Crest Factor Reduction through In-band and Out-of-band Distortion Optimization

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***Abstract*—A new crest factor reduction (CFR) technique is presented to reduce the peak to average ratio (PAR) of a wide-band code division multiple access (WCDMA) signal. Simple CFR techniques hard limit the desired signal to reduce the amplitude peaks and filtering is used to remove the out-of-band distortion. Here the trade-off between allowing out-of-band distortion and the error vector magnitude (EVM) is investigated for different levels of PAR reduction. It is demonstrated that there is an optimum clipping level for a desired PAR when trading off adjacent channel power ratio (ACPR) and EVM.**

***Index Terms*—Autocorrelation, Clipping, Crest Factor Reduction, In-band Distortion, Out-of-band Distortion, Power Amplifier, Uncorrelated Noise.**

I. INTRODUCTION

Present day 2.5G and 3G communication systems use sophisticated non-constant envelope schemes like WCDMA and orthogonal frequency division multiplexing (OFDM) to achieve high spectral efficiency. One of the main drawbacks of these modulation schemes is that they have very high PAR often exceeding 10 dB. Since the information is contained in amplitude as well as phase of the signal, the RF power amplifier (PA), at the output of the transmitter needs to be highly linear over a wide dynamic range. This requires the amplifier average output power to be backed-off from the 1 dB gain compression point by at least the PAR of the input signal. The PA has to be designed for the peak power but will be operating mostly around the average power level. Hence, working in a backed-off mode results in really poor power efficiency of the PA and the transmitter. This implies that there is a direct trade-off between the linearity and power efficiency for spectrally efficient modulation schemes. However, if the PAR of the signal is reduced, then the amplifier can operate at higher average powers for the same linearity and thereby achieve higher power efficiency.

Crest factor reduction (CFR) is a technique to reduce the magnitude of the less frequent peaks of the signal and achieve lower PAR. Simple CFR techniques clip off the peaks of the signal resulting in wideband distortion which is filtered out; however, the distortion generated over the signal bandwidth cannot be filtered resulting in degradation in EVM for a reduction in PAR. WCDMA systems have more margin to trade off degradation in EVM for a reduction in PAR; however, OFDM WLAN systems have stringent EVM specifications which cannot be compromised for a reduction in PAR.

This paper describes a CFR technique that trades-off the clipping distortion between in-band and out-of-band spectrum for a desired level of PAR. It is shown that the EVM is significantly reduced when the out-of-band distortion is allowed to increase. A downlink WCDMA signal with an inherent PAR of 10.25 dB is used to show the optimization and trade-offs. Measurements of distortion and error vector magnitude are measured for signals with reduced PAR applied to a 15 W gallium nitride (GaN) PA operating at 1.8 GHz.

II. CREST FACTOR REDUCTION

Crest factor reduction reduces the PAR of the signal by reducing the magnitude of the peaks. In the frequency domain, CFR translates to transfer of energy in the peaks of the signal in the signal bandwidth to uncorrelated noise within and outside the signal bandwidth. Noise addition within the signal bandwidth results in degradation of the Signal to Noise Ratio (SNR) and EVM of the signal. Out-of-band noise results in poorer ACPR. PAR is traded off with In-band and out-of-band distortions.

Various techniques of CFR have been reported in literature. Li [1] and Armstrong [2] utilize a hard limiter followed by out-of-band filtering. This results in good ACPR but very poor EVM since the in-band distortion cannot is not reduced by the filter. Wegener [3] and Sperlich [4] use an interpolation technique to reduce CFR by selectively adding uncorrelated in-band noise to the signal. Vaananen [5] adopts a peak windowing method to avoid addition of adjacent channel power. In the above mentioned techniques, complete PAR reduction is achieved by addition of in-band distortion. The out-of-band is completely filtered out or is not added in the first place. Constrained clipping [6] does separate in-band and out-of-band processing following the hard limiter. Clipping reduces the PAR of the signal. In-band processing is done to limit the EVM to the FCC specifications and is followed by out-of-band processing to limit the out-of-band processing. The three processes are done serially and no trade-off is demonstrated between them. The work presented here shows that there is an explicit trade-off between the clipping level, in-band distortion and out-of-band distortion.

III. NEW CFR TECHNIQUE

The block diagram of the proposed technique is shown in Fig. 1. Simple hard limited clipping is used to reduce PAR of a signal by limiting the magnitude of the signal to a threshold value. For a clipping level threshold of CL, the output y, in terms of the input signal x is given as follows:

$$y = \begin{cases} |CL| e^{jx} & |x| \geq CL \\ x & |x| < CL \end{cases} \quad (1)$$

Clipping results in the generation of uncorrelated noise in-band and out-of-band. The distorted clipped output is now separated into correlated and uncorrelated components using autocorrelation function. The component correlated with the input signal is the valuable desired signal, whereas the component uncorrelated with the input signal is the unwanted noise.

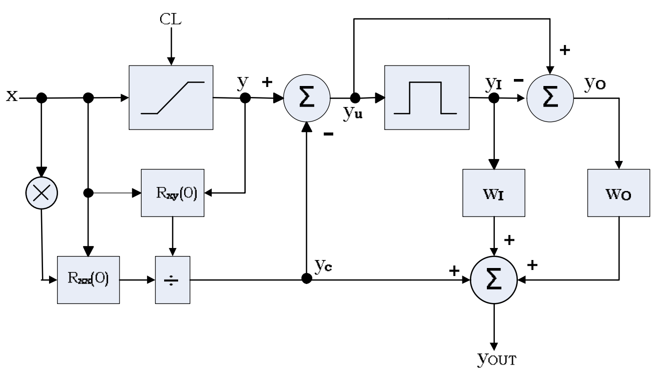

Fig 1. Block Diagram of the proposed CFR technique.

The correlated component y_C is given by

$$y_C = \frac{Rxy(0)}{Rxx(0)} x \quad (2)$$

The uncorrelated component y_U is given by

$$y_U = x - y_C \quad (3)$$

Here R_{xx} and R_{xy} are autocorrelation and cross-correlation functions respectively defined as

$$R_{xx}(\tau) = E[x(t)x^*(t+\tau)] \quad (4)$$

$$R_{xy}(\tau) = E[x(t)y^*(t+\tau)] \quad (5)$$

The uncorrelated component contains both in-band and out-of-band noises. They are further separated by passing y_U through a band-pass filter. Filtering is done using the filtfilt function in Matlab, which performs zero phase digital filtering. In-band distortion y_I is given by

$$y_I = y_U \otimes h \quad (6)$$

Here h is the time domain representation of the band-pass filter. The out-of-band distortion y_O is given by

$$y_O = y_U - y_I \quad (7)$$

The spectrum of correlated and uncorrelated components is shown in Fig. 2.

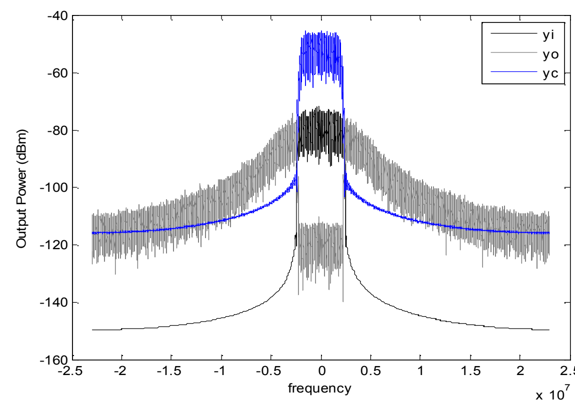

Fig 2. Spectrum of Correlated and Uncorrelated components.

y_I and y_O are weighted by independent weighting factors w_1 and w_2 and added with the correlated signal to give the desired output signal.

$$y_{OUT} = y_C + w_I y_I + w_O y_O \quad (8)$$

The significance of w_I and w_O is discussed in the next section.

IV. OPTIMIZATION

The three parameters clipping level threshold CL, and the weighting factors w_I, and w_O determine the PAR, In-band and out-of-band distortions. CL determines the amount of energy that is transferred from the signal to uncorrelated noise. w_I and w_O determine the amount of uncorrelated noise energy retained within and outside the signal bandwidth respectively. Weighting factors in the range of 0 to 1 essentially translates to different levels of noise component filtering, with 0 representing complete noise filtering and 1 representing no noise filtering. Weighting factor greater than 1 will amount to addition of extra uncorrelated noise.

Filtering of the noise component is equivalent to transferring of lesser amount of energy from signal to noise and hence an increase in PAR of the signal. Weighting factor greater than one is tantamount to transfer of more energy from the signal to uncorrelated noise. This reduces the PAR of the signal. The weighting factors w_I and w_O

improve or degrade the EVM and ACPR respectively, accordingly as they are lesser or greater than 1. Plots of ACPR and EVM for different values of PAR and w_O, keeping $w_I = 1$ are shown in Fig. 3 and Fig. 4 respectively. CL varies from 0.7 to 0.45 in steps of 0.05.

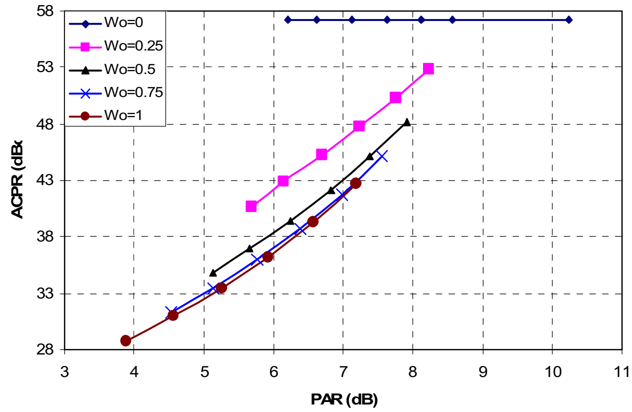

Fig 3. ACPR for various values of PAR and w_O; $w_I = 1$.

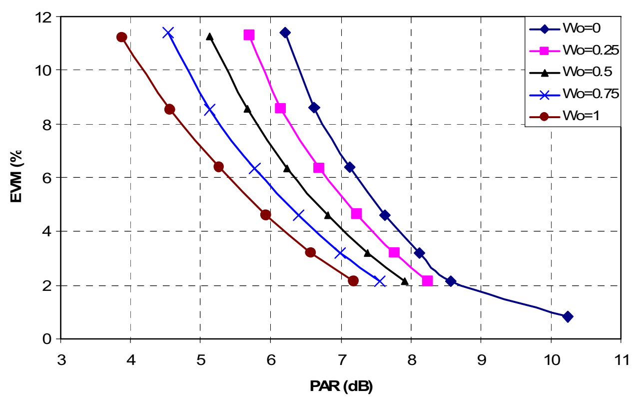

Fig 4. EVM for various values of PAR and w_O; $w_I = 1$.

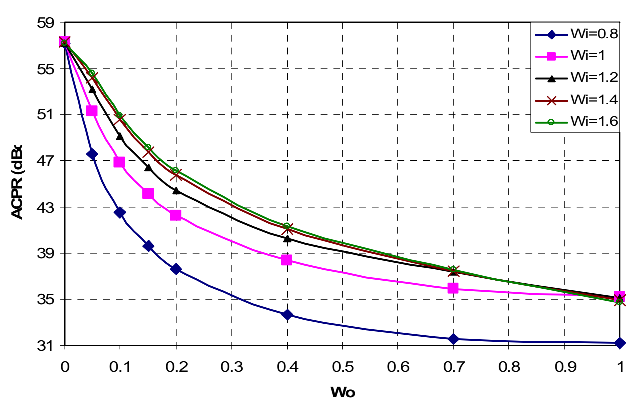

Fig 5. ACPR for various values of w_O and w_I; PAR= 5.7dB.

From Fig. 3 and Fig. 4, we can infer that complete filtering of out-of-band distortion [2], or no out-of-band distortion [3], [4] is not the best means to achieve good EVM. There is an explicit trade-off that can be made between EVM and ACPR based on the requirement. The trade-off can be observed from the plots of ACPR and EVM for PAR=5.7 dB and PAR =7 dB for different values of w_I and w_O in Fig. 5-8 respectively.

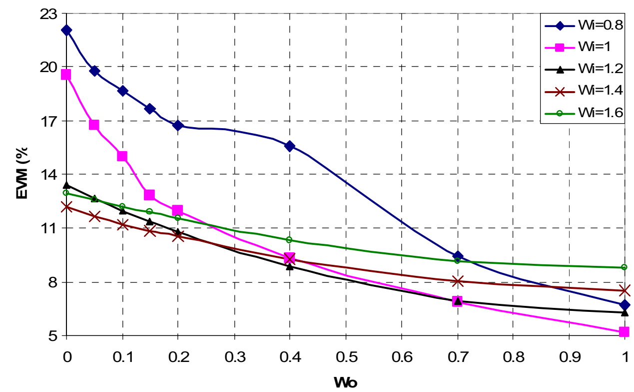

Fig 6. EVM for various values of w_O and w_I; PAR= 5.7dB.

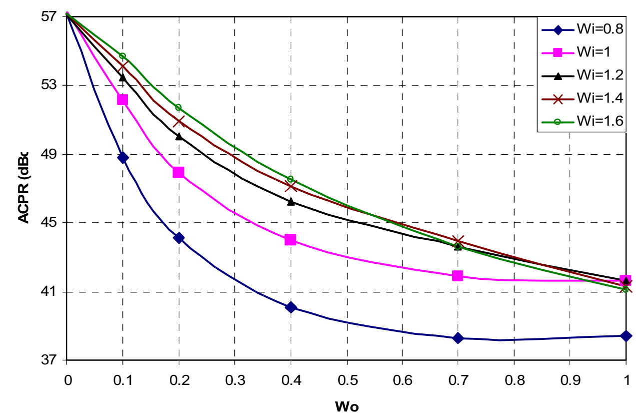

Fig 7. ACPR for various values of w_O and w_I; PAR= 7dB.

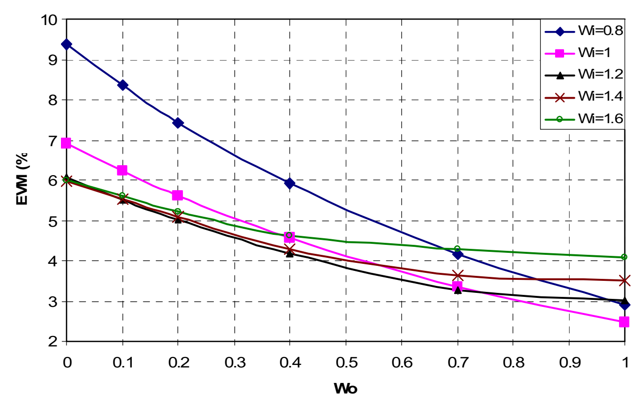

Fig 8. EVM for various values of w_O and w_I; PAR= 7dB.

ACPR performance of a WCDMA base station is limited to -45 dBc while the EVM performance is limited to 17.5 % therefore a CFR ACPR of -50 dBc is reasonable for comparing trade-offs between EVM and ACPR. The ideal out-of-band filtering CFR case of w_O=0 and w_I=1 yields an EVM of 6.9% and 19.5% at PAR of 7 dB and 5.7 dB respectively. For these values of PAR, the EVM drops to

5% and 11% for the w_O=0.2 and w_I=1.4 case and w_O=0.1 and w_I=1.4 case respectively, when allowing the out-of-band CFR distortion to degrade to 50 dBc. This represents a 3 dB and 5 dB improvement respectively in SNDR compared to the ideal out-of-band filtering case.

V. PA Measurement Results

Measurements are done on a 15 W GaN PA. ACPR and EVM measurements for PAR of 5.7dB and PAR of 7dB with comparison to the unclipped signal result are shown in Fig. 9-12 respectively. The distortion observed is a combination of PA non-linearity and CFR added noise. CFR added noise dominates at lower power levels and PA non-linearity dominates at higher power levels. ACPR and EVM performance at higher power levels can be improved by using linearization techniques such as digital predistortion.

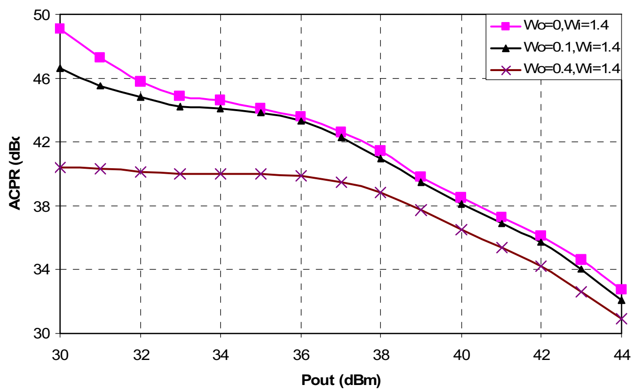

Fig 9. ACPR of 15W GaN PA; PAR= 5.7 dB.

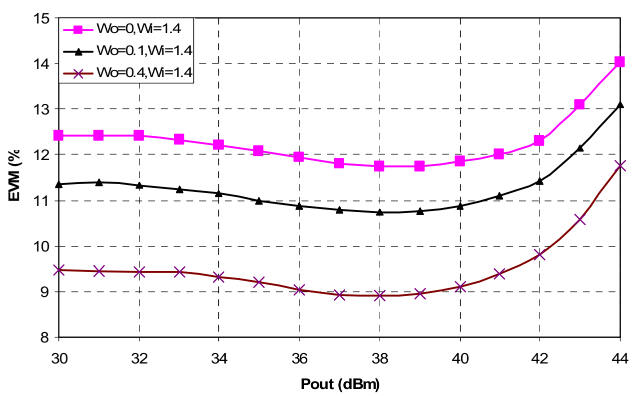

Fig 10. EVM of 15W GaN PA; PAR=5.7 dB

VI. Conclusion

A new crest factor reduction technique is proposed using autocorrelation and weighting factors. It is shown that there is an explicit trade-off between EVM and ACPR for desired levels of PAR with an optimum clipping level and weighting factors. Lower clipping thresholds and in-band weighting factor greater than one usually produces optimum values of EVM and ACPR. Complete filtering of out-of-band noise is not good when both ACPR and EVM are being optimized.

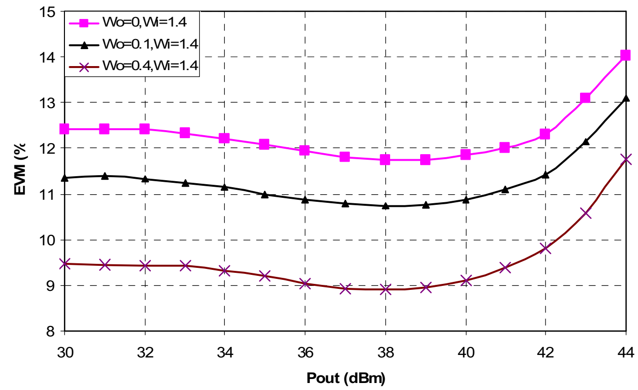

Fig 11. ACPR of 15W GaN PA; PAR= 7dB.

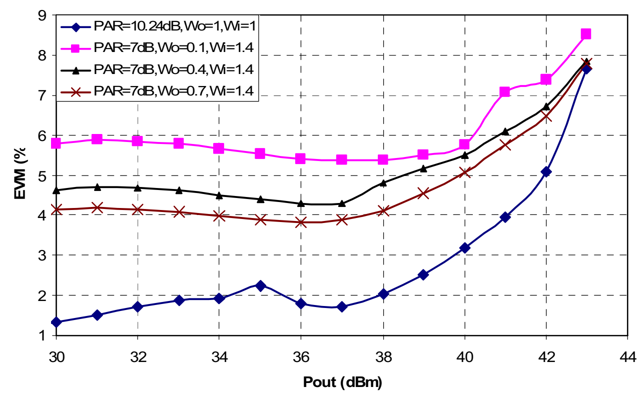

Fig 12. EVM of 15W GaN PA; PAR= 7dB.

References

[1] X. Li and L. J. Leonard Jr., "Effect of Clipping and Filtering on the performance of OFDM", Proc. IEEE Vehicular Technology Conference, 1997, Vol. 3, pp-1634-1638.

[2] J. Armstrong, "New Peak to Average Reduction Scheme", Proc. IEEE Vehicular Technology Conference, 2001, Vol. 1, pp. 756-760.

[3] A. Wegener, "High Performance Crest Factor Reduction Processor for W-CDMA and OFDM Applications", IEEE Radio Frequency Integrated Circuits Symposium, Jun 2006.

[4] R. Sperlich, Y. Park, G. Copeland, and J. S. Kenney, "Power Amplifier Linearization with Digital Predistortion and Crest Factor Reduction", IEEE Microwave Theory and Techniques Symposium, 2004, pp. 669-672.

[5] O. Vaananen, J. Vankka, and K. Halonen, "Simple algorithm for peak windowing and its application in GSM, EDGE and WCDMA systems", IEE Proceedings on Communications, Jun. 2005, pp. 357-362.

[6] R. J. Baxley, C. Zhao, G. T. Zhou, "Constrained Clipping for Crest Factor Reduction in OFDM", IEEE Transactions on Broadcasting, Dec. 2006, Vol. 4, pp. 570-575.