A Comparison between Time and Frequency Domain Filter Design Applied to Limiting and Filtering Technique

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Abstract*— A popular crest factor reduction (CFR) technique like limiting and filtering technique can be implemented to reduce a complex enveloped signal peak-to-average power ratio (PAPR). In the literature, reported works use a nonlinear constrained optimization tool that can be applied to obtain PAPR reduction, for a CFR technique composed by a hard-clipping limiter and linear digital filters, such as finite impulse response (FIR). In this work, a CFR technique implementation is proposed, using linear digital filter in frequency domain, which is described by a transfer function, not a linear constant-coefficient difference equation. The digital linear filter designs in time and frequency domain present a few differences. Matlab simulation results from a case study that employs a WCDMA complex enveloped signal point that the optimized CFR realization with FIR filter in frequency domain has achieved a further PAPR reduction of 1.2 dB in comparison of a CFR with FIR filter in time domain, where they have the same number of initial filter optimizable coefficients.

***Keywords:* FIR filter, constrained nonlinear optimization, power amplifier, crest factor reduction.**

I. Introduction

The wireless communications, present in smartphones as well as in satellites, are means of data transmission that has become one of the most important in the last decades. In order to meet an increasing demand of higher data rate, lower power consumption and greater handsets battery autonomy, high linearity and efficient transmission systems are required. In these systems, the power amplifier (PA) is the main responsible for the non-linearity effects and for the highest energy drain [1-2], hence being essential to optimize this component, where there is a trade-off between the linearity behaviour and the power efficiency [3]. This one rises with the increasing average output power.

To achieve high efficiency, the PA should operate at regimes of string power gain compression, near saturation. In particular, the nonlinearities generated by the PA can be compensated though a digital predistorter (DPD), that presents an inverse characteristic compared to the PA. The combination of the PA and DPD will present a linear behaviour up to the saturation point. Communication standards impose maximal tolerable distortion levels produced from RF circuits aiming to avoid that this particular circuit causing interference in other narrow-band systems. However, there are a few techniques that target to exploit the distortion margin [4], thereby developing the transmitter efficiency by reducing the peak-to-average power ratio (PAPR) of a complex-valued envelope signal [5]. Among the reported techniques in the literature, the crest factor technique (CFR) based on limiting and filtering approach, that is quite popular, can be applied. This technique consists of reducing the PAPR value by clipping the input signal peaks and filtering the distortions at adjacent channels.

In [6], it was reported a constrained nonlinear optimization that targets to identify simultaneously the limiter clipping factor as well as the taps of a finite impulse response (FIR) filter. In [7], this constrained nonlinear optimization was expanded to the infinite impulse response (IIR) filter, where an additional restriction was included to deal with the instability issues. Lower PAPR values were achieved using optimized IIR filters. In [8], the CFR technique based on limiting and filtering technique architecture was extended by including a new hard-clipping limiter after the digital filter, where it was achieved a slight reduction of the PAPR value. The contribution of this work is proposing a new nonlinear constrained optimization method, using the digital linear filters in frequency domain.

This work is organized as follows. Section II details the CFR technique based on limiting and filtering. Section III describes the FIR and IIR digital filters. Section IV addresses two different constrained nonlinear optimizations approaches for the CFR parameter identification. Section V reports Matlab results from a case study. Conclusions are given in Section VI.

II. LIMITING AND FILTERING PAPR REDUCTION TECHNIQUE

The CFR technique aims to reduce the complex-valued envelope signal PAPR value. Among the CFR techniques, a popular one is the limiting and filtering, that is based on a set of two cascaded blocks characterized by a limiter followed by a linear digital filter, as shown in Fig. 1.The CFR first block is the hard-clipping limiter. If the sampled complex-valued envelope signal amplitude surpasses a pre-established threshold, the limiter must clip it. Otherwise, the time domain samples are kept unchanged.

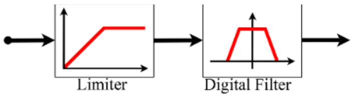

Fig. 1.*CFR Limiting and filtering technique block diagrams.*

Notice that this limiter only changes the signal magnitude, thereby the signal phase always remains with no changes. The hard-clipping limiter time domain mathematical expression is given by [6-7]:

$$x[n] = \begin{cases} w[n] & , |w[n]| < L \\ L \exp\{ j\angle w[n]\} & , |w[n]| \geq L \end{cases} \quad (1)$$

where *w[n]* is the input signal, *x[n]* the output signal, and *L* the clipping factor, that is the unique limiter parameter and whose value is chosen, in this work, through a constrained optimization. When the limiter clips the signal peaks to reduce the PAPR value, it generates significant distortion levels within the main and adjacent channels.

III. LINEAR DIGITAL FILTER

The linear digital filters are the second CFR technique block. Their objective is to partially reduce the generated distortion levels, mainly at adjacent channels, by the limiter block. When the linear filter performs such task, it partially restores the signals clipped by the limiter, rising the complex signal PAPR value. Thus, there is a trade-off between the PAPR reduction and the distortion levels at the main and adjacent channels. In this work, one digital filter class is approached: finite impulse response (FIR) filter.

The FIR filter is a digital linear filter class where the output signal, for a determinate discrete time instant, can be described by a linear combination of the input signal samples, both in present discrete time and past discrete times, and of the filter coefficient set [9]. This combination is expressed by the following mathematical expression [10]:

$$y[n] = \sum_{k=0}^{M-1} b_k x[n-k] \quad (2)$$

where *x[n]* are the input samples, *y[n]* the output samples, b_k the FIR filter coefficients, and *M-1* the number of past samples and the FIR filter order. Besides, shifting to the frequency domain, the FIR filter output signal *Y(s)* can be expressed as [10]:

$$Y(s) = X(s) \cdot \sum_{k=0}^{M-1} b_k s^k \quad (3)$$

where *X(s)* is the filter input signal at frequency domain. The realizations of filters of (2) and (3) are not the same. The (3) represents a digital filter described by a transfer function that has the number of coefficients equals to the number of samples. In (3), the coefficients b_k define the filter frequency response, while the number of coefficients define the filter order. Hence, the order of these filters depends on different factors. In this work, the goal is to optimize this set of coefficients b_k for the filters described in (2) and (3). Despite the different order, the number of optimizable coefficients b_k will be the same in the case study. From the FIR filter mathematical expressions, (2) and (3), it can be inferred that the FIR filter has a propriety which is the immunity to instability issues because of the feedback absence and lack of poles.

IV. CFR PARAMETER IDENTIFICATION

In this work, the CFR technique coefficients, which are the clipping factor *L* from (1), the FIR filter coefficients b_k from (2) and (3), are selected based on nonlinear constrained optimization. This optimization goal is to minimize the PAPR of the CFR output complex-valued signals and at same time to respect two constraints associated to the tolerable levels of signal distortions: adjacent channel power ratio (ACPR) and error vector magnitude (EVM). ACPR is a metric which works with frequency domain samples and quantifies the distortions within the adjacent channel, being expressed as follows [6]:

$$ACPR = 10\log\left[\frac{\int_{adj} |Y(f)|^2 df}{\int_{main} |Y(f)|^2 df}\right] \quad (4)$$

where *Y(f)* represents the frequency domain description of the CFR output signal, and the indexes *adj* and *main* refer to adjacent and main channels, respectively. On the other hand, EVM works with time domain samples, measuring the distortions within the main channel. This metric numerical value is given by [6]:

$$EVM = \frac{\sqrt{\sum_{n=1}^{N_S} |y[n] - w[n]|^2}}{\sqrt{\sum_{n=1}^{N_S} |w[n]|^2}} \quad (5)$$

where *w[n]* and *y[n]* are input and output signals, respectively, ad N_S the available samples total samples.

Two optimization methods are approached in this work: both use the hard-clipping limiter in time domain from (1). However, the first method uses the FIR filter time domain representation from (2) (Fig. 2), whereas the second method uses the FIR filter frequency domain representation from (3) (Fig. 3). The second is more complex due the fast Fourier transforms operations. The main interest of this work is to compare the optimization approaches, comparing how capable these nonlinear constrained optimizations are to reduce the CFR output signal PAPR.

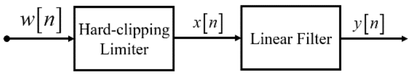

Fig. 2. *CFR technique diagram blocks with time domain linear filter.*

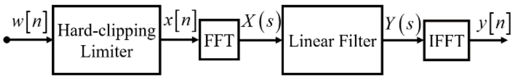

Fig. 3. *CFR technique diagram blocks with frequency domain linear filter.*

In summary, the nonlinear constrained optimization algorithm is:

$$\min_{z} PAPR(z) \text{subject to} \begin{cases} EVM(z) \leq MAX_{EVM} \\ ACPR(z) \leq MAX_{ACPR} \end{cases} \quad (6)$$

where MAX_{ACPR} is the maximum tolerable level of ACPR distortions, MAX_{EVM} the maximum tolerable level of EVM distortions, and z is the optimization variable vector, that is consisted of L from (1), with b_k from the (2) and (3). Moreover, the objective function and all the constraint functions are nonlinearly subject to the optimization variables, such that a nonlinear tool is required to execute this optimization [11]. Indeed, nonlinear algorithms request an initial guess for each optimization variable. These may converge into local minima depending on the chosen starting point.

V. MATLAB SIMULATION RESULTS

In this section, the hard-clipping limiter and FIR filter are applied to a PAPR reduction of a test signal, that is a WDCMA complex enveloped time domain sequence of 2048 samples, with a sampling frequency of 61.44 MHz and a bandwidth of 3.84 MHz. This signal presents a PAPR of 9.7 dB. The constrained nonlinear optimization is performed in MATLAB by applying an interior point algorithm with double precision floating-point arithmetic. Concerning the nonlinear optimization initial guesses, for the limiter, the clipping factor L was selected from a closed interval between 0.3 and 0.8, whereas for the FIR filter, its initial coefficients were chosen randomically from an open interval within 0 to 1. As done in [6-8], the 3GPP standard has been adopted, where the ACPR and EVM maximum tolerable values are set to -45 dB and to 17.5% respectively. Regarding the ACPR calculus, the adjacent channel has a bandwidth of 3.84 MHz whose center is 5 MHz from the main channel center.

The Fig. 4 presents the PAPR reduction provided by the optimized CFR realizations, either with time domain FIR filter or frequency domain FIR filter realizations, in function of the number of the FIR filter optimizable coefficients. For the filter of (2), the number of coefficients is the number of optimizable coefficients, and the filter order is the number of coefficients subtracted by one. Meanwhile, for the filter of (3), the number of coefficients, that is independent of the number of optimizable coefficients, is the number of samples used during the FFT, thereby 2048. From the Fig. 4, it can be noticed that nonlinear constrained optimization of the CFR with FIR filter in frequency domain has provided better PAPR reduction for a number of filter optimizable coefficients greater than 8, whereas the CFR with FIR filter in time domain has provided a maximum PAPR reduction of 2.6 dB. The reason for this difference may be explained by the fact that the FIR filter in frequency has number of coefficients equals to number of samples, then superior to the FIR filter in time domain, and a better modelling capacity.

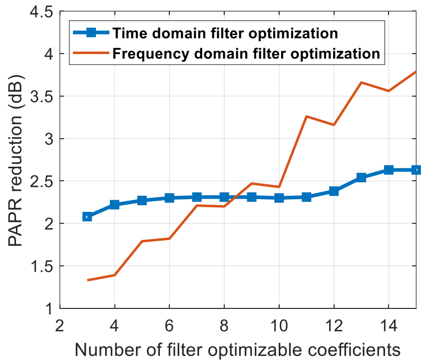

Fig. 4. *PAPR reduction in function of the number of filter optimizable coefficients.*

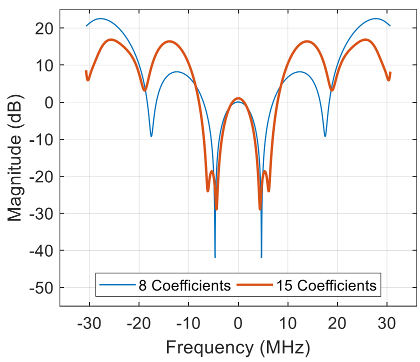

Fig. 5. *Optimized FIR filter frequency responses.*

In the Fig. 5, it is presented the optimized FIR filter, described in (3), frequency responses for filters of 8 and 15 initial optimizable coefficients. From the Fig. 5, it can be seen the strong signal attenuation within the narrow band adjacent to the baseband channel, that are the main channel, whereas for |10-30| MHz band, the filter gain is positive. Considering that the spectrum power decreases when it is more distant from the main channel, the better PAPR reduction provided by the 15 optimizable coefficients FIR filter can be attributed to the stronger power reduction within the narrow band adjacent to the main channel and the higher gain within the |10-30| MHz band, exploiting better the ACPR and EVM metric margins.

The Figs. 6 and 7 illustrate how the CFR technique, with limiter and FIR filter optimized, acts to decrease the complex-valued enveloped signal PAPR. The time domain filter has 15 coefficients, thus it is 14^{th} order FIR filter, whereas the frequency domain filter has 2048 coefficients. Fig. 6 shows waveforms of the CFR input and output amplitudes, for the time domain and frequency domain FIR filter case studies. Fig. 7 shows the power spectral densities (PSD) of the CFR input and output signals, again for the time domain and frequency domain FIR filter case studies. From the Fig. 6, it is noticed both CFR realizations clipped the signal peaks, where the FIR filter of (3) presents a stronger compression of the signal peaks, thus having a greater PAPR reduction. From the Fig. 7, it can be observed that the CFR realizations have inserted distortions mainly in adjacent channels, where the CFR with FIR filter of (2) presents more distortions within the adjacent channels. Thereby, the CFR with FIR filter of (3) has handled better with the available margin of ACPR.

Moreover, between the CFR implementations, the FIR filter of (2) approach is less complex and presents better PAPR reduction for a small number of optimizable coefficients, whereas filter of (3) approach has better PAPR reduction for larger number of optimizable coefficients, however is more complex because of the fast Fourier transform operations and the larger number of filter coefficients, that are equal to the number of samples.

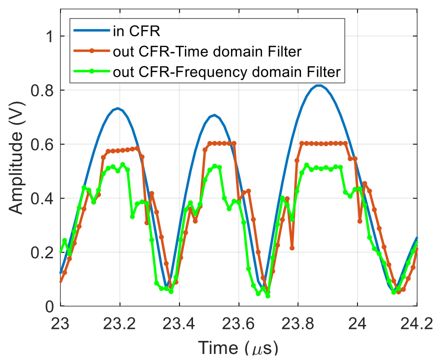

Fig. 6.*Amplitude waveforms at CFR input and output with 15 optimizable coefficients.*

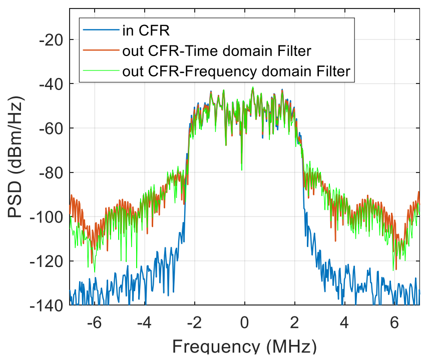

Fig. 7. *Power spectral densities at CFR input and output with 15 coefficients.*

VI. Conclusion

In this work, the CFR limiting and filtering technique, composed by a hard-clipping limiter and a linear digital filter, was approached. The FIR filter realizations were done, using two different representations, in time domain and in frequency domain, that have several differences, like the number of coefficients, despite the same number of optimizable coefficients. For the nonlinear constrained optimization, the filter coefficients could be chosen randomically due the FIR filter immunity to instability. Based on simulation results from a WCDMA test signal and interior point algorithm, a further 1.2 dB reduction in PAPR was achieved using the frequency domain FIR filter instead of the time domain FIR filter, for a set of 15 filter optimizable coefficients. A future direction for this work is implement the CFR technique, with the achieved optimized coefficients values, in field programmable gate arrays (FPGA) through the fixed-point arithmetic description.

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