# Peak Cancellation and Digital Predistortion of High-Order QAM Wideband Signals for Next Generation Wireless Backhaul Equipment

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**Abstract — This paper evaluates the linearity performance in a wideband wireless backhaul transmitter when applying crest factor reduction (CFR) and digital predistortion (DPD) techniques to enhance the transmitted output power, and thus the power efficiency of the overall system, while fulfilling the communications system quality requirements and regulations. The CFR technique applied is the peak cancellation (PC), while the linearizer is based in an adaptive DPD with memory effects compensation. Order reduction techniques are also applied to mitigate the complexity of the DPD structure. The power amplifier is based in a 15 Watts GaN transistor. The test signal follows a multiband 4 channel 1024-QAM configuration (reaching up to 1 Gbps) with 12 dB of PAPR at RF and 112 MHz bandwidth (28 MHz each channel). A testbed for evaluating the PC and DPD linearization performance of the RF subsystem was deployed and experimental results are presented in this paper.**

**Index Terms — Wideband digital predistortion, memory effects, peak cancellation, order reduction.**

## I. INTRODUCTION

One of the key enablers of the forthcoming generation of wireless communication systems is the wireless backhauling of small cells. The role of wireless backhauling is expected to be critical considering: I) the exponential growth of mobile broadband traffic, II) the every time more important share of small cells as an alternative mobile traffic handling III) the cross-sector requirements aiming at increasing the overall energy efficiency of wireless networks.

The traditional line-of-sight (LoS) high distance and high availability 6-42 GHz point-to-point (PtP) solutions will be kept employed for high-capacity aggregation, combined with lower distance millimeter wave (60 GHz) and E-Band (70-80 GHz) LoS PtP high-capacity solutions, and sub-6GHz LoS and NLoS PtP and PtMP medium capacity aggregation solutions. In such a demanding scenario, reducing both the capital and operating expenditures (CAPEX and OPEX) plays a determinant role.

From a technology perspective, in order to reduce the size of the antennas (impacting CAPEX) while keeping the same link quality the output power yielded by the power amplifier (PA) must be maximized, which implies that it must be driven as close to saturation as possible. Moreover, energy consumption accounts for up to 60% of the OPEX for backhauling the Macro cell sites, and keeps increasing with the cost of fuel in remote sites that rely on diesel generators for their power supply. In long haul microwave radios that are deployed on microwave towers, 90% of the power dissipation is encountered in the PA.

Therefore the aim of this paper is to experimentally evaluate possible strategies to mitigate the well-known trade-off between linearity and efficiency by combining crest factor reduction (CFR) and digital predistortion (DPD) techniques.

## II. DIGITAL BASEBAND PROCESSING ALGORITHMS

### A. Peak Cancellation

In this paper, the CFR technique used to reduce the PAPR of a multiband QAM modulated signal is the peak cancellation (PC) technique [1]. The block diagram of the PC is presented in Fig. 1. The PC is based in the clipping and filtering CFR techniques. In a first stage a peak signal $p[n]$ is generated,

$$p[n] = s[n] - s[n]\mathrm{c}[n] \tag{1}$$

where $s[n]$ is the input signal and $\mathrm{c}[n]$ the clipping signal defined as,

$$c[n] = \begin{cases} \dfrac{A}{|s[n]|} & if\ |s[n]| > A \\ 1 & if\ |s[n]| \le A \end{cases} \tag{2}$$

with $A$ being a clipping threshold. In a second stage the peak signal ($p[n]$) is filtered (noise shaping), obtaining $p_f[n]$. Finally the PAPR reduced output signal is calculated by subtracting a weighted version of the filtered peak signal from the original (properly time-aligned) input signal,

$$u[n] = s[n-D] - \alpha\, p_f[n] \tag{3}$$

with $\alpha$ being the subtraction parameter.

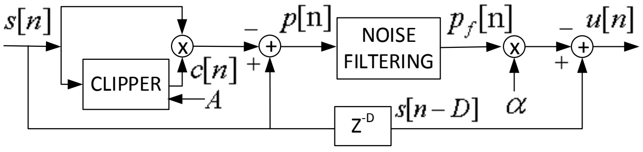

Fig. 1.Block diagram of the peak cancellation CFR technique.

### *B. Digital Predistortion*

The block diagram of the adaptive DPD implemented in this paper is depicted in Fig. 2. It follows a direct learning approach, as explained in [2]. The input-output relationship of the DPD block is

$$x[n] = u[n] - d[n] \tag{4}$$

where the signal *d[n]* is a nonlinear distortion signal that models the one introduced by the PA. By considering a memory polynomial (MP) behavioral model, this additive distortion can be estimated as

$$d[n] = \mathbf{u}_n \mathbf{w} \tag{5}$$

$\mathbf{w} = \left(w_{0,0}, \ldots, w_{0,P-1}, \ldots, w_{K-1,0}, \ldots, w_{K-1,P-1}\right)^T$ is a *Mx1* vector of coefficients, where *M=P·K*, *P* is the polynomial order and *K* the number of delays in the MP model. Moreover, $\mathbf{u}_n = \begin{pmatrix} u[n], \cdots, u[n]\left|u[n]\right|^{P-1}, \cdots, u[n-\tau_{K-1}], \\ \cdots, u[n-\tau_{K-1}]\left|u[n-\tau_{K-1}]\right|^{P-1} \end{pmatrix}$ is the *1xM* data vector containing the MP basis waveforms and where $\tau_i$ (with $\tau \in \mathbb{Z}$ and $\tau_0 = 0$) are the most significant sparse delays of the input signal that contribute to characterize memory effects.

Following the direct learning approach, the coefficients can be estimated iteratively using a weighted LS algorithm.

$$\Delta\mathbf{w} = \left(\mathbf{U}^{\mathbf{H}}\mathbf{U}\right)^{-1}\mathbf{U}^{\mathbf{H}}\mathbf{e} \tag{6}$$

$$\mathbf{w}^{i+1} = \mathbf{w}^{i} + \lambda\,\Delta\mathbf{w} \tag{7}$$

with $\mathbf{U} = \left(\mathbf{u}_0, \mathbf{u}_1, \ldots, \mathbf{u}_L\right)^T$ being the *LxM* data matrix (*n=1, 2,⋯ L*); with $0 \leq \lambda \leq 1$ being the weighting factor and where $\mathbf{e}$ is the *Lx1* vector of the error defined as

$$e[n] = y[n]/G_0 - u[n] \tag{8}$$

where $G_0$ is the linear gain of the PA.

Moreover, to reduce the computational complexity introduced by the DPD block, the principal component analysis (PCA) technique was used. Further details on this model order reduction technique can be found in [3].

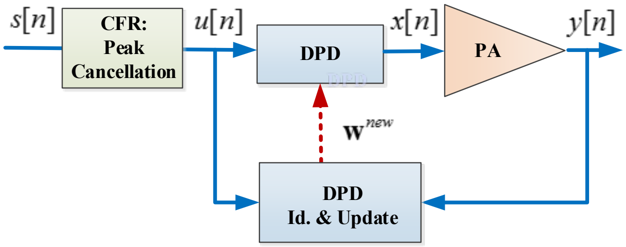

Fig. 2.Block diagram of the direct learning approach.

## III. EXPERIMENTAL SET-UP AND RESULTS

The experimental testbed is illustrated in Fig. 3. We used a multiband 4 channel 1024-QAM configuration (4CH1011 -one channel is off) with 12 dB of PAPR at RF and 112 MHz bandwidth. The generated waveform passes through the PC and DPD blocks implemented in Matlab and is downloaded for playback in the Texas Instruments boards (TSW1400EVM pattern generator and TSW30H84EVM DACs and IQ modulators) that output the signal that will be fed into the GaN PA (DUT) with 16-bit resolution at 625 Msa/s after upconversion at the 2 GHz IF. The DUT is a 6 GHz RF Unit used for microwave backhaul applications. The output of the PA is digitized using a Digital Storage Oscilloscope (DSO) at 20 Gsa/s. Despite showing results within 560 MHz of bandpass bandwidth, the DAC + IQ modulator board cannot provide optimal synthesis for values above 500 MHz.

Fig. 4 shows the linearity performance in terms of NMSE (worst channel case), ACLR and EVM (worst channel case), when considering different PAPR reduction factors and with DPD. By combining the PC technique and DPD, and considering an EVM threshold of 3%, we can observe that the maximum allowed PAPR reduction is around 2.75 dB (without DPD would be around 2 dB). Moreover, with PC and keeping the same DPD gain, the ACLR is slightly improved (around 1 dB) since we have prevented the signal peaks from going into hard compression.

Alternatively, thanks to the PAPR reduction the mean output power could be increased without excessively compromising the ACLR and EVM figures. Fig. 5 shows again the linearity performance for different PAPR reduction factors but now at 2 dB higher output power (thus driving the PA further into compression). Severe PAPR reductions imply that the switched-off channel will be more interfered by the neighboring channels. However, there are PAPR reduction values at which applying PC+DPD, and despite having increased the power 2 dB, the EVM is kept reasonably below 2%. In addition, in comparison to the previous nominal power case with DPD, the ACLR is degraded less than 2 dB (see Fig. 5 and Fig. 7).

Fig. 6 shows the DPD linearity performance for different memory lengths and thus number of coefficients. As it can be observed, after a certain value of coefficients (e.g., 75) there is no further improvement, and moreover increasing the number of coefficients can only lead to worsen the linearity figures due to a worse conditioning of the data matrix $\mathbf{U}$ in (6).

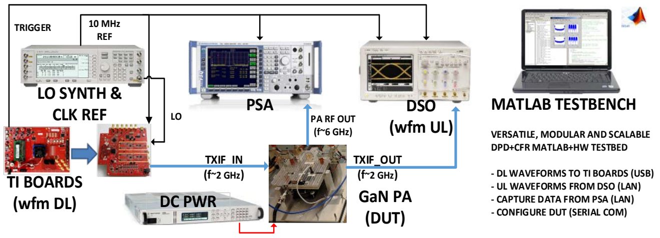

Fig. 3. Wideband CFR and DPD test bench.

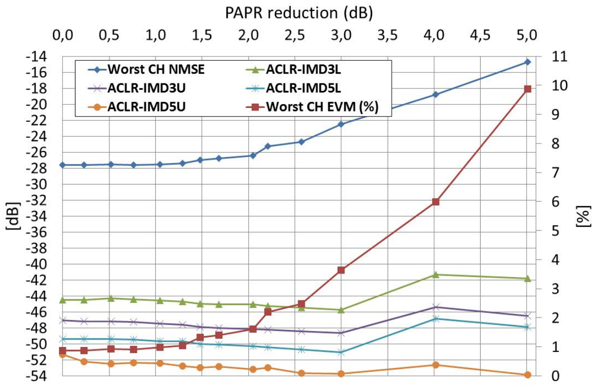

Fig. 4. NMSE, EVM and ACLR vs PAPR reduction with DPD.

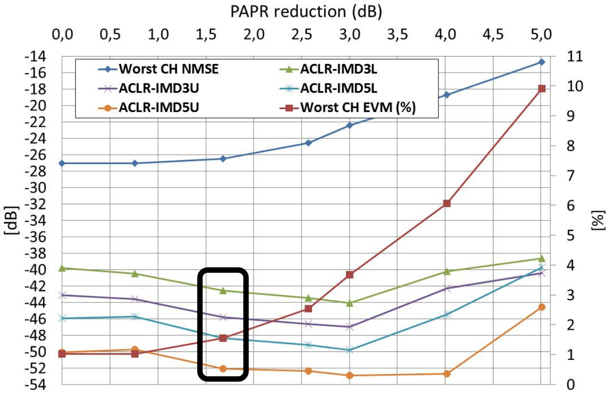

Fig. 5. NMSE, EVM and ACLR vs PAPR reduction with DPD at 2 dB higher output power.

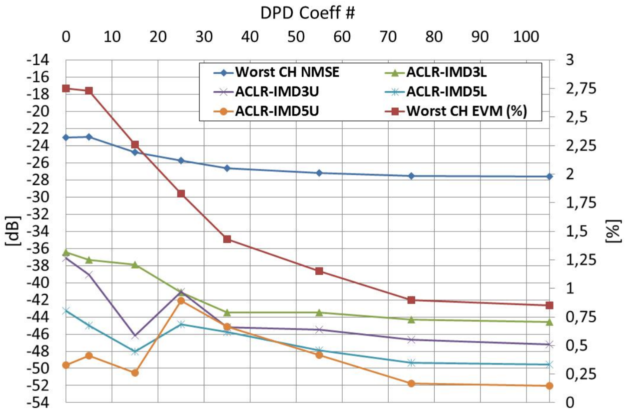

Fig. 6. NMSE, EVM and ACLR vs number of DPD coefficients.

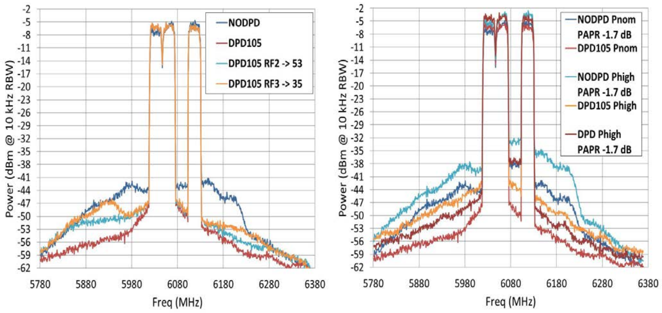

Fig. 7. Spectrum plots of a 112 MHz BW multi-channel 1024-QAM.

TABLE I
DPD LINEARIZATION PERFORMANCE

| Config. | ACLR (dB) | | | | WC EVM (%) | NMSE (dB) | # Coeff. |
|---|---|---|---|---|---|---|---|
| | IMD3 L | IMD3 U | IMD5 L | IMD5 U | | | |
| No DPD | -36,4 | -37,1 | -43,3 | -49,6 | 2.75 | -19,05 | - |
| DPD 3 taps | -37,9 | -46,2 | -48,0 | -50,5 | 2,26 | -25,57 | 15 |
| DPD 21 taps | -44,6 | -47,2 | -49,6 | -52,0 | 0,85 | -28,44 | 105 |
| DPD 21 taps RDF=2 | -41,8 | -45,6 | -44,7 | -50,2 | 0,99 | -28,11 | 53 |
| DPD 21 taps RDF=3 | -39,9 | -44,4 | -43,6 | -49,6 | 0,92 | -28,09 | 35 |
| DPD 21 taps RDF=7 | -37,2 | -41,4 | -42,6 | -49,9 | 1,24 | -27,21 | 15 |

As listed in Table I, thanks to the PCA technique it is possible to apply model order reduction and, with the same number of coefficients, obtaining better in-band linearity figures. However, as shown in Fig. 7, the out-of-band linearity is degraded when increasing the model order reduction factors. As expected, there is a trade-off between the ACLR performance and the DPD complexity in terms of number of coefficients.

## IV. CONCLUSION

The use of the PC technique combined with DPD with model order reduction, helps to mitigate the trade-off between linearity, efficiency and computational complexity. We have experimentally demonstrated that gaining near 2 dB of output power thanks to the use of DPD and CFR techniques can be achieved with the PCA technique minimizing the computational resource usage and still keeping reasonable performance.

## ACKNOWLEDGEMENT

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