Peak Windowing for Peak to Average Power Reduction

Borisav Jovanović, Srđan Milenković

Abstract - Linearization improves power amplifier (PA) efficiency and reduces running cost of the wireless infrastructure. The out-of-band radiation and bit error rate performance degradation are caused by PA nonlinearity. The operation of PA can be restricted to PA linear region by reduction of peak to average power ratio. The peak windowing method for peak to average power reduction is presented in the paper. The results are presented for Quadrature Phase Shift Keying (QPSK) and Wideband Code Division Multiple Access (WCDMA) waveforms.

Keywords - Crest factor reduction, Peak to Average Power Ratio, Peak Windowing method.

I. Introduction

The drawback of state-of-the-art modulation schemes is the high peak-to-average power ratio (PAPR), which results in intercarrier interference, high out-of-band radiation and bit error rate performance degradation [1]. To overcome this, large peaks at power amplifier (PA) input must stay within linear region of transfer function (Fig. 1). This requires that average PA output power must be much less than maximum saturated power (Fig. 1). PA power is reduced from its optimum operating point for the amount of output backed-off power (OBO). PA becomes energy inefficient. One solution which solves this problem and consequently reduces running cost of wireless infrastructure is dealing with signals which have reduced peak-to-average power ratio. In this case it is possible to increase signal average power without the risk of having the PA operating in non-linear region [1].

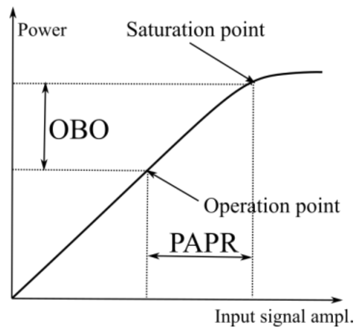

Fig. 1. The nonlinear and linear regions of PA transfer function

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The occurrence of large peaks in waveform can be generally avoided:

1) by increasing complexity of the transmitter, including the transmission of some additional data needed at receiver side for the reliable reconstruction of useful data,

2) by modifying the shape of the signals to limit the magnitude of the large peaks at the cost of increased signal distortion [2].

II. Crest Factor Reduction

A. Crest Factor Measurement

We have already explained how signal characteristics have influence on PA power efficiency. One of these characteristics is the Crest Factor (CF). CF of a signal *s(n)* is defined as the ratio between the magnitudes associated to the largest $s(n)_{\max}$ and the average values $s(n)_{\mathrm{rms}}$ of a signal:

$$CF = \frac{\|s(n)\|_{\max}}{s(n)_{rms}} \qquad (1)$$

In literature one more parameter can be found - the Peak to Average Power Ratio (PAPR), which is the squared value of CF:

$$PAPR_{dB} = 10\log_{10}\frac{\|s(n)\|_{\max}^2}{s_{rms}^2} \qquad (2)$$

When CF value of a signal is reduced, the PA can operate in the linear region. The primary goal when implementing the Crest Factor Reduction (CFR) is to reduce the CF value without introducing significant in-band and out-of-band distortions. Unfortunately, signal distortion cannot be completely avoided. To quantify the performance of CF reduction operations, the distortion is measured by Error Vector Magnitude (EVM) and Adjacent Channel Power Ratio (ACPR). [2]

B. Signal Quality Measurement

The EVM measures in-band signal distortion. EVM is defined as displacement of the received symbols in I/Q plane compared to the referent symbol positions. To calculate EVM, the average value of symbol power P_{ref} is computed, as well as the mean value of error vector power

P_{error}. The error vector represents the difference vector in I/Q plane that connects the received symbol vector to the referent one. The EVM is defined as a square rooted value of the ratio of mean error vector power P_{error} and average value of referent signal power P_{ref}: For WCDMA the EVM should be less than 12.5%.[3]

$$EVM(\%) = \sqrt{\frac{P_{error}}{P_{ref}}} \cdot 100 \qquad (3)$$

The ACPR measures out-of-band signal distortion and it is defined as the ratio of power leaked to the adjacent channels P_{adj} and main channel power P_{main}.

$$ACPR = \frac{P_{adj}}{P_{main}} \qquad (4)$$

The most important reason to keep the ACPR low is to prevent unwanted power to be transmitted outside of the frequency band of interest. For WCDMA signal the technical specifications define a minimum allowable ACPR limits for first and the second adjacent channels. These limits are 45 dBc for a first adjacent channel (5 MHz channel offset) and 50 dBc for a second adjacent channel (10 MHz channel offset). [3]

C. Crest Factor Reduction Techniques

Different techniques can be used for CF reduction. They can be divided into following groups: probabilistic (scrambling), coding, adaptive predistortion, clipping techniques, etc. [1] Some of the techniques don't distort the signal at all, at the price of a greater complexity, the others inject some distortion. Scrambling and coding technique requires special coding/decoding of the signal at the receiver side, which is not possible for implementation in our case.

The clipping techniques do not require special signal processing at receiver side, but have disadvantages in introducing both in-band and out-of-band signal distortion. The clipping techniques include Clipping and Filtering Technique (CAF), Block-scaling technique, Peak Windowing technique (PW), Peak Cancellation technique (PC) [3].

We have adopted PW algorithm for CF reduction. To evaluate the performance of PW method, we have created a PW CFR model in SystemC. The designed model has several options. The model implements a FIR filter operation, which is described in the next section in detail. Beside options dedicated for FIR filter configuration, we have option to set desired PAPR value of the output signal. The programmability is another goal of the future final implementation of CFR module in ASIC. When input waveform is changed, ASIC implementation should support adaptation to new parameters (new FIR filter order and coefficients).

The implemented module is evaluated using following waveforms: Quadrature Phase Shift Keying (QPSK) and Wideband Code Division Multiple Access (WCDMA). The results of evaluation are clearly presented.

III. Peak Windowing Method for Crest Factor Reduction

A. Method Description

Clipping and filtering is the conventional method. It includes hard clipping and low-pass filtering. In Peak Windowing method the original signal in the region of the peak is multiplied with a specific windowing function. The Kaiser, Hamming or Hanning functions can be used for this purpose [3].

The operation of clipping is described by Eq. (5):

$$y(n) = c(n)x(n), \qquad (5)$$

where *x(n)* is the input signal, *y(n)* is the signal obtained after clipping operation is performed. The signal *c(n)* represents the clipping function:

$$c(n) = \begin{cases} 1, |x(n)| \le A \\ \frac{A}{|x(n)|}, |x(n)| > A \end{cases}, \qquad (6)$$

where the parameter *A* is the clipping amplitude threshold. The process of clipping limits the *y(n)* to the level of *A*. Note that the signals *x(n)* and *y(n)* are complex signals consisting of I and Q signal components.

The process of clipping causes sharp edges in an output signal waveform, which gives unwanted out-of-band distortion. To reduce this distortion, the windowing function *w(n)* is applied. PW method intends to smooth sharp edges of a shortened signal. This not only improves the ACPR of the resulting signal but also preserves peak amplitude at the selected threshold value.

The windowing operation replaces the clipping coefficients *c(n)* with new ones *b(n):*

$$b(n) = 1 - \sum_{k=-\infty}^{k=\infty} a_k w(n-k), \qquad (7)$$

where a_k are the weighting coefficients. Because the input signal is multiplied with windowing function, the output signal spectrum can be considered as convolution of the original signal spectrum and the spectrum of the used window [3]. This convolution is implemented by FIR filter. Also, to ensure that the value of *y(n)* is less than the threshold level A, the condition given by Eq. (8) must be satisfied:

$$b(n) \le c(n) \qquad (8)$$

To minimize EVM the last inequality must be near the equality as much as possible. [3] This implies that window length should be narrow. If clipping rate and window length are too large, the adjacent windows overlap. Then, the convolution is generally larger, causing lower values of *b(n)*, more attenuation of *y(n)* and higher EVM.

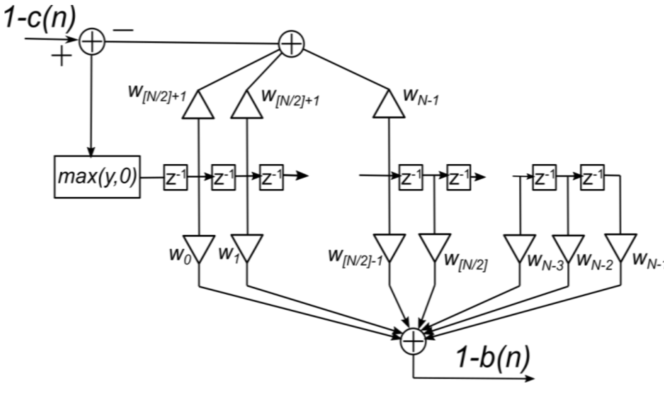

Fig. 2. The Peak Windowing CFR filter architecture

The PW filter structure is shown in the Fig. 2. The FIR filter takes at input the signal 1-*c(n)* (the *c(n)* is defined by Eq. (6)) and produces at output the signal 1-*b(n)*. A feedback structure adjusts the input values of the FIR filter. The delay of the FIR filter is equal to the time required for an input signal to reach the centre tap. Without a feedback, the resulting filter output will be larger than input value due to contributions of adjacent filter taps when clipping extends interval of several samples.

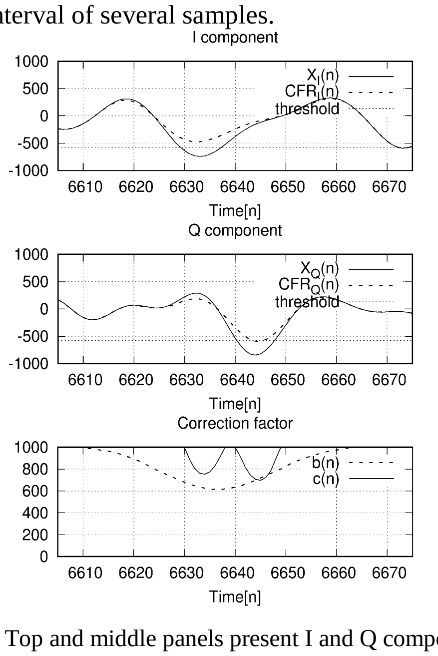

Fig. 3. Top and middle panels present I and Q components respectively of the signals at CFR block inputs X(n) and output CFR(n); the bottom panel presents the signals *b(n)* and *c(n)*

The feedback path scales filter input values. Looking forward to when clipped input value reaches the centre tap, the contribution of all previous input values (between first and centre tap) are calculated and used for correction of the next input value. [3] When incoming clipped signal reaches the centre tap, the contributions from all previous values have already been compensated. Then, the filter output *b(n)* becomes equal to the *c(n)*.

B. The Modelling of PW CFR block in SystemC

The PW algorithm is simulated using SystemC. Several modules are created to support SystemC simulations: the Crest Factor Reduction (CFR) block, PAPR and EVM calculation modules.

The CFR module takes at inputs I and Q quadrature signal components of signal *X(n)* and modifies them by clipping their magnitude to threshold level. Beside operation of clipping, the peak windowing is realized by the same module. For the realization of *c(n)* (Eq. (6)), the magnitude of input signal *X(n)* is calculated and after that, divided by threshold value. The peak windowing implementation is based on the FIR filter architecture given in the Fig. 2. The filter output produces signal *b(n)* (defined by Eq. (6)) which is later used as gain correction of delayed version of input signal. After these signals are multiplied the output signal *CFR(n)* (given in Fig. 3) is derived. Note that *CFR(n)* is complex signal consisting of I and Q components. The CFR module has following parameters: the order of embedded PW CFR filter, the clipping threshold level and arithmetic precision (number of bits of input signals).

For calculation of the PAPR value the new PAPR module is implemented in SystemC. PAPR value can be calculated for any input waveform and its operations are based on Eq. (2). In simulations the PAPR value is calculated for both input and output signals of CFR block.

The EVM module is created to find Error Vector Magnitude of QPSK signal. We have applied the Root Raised Cosine filter for QPSK demodulation. For obtaining ACPR we use already implemented SystemC modules.

III. Simulation Results

In simulations we evaluated different clipping thresholds and filter orders. The clipping threshold is changed from 1.0, down to 0.56, with the 0.02 step. When threshold is changed, the PAPR value is also changed. It is calculated using PAPR module. The filter orders are: N=9, 19, 29 and 39. For each combination of selected threshold and filter order we have calculated PAPR, ACPR and EVM for the signal at the output of CFR block.

The goal was to find optimum filter order and clipping threshold which give the best performance in terms of ACPR and EVM. The utilized different waveforms are - QPSK and WCDMA (Test Model 1). The sample rate of these waveforms is 30.72 MS/s.

The results for QPSK and WCDMA are presented in diagrams below. It is known that reduction of PAPR will increase EVM and ACPR. The diagrams clearly show the effects of varying the filter order.

A. Case 1: The QPSK signal

Without CFR, the PAPR of unclipped QPSK waveform is 6.29dB. The EVM is equal to 0.5% and ACPR is -90dBc.

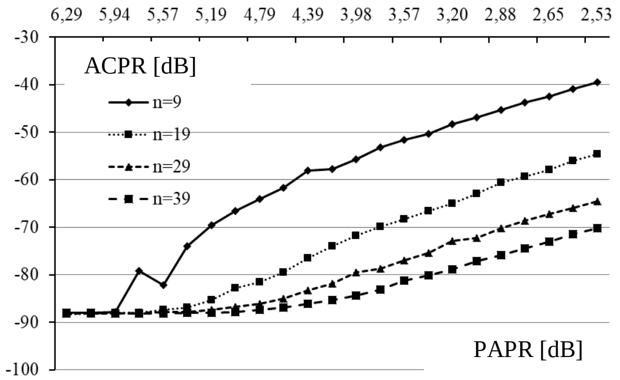

Fig. 4. The ACPR for QPSK signal at the PW filter output as a function of PAPR. The filter order values are: N=9, 19, 29 and 39

When CFR is used, the filter order is N=39 and the PAPR is reduced by 3dB, the ACPR is increased to nearly -80 dBc. EVM is worsened to 3.7%. In the case when PAPR is reduced by 3dB and N=9, the EVM = 1.8% and ACPR = -50 dBc. The Figs. 4 and 5. show trade-off in ACPR and EVM when selecting different filter order. Lower filter orders produce better EVM, but ACPR values get worsened.

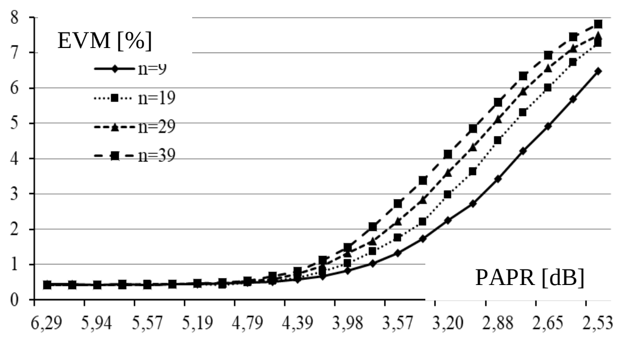

Fig. 5. The EVM of QPSK signal at the PW filter output as a function of PAPR. The filter order values are: N=9, 19, 29 and 39

B. Case 2: The WCDMA signal

The PAPR of input unclipped WCDMA waveform is 10.59 dB. The EVM = 0.3 % and ACPR = -90 dBc. When filter order N=39 is selected and PAPR is reduced by 3dB, the ACPR is increased to nearly -70 dBc and EVM is degraded to 3%. When N=9, the EVM=1.8% and ACPR = -45 dBc The Figs. 6 and 7. show ACPR and EVM plots versus PAPR for WCDMA signal.

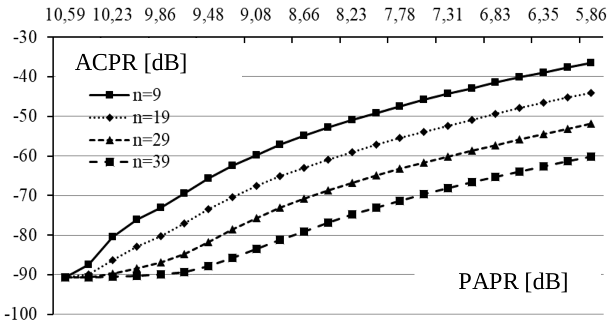

Fig. 6. The ACPR of WCDMA signal at the PW filter output as a function of PAPR. The filter order values are: N=9, 19, 29, 39

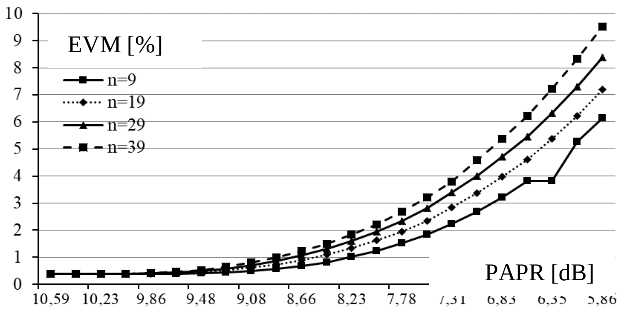

Fig. 7. The EVM of WCDMA signal at the PW filter output as a function of PAPR. The filter order values are: N=9, 19, 29, 39

IV. Conclusion

The signals with large peak to average power ratio require expensive wireless infrastructure and increase the running cost of equipment exploitation. This paper presents the peak windowing method for peak to average power reduction. The method was verified by simulation results. The various windowing lengths and clipping levels are changed for best performance, which is determined by measuring EVM and ACPR. Shorter window length minimizes EVM but degrades the ACPR value. The best performance is obtained for filter order value equal to 39.

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