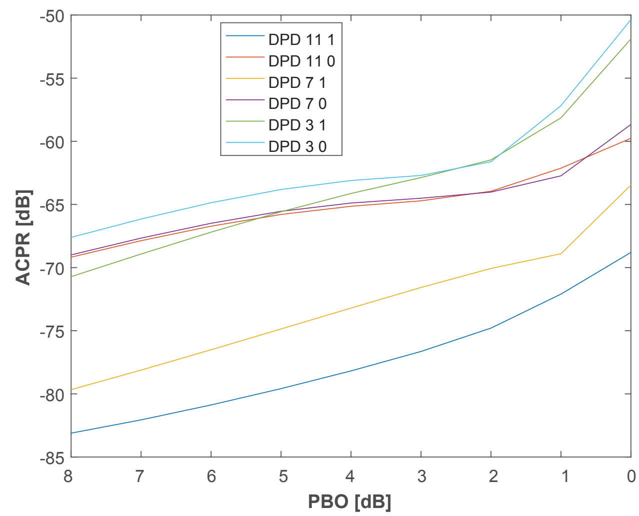

Fig. 6: ACPR as a function of PBO for system without imperfections

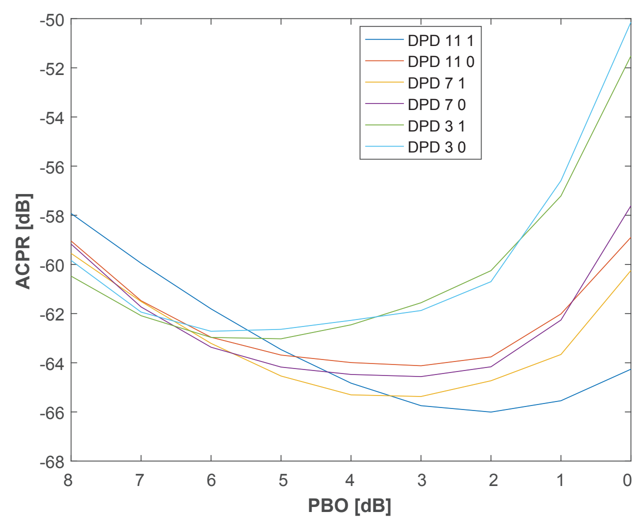

Fig. 7: ACPR as a function of PBO with influence of TX imperfections (the values set according to real measured HW parameters, i.e., gain imbalance $= 0.01$dB, phase imbalance $= -0.390$ degrees, DC offset $= 0.00569-\mathrm{j}0.00569$)

V. Conclusion

We have investigated the performance of power amplifier linearizers based on the digital pre-distortion principle. As the use case, we considered the filtered OFDM signal, chosen for application in the forthcoming 5G mobile communication systems and the power amplifier model extracted from data measured by USRP N210 software defined radio. We analysed, how the performance of predistorters with varied number of coefficients is degraded by the front-end imperfections. Based on the presented analysis, we may conclude:

- with no front-end imperfections, higher order DPDs usually provide superior ACPR performance
- with practical values of front-end imperfections, the ACPR performance of DPD is degraded for the whole power amplifier operation range. In the linear region of power amplifier characteristics, i.e., for high peak back-off values, the use of lower order pre-distorters may result in better performance in contrast to higher order pre-distorters, while close to the saturation (peak back off approaching zero) the need for higher pre-distorter order is evident.

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