Análise de filtros FIR na limitação da largura de banda de Amplificadores de Potência

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***Abstract*—This work addresses the application of Finite Impulse Response (FIR) filters combined with windowing techniques to mitigate the spread spectrum generated by the saturation of power amplifiers (PA) in concurrent dual-band transmission systems (2.4 GHz and 3.5 GHz). The proposed method integrates a digital predistorter (DPD) and a signal saturation stage, followed by FIR filtering, aiming to limit the bandwidth and meet the regulatory spectral standards. Triangular and Hanning windows, with adjusted coefficients, were tested on Wi-Fi (802.11n) and LTE signals, simulated in Python with sampling rates of 120 MHz. The results, evaluated by means of power spectral density (PSD) and Error Vector Magnitude (EVM) curves, demonstrated that the FIR filter significantly reduces the high-order intermodulation components, keeping the signal within the required spectral mask. The triangular window proved to be effective in limiting the band, while the Hanning window provided greater control in the transition between bands. It is concluded that the proposed approach is viable for improving spectral efficiency, with a direct impact on regulatory compliance and signal quality.**

***Index Terms*—FIR Filters, Power Amplifiers, Saturation, Digital Pre-Distortion (DPD), Spread Spectrum, Concurrent Dual Band**

I. Introduction

Currently, there is a high demand for developing systems that enable spectral efficiency in wireless communication, especially concerning the transition from 4G to 5G. The main challenges in this field involve achieving high linearity while maximizing efficiency, reducing power consumption, and ensuring energy efficiency in implementation. Furthermore, increasing bandwidth is crucial, as power amplifiers (PAs) introduce inter-modulation and cross-modulation effects [1]. One method to enhance the linearization performance of a PA is by adding a device called a digital predistortion (DPD) which is placed before the PA and cascaded with it. The DPD is implemented digitally with characteristics inverse to those of the PA, applying an inverse linear function at the input of the amplifier. This allows the system to maintain both linearity and efficiency simultaneously. To ensure that DPD does not limit the PA's efficiency, signal saturation is applied before the pre-distorter. This is done using one of the two main approaches: summation or division, implemented separately for each band. Saturation essentially consists of clipping the signal at an ”L” threshold while preserving its original phase. This method helps improve the efficiency of the PA in a concurrent dual-band system [2]. In this work, we focus on a concurrent dual-band (2D) scenario, where a device operates at two distinct frequencies: one at 2.4 GHz and the other at 3.5 GHz. One of the challenges addressed in this study is the increase in background spectrum, or spectral spreading, primarily caused by PA saturation. When we refer to saturation, we mean that the device has reached its limit at that moment, the output amplitude no longer varies proportionally to the input. This increase is largely due to the inter-modulation components generated by the PA, which create high-order spectral products [3].

In summary, the amplified signal is not limited to the desired frequency. Since the signal passes through a pre-distorter (which increases its bandwidth) and a power amplifier (which introduces noise and harmonics due to the physical characteristics of its internal components), these combined factors induce unwanted frequencies in the signal amplification process.

Thus, one of the main objectives of this work is to reduce the background spectrum by implementing an FIR filter within the cascaded system, positioned between saturation and DPD. This serves as an alternative to improve signal quality by filtering out unwanted signals before they are amplified. Through graphical analysis, this study aims to observe improvements in signal transmission and amplification without compromising quality. By analyzing power spectral density (PSD) curves, we expect to achieve an adequate response without affecting the transmitted content.

II. Equivalent wrap

The equivalent envelope [2] for a concurrent dual-band signal is given by the formula below:

$$x\left(n\right) = x1\left(n\right)\ \exp\left(\frac{-j\Delta\omega\left(n-1\right)}{fs}\right) + x2\left(n\right)\exp\left(\frac{j\Delta\omega\left(n-1\right)}{fs}\right). \tag{1}$$

In this formula, we see that $x1(n)$ is the signal from channel 1, $x2(n)$ is the signal from channel 2 and fs is the sampling frequency, 120 MHz for our tests. And also in this case, we have:

$$\Delta\omega = \frac{\omega_2 - \omega_1}{2} \tag{2}$$

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Where $\Delta\omega$ is the difference between the carriers of the transmitted signals, where $\omega = 2\pi f$.

III. Saturation for dual-band transmission

After obtaining the equivalent envelope [1], we were able to perform the saturated envelope of both signals, known as x_{1c} and x_{2c}. In this case, two approaches are known to perform saturation, which consists of cutting the envelope at a threshold “L”: Sum (which will be used throughout the examples) and division. In order to streamline the studies, we chose to choose only one form of signal saturation, the sum. Since it is the most convenient and efficient way to demonstrate the results comparing both forms of saturation [3]. Below is an example of the saturated envelope of a 2.4 GHz LTE signal, for L = 0.7 V:

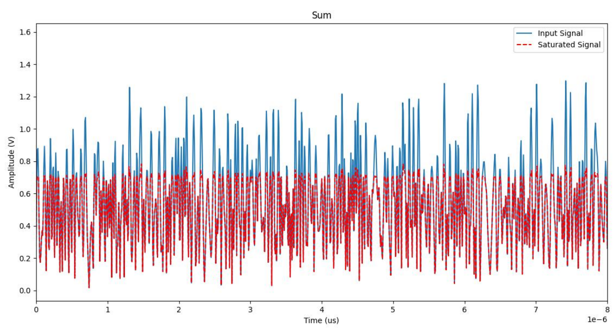

Fig. 1. Example of amplitude over time applying saturation with threshold L=0.7 V

A. Summation approach

In this method, we have the characteristic of separating the absolute surplus between the channels, while maintaining the original phase. Having $z(n) = |x(n) - L$, the saturated envelope of each channel can be expressed by [1]:

$$x_{ic}(n) = \begin{cases} x_i(n), & \text{if } |x(n)| \leq L \\ \left(\frac{|x_i(n)| - z(n)}{2}\right) e^{j\angle x_i(n)}, & \text{if } |x(n)| > L \end{cases}. \tag{3}$$

With i being the signal of each channel.

IV. Filter and windowing

The simplest method for designing an FIR filter is called the windowing method, applying a window to an ideal impulse response, which can be represented by [4]:

$$H_d(e) = \sum h_d[n] e^{-j\omega t} \tag{4}$$

Given that $H_d[n]$is the impulse response sequence, which can be written as:

$$h_d[n] = \frac{1}{2\pi} \int_{-\pi}^{\pi} H_d(e^{j\omega}) e^{j\omega n} \, d\omega \tag{5}$$

A simple way to obtain the filter from $H_d[n]$is to truncate it, that is, define a system with impulse response given by

$$h[n] = \begin{cases} h_d[n], & 0 \leq n \leq M \\ 0, & otherwise \end{cases} \tag{6}$$

Where $h[n]$ it is typically represented as a product of the impulse response by a window of finite duration $w[n]$.

$$h[n] = h_d[n].w[n] \tag{7}$$

V. Methodology and tests

When running the tests, Python was used to program the data processing, perform saturation, apply windowing and filtering. For integration into Python, we used well-known libraries for dealing with data, including Panda, Scipy, Numpy, and some other integrated tools. To generate the PSD graphs, we ended up using Octave, and for the EVM graphs we plotted them in Cadance itself. The data was obtained from the Cadence Virtuoso software, provided by the Federal University of Paraná. The data obtained follows the 802.11n and LTE standards. Both signals have a bandwidth of 20 MHz and a sampling rate of 120 MHz.

VI. Obtained results

A. Response applying windowing and filtering

To obtain the PSD graph to compare the response of each window, the following steps were performed:

- Application of saturation, remembering that we applied the summation method. The saturation threshold applied was L=1.25 V.
- Definition of the number of coefficients of our windowing, in this case we chose to use M=50, for the Wi-Fi signal value of 2.4 GHz, and M=80, for the LTE signal of 3.5 GHz, as it is an adequate value for the data we have.
- Window application with the scipy.signal.firwin library in Python, and to define the filter the scipy.signal.ifilter library.
- Plot of PSD graphs, for both signals, with the saturated signal and the responses of each windowing with the filter.

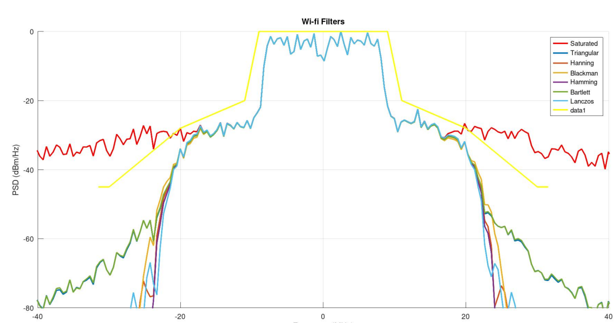

Fig. 2. Comparison of windows, plus filter, on the Wi-Fi signal.

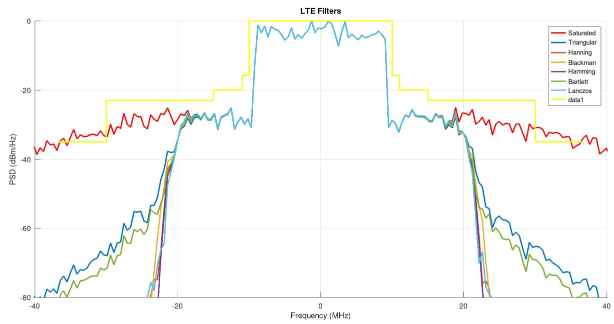

Fig. 3. Comparison of windows, plus filter, on the LTE signal.

As we can see in the graphs above, with the application of windowing, in yellow, it was possible to observe the efficiency in keeping the signal within the limits of the mask imposed by law. After saturation, in red, the signal, in both cases, ends up spreading beyond the limits. When we apply the filter, we limit the frequency, a limitation based on the number of coefficients in each case.

B. EVM testing and comparison without using windowing and filtering

After performing the PSD tests, we end up performing the EVM (Error Vector Magnitude) tests, as this allows us to have further confirmation of the signal quality, comparing the filtered signal, with windowing, and without the application of the filter. The EVM measures the difference between a reference, ideal signal, and the real signal and ends up quantifying the error introduced into the signal. This result is expressed by a ratio of the magnitude of the error vector (difference between the real signal and the reference) and the magnitude of the reference signal. It is normally given as a percentage and the lower its value, the better the signal quality. For the graphs and results below, the Hanning filter was applied.

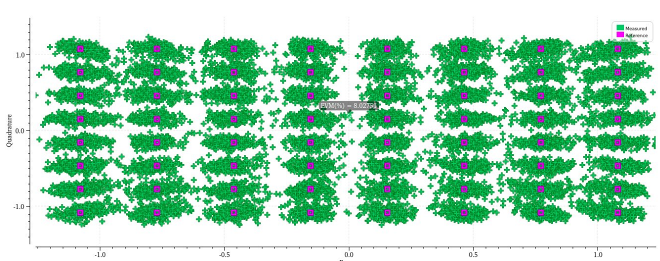

Fig. 4. EVM of signal LTE with filter hanning.

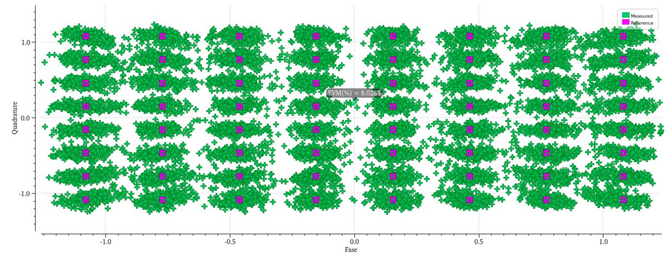

Fig. 5. EVM of signal LTE without filter hanning.

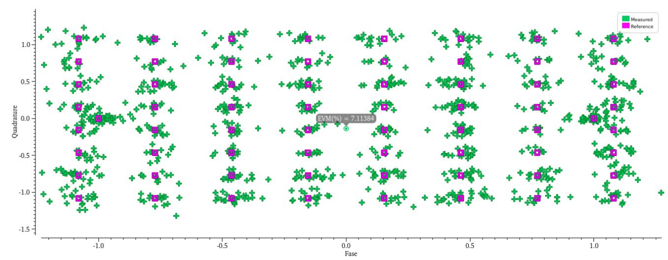

Fig. 6. EVM of signal Wi-fi with filter hanning.

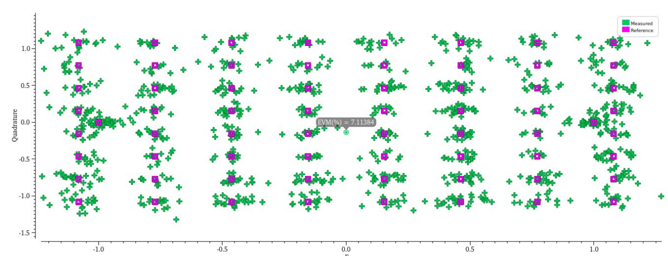

Fig. 7. EVM of signal Wi-fi without filter hanning.

In both cases, for both the Wi-Fi signal and the LTE signal, a decrease in the EVM value was observed, this result is in line with what was expected and what we had already observed in the PSD tests. The results are tabulated below more clearly:

TABLE I
EVM RESULTS TABLE

Signal	With filter	Without filter
Wi-fi	7.11384%	7.26071%
LTE	8.02751%	8.0285%

VII. CONCLUSION

With the tests performed, it was possible to observe a significant improvement in the signal, compared to the standards established in relation to the spectral mask, both for the Wi-Fi standard at 2.4 GHz and for LTE at 3.5 GHz, with the addition of an FIR filter plus windowing. We also observed the impact of windowing on bandwidth, and how we can limit it by simply changing it. The spectral density graphs showed how saturation ends up messing up the signal, causing the equivalent signal to end up exceeding the standard. The EVM result was added to confirm the improvement in signal quality, as we achieved lower error values with the application of the filter, compared to the situation without its use.

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