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A Figure-Of-Merit for Evaluating the Overall Performance of OFDM PAPR reduction techniques in the Presence of High Power Amplifier

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***Abstract*—One of the major drawbacks of Orthogonal Frequency-Division Multiplexing (OFDM) is the large envelope fluctuations which either require an inefficient use of High Power Amplifiers (HPA) or decrease the system performance. Peak-to-Average Power Ratio (PAPR) is a very well known measure of the envelope fluctuations and has become the cost function used to evaluate and design multicarrier systems. Several PAPR-reduction techniques have been proposed with the aim to increase the system performance. Besides the fact that these techniques have varying PAPR-reduction performance, most previous studies haven't considered the loss of performance due to the average transmit power variation. In this paper, the Overall Performance (OP) due to PAPR reduction of clipping, Tone Reservation(TR) and Active Constellation Extension (ACE) techniques in the presence of a HPA is investigated by evaluating a figure-of-merit which takes account the PAPR-reduction performance, the average power variation and the in-band distortion. Based on this figure-of-merit OP, simulation results show that, TR is the best, followed by ACE and followed from afar by clipping.**

***Keywords*-Orthogonal Frequency Division Multiplexing (OFDM), Peak-to-Average Power Ratio (PAPR), Overall Performance (OP), High Power Amplifier (HPA).**

I. Introduction

Orthogonal Frequency-Division Multiplexing (OFDM) has recently attracted considerable attention since it has been shown to be an effective technique to combat delay spread or frequency selective fading of wireless or wireline channels. This approach has been adopted as the standards in several outdoor and indoor high-speed wireless and wireline data applications, including Wireless Local Area Networks (WLAN), Digital Audio and Video Broadcasting (DAB and DVB), and Digital Subscriber Line (DSL) modems [1]. OFDM transmission requires no equalizers, which makes it possible to combine with many advanced techniques to improve the capacity and enhance the performance of transmission.

The well-known drawback of OFDM signals is that they have a large dynamic range. The baseband signals having such property result in sensitivities to resolution of digital-analog/analog-digital converters and difficulties in High Power Amplification (HPA). In particular, HPA is critical in order to avoid adjacent channel interference, and if one wishes to maintain linearity by operating HPA with a large back-off, its amplifier power conversion efficiency becomes prohibitively low. Therefore, in order to mitigate this undesirable property, an enormous number of PAPR reduction techniques have been recently proposed in the literature [2, 3].

PAPR is commonly defined as a ratio of the highest instantaneous power to average power:

$$\mathrm{PAPR}_{[x]} = \frac{\|x\|_\infty^2}{\|x\|_2^2},$$

where $\|.\|_2$ and $\|.\|_\infty$ are Euclidean and maximum norms respectively. Since occurrence of peak power is a probabilistic event, PAPR is also a probabilistic event and its probabilistic distribution derived by the Complementary Cumulative Distribution Function (CCDF) for an OFDM signal is known as [4]:

$$\begin{aligned}\mathrm{CCDF}(\psi) &= \Pr\{\mathrm{PAPR} \geq \psi\} \\ &\simeq 1 - \left(1 - e^{-\psi}\right)^N,\end{aligned} \tag{1}$$

where N is the number of OFDM subcarriers.

When a PAPR reduction technique is investigated in an OFDM system, of course, the PAPR of each OFDM symbol is reduced, but in most cases, the average power is changed (decreased or increased). Many researchers are focused just on the PAPR reduction and do not take into account the average power variation in the overall performance of PAPR reductions techniques.

In the literature, a metric for systems performance analysis is the Total Degradation (TD). TD is a parameter which is used in [5, 6] for jointly describe the power losses due to non-linear distortion and inefficient use of the HPA. However, TD do not take into account the average power variation due to PAPR reduction in the overall performance of the system. In this paper, the gain in performance due to PAPR reduction and the loss in performance due to non-linear amplification are investigated by evaluating a figure-of-merit called "Overall Performance" (OP) which takes account the PAPR-reduction performance, the average power variation and the in-band distortion due to both PAPR reduction and non-linear amplification.

The remainder of this paper is organized as follows: section II reviews clipping, TR and ACE techniques that are widely studied in the literature. Section III describes HPA in OFDM

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applications and introduces the Rapp's Solid State Power Amplifier (SSPA) model which is used for simulation results, while section IV defines the OP metric which includes the PAPR reduction performance, the average power variation and the non-linear distortion. Section V is about simulation results while section VI draws a conclusion.

II. PAPR REDUCTION TECHNIQUES

We start with reviewing the three major PAPR reduction techniques that are widely studied in the literature. The gain in performance of these three techniques combined with a non-linear HPA will be evaluated in terms of OP metric.

A. Clipping technique

Envelope clipping [7–11] is a simplest approach to reduce PAPR. In clipping, all the samples exceeding a given threshold are forced to this maximum value. Among all PAPR-reduction techniques clipping is probably the most intuitive one. When clipping is investigated in an OFDM system, both the PAPR of each OFDM symbol and the average power are reduced.

The major disadvantage of clipping technique is that it increases both the out-of band radiation and BER. Note that clipping a signal can be seen as passing it through a soft limiter nonlinearity. In [12], it is shown that, when an OFDM signal is passed through a nonlinear device a distortion term that gives rise to both spectral outgrowth and BER, is introduced. Filtering [8, 10] and windowing [9] can be introduced to control the performance degradation, however, they will generate a regrowth in some time-domain samples that will increase both PAPR. In [11] repeated clipping and filtering is considered to reduce both PAPR and at the same time decrease the performance degradation. In this paper, the clipping and filtering investigated in [8] is used for simulations results.

B. Tone Reservation technique

Tone Reservation (TR) consists in reducing the envelope fluctuations of an OFDM signal by reserving a few tones in order to generate a peak reducing signal which reduces the high peaks in the information carrying signals at the transmitter. These tones do not bear any useful information and are orthogonals to the data bearing tones. This orthogonality makes that the peak reducing signal is easily discarded at the receiver after FFT processing, so the BER of the system is not degraded. Additionally, any side information is not sent from transmitter to receiver.

However, this technique suffers from a loss of data rate and an increase in the average power, which has to be considered in the overall performance of the system. Optimal PAPR reduction by TR can be obtained by solving a Quadratically-Constrained Quadratic Program (QCQP) [13]. However, finding the QCQP optimal solution is computationally demanding; therefore several low complexity methods have been proposed in the literature [13, 14] that achieve sufficiently accurate suboptimal solutions. In [14], a suboptimal PAPR reduction by TR is implemented based on the Gradient-Project (GP) algorithm called "GP-based TR". It will be evaluated in terms of OP metric later in this paper.

C. Active Constellation Extension technique

Active Constellation Extension (ACE) [15, 16] is a technique for PAPR reduction in which, some of the outer signal constellation points of each OFDM block are extended toward outside of the constellation such that the envelope variations of the resulting block are reduced. The basic idea is to reduce the envelope fluctuations of the transmitted signal without directly increasing the BER by setting some constellation points farther from the decision boundaries than the nominal constellation points. This technique can be applied to any PSK and QAM constellation. However, in general the larger the constellation size is, the lower the number of extensible constellation points will be, resulting in less flexibility and thus less reduction of the envelope fluctuations.

The advantages of ACE are that it is transparent to the receiver, there is no loss of data rate and no side information is required. However, a direct result of the extension of the constellation is the increase in the average power, that has to be considered in the overall performance of the system. Similar to TR, the optimal solution of ACE can be obtained by solving a QCQP [15]. However, as stated in [16], obtaining the exact solution of the optimization problem is a very computationally demanding. Therefore, low complexity methods to compute ACE have been proposed in the literature. In [16], a low-complexity ACE is computed based on the Smart Gradient Project (SGP) algorithm. In this paper, the SGP version of ACE technique will be considered for simulation results.

III. HIGH POWER AMPLIFIERS (HPA) IN OFDM APPLICATIONS

Ideally, a power amplifier produces a scaled version of the input signal. However, real amplifiers do not behave in this way. They act on the signal in an nonlinear way depending on the magnitude and frequency of the signal. In this paper, we suppose that power amplifiers are memoryless amplifiers [(a)]. Detailed information about memoryless amplifiers are presented in [17].

Nonlinearities in amplifiers can be described by their amplitude transfer characteristics - also referred as Amplitude Modulation/Amplitude Modulation (AM/AM) conversion - and phase transfer characteristics or Amplitude Modulation/Phase Modulation (AM/PM) conversion. An example of typical AM-to-AM and AM-to-PM characteristics of a bandpass amplifier is shown in Fig.1.

The normalized powers input backoff (IBO) and output backoff (OBO) are defined as:

$$\begin{aligned} \mathrm{IBO} &= 10\log_{10}\frac{\mathcal{P}_{in}^{(sat)}}{\mathcal{P}_x}\ [\mathrm{dB}]\,, \\ \mathrm{OBO} &= 10\log_{10}\frac{\mathcal{P}_{out}^{(sat)}}{\mathcal{P}_y}\ [\mathrm{dB}]\,. \end{aligned} \tag{2}$$

If the average input power ($\mathcal{P}_x$) is very small compared to the input power required to produce the maximum output

[(a)]The memoryless amplifiers are the power amplifiers whose nonlinearities are depending only on the magnitude of the input signal.

power, i.e., if IBO (or OBO) is very large, the amplifier will behave linearly. As the input power is increased from this low level, the device will begin to exhibit nonlinear behavior. Several AM/AM and AM/PM characteristics can be found in the literature, such as the one proposed by Saleh [18] and Rapp [19].

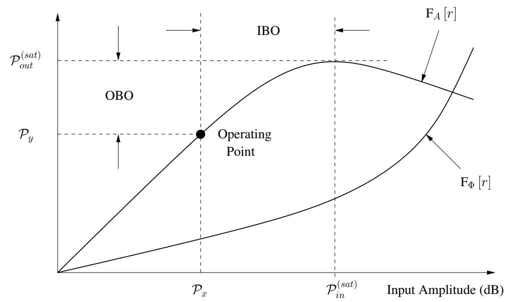

Fig. 1: AM-to-AM and AM-to-PM characteristics.

In this paper, the HPA model used for simulation results is the Rapp's SSPA model which their AM/AM and AM/PM characteristics are expressed as

$$\begin{aligned} \mathrm{F}_A\,[r] &= \frac{r}{\left[1+\left(\frac{r}{\mathrm{V}_{sat}}\right)^{2p}\right]^{\frac{1}{2p}}} \\ \mathrm{F}_\Phi\,[r] &= 0, \end{aligned} \qquad (3)$$

where, $\mathrm{F}_A\,[.]$ and $\mathrm{F}_\Phi\,[.]$ are the AM/AM and AM/PM conversion functions respectively, $\mathrm{V}_{sat} = \sqrt{\mathcal{P}_{out}^{(sat)}}$ corresponds to the output saturation level, p often called "knee factor" is the smooth factor of the transition between the linear operation and the saturation operation. Note that, the AM/PM is zero [(b)], therefore it can be said that Rapp's SSPAs introduce only AM/AM distortion.

IV. PAPR reduction techniques Performance Evaluation and OP metric

The gain in performance of the pair (PAPR reducer/HPA) is evaluated by the OP metric which takes account the PAPR-reduction performance, the average power variation and the non-linear distortion.

A. PAPR-reduction performance

Let consider a PAPR reduction technique and let τ the parameter which controls the PAPR reduction. In the literature, the PAPR reduction is evaluated based on the CCDF. In this paper, we denote as ΔPAPR the gain in PAPR reduction defined as

$$\Delta\mathrm{PAPR}\,(\tau) = \mathrm{PAPR}_{[\mathrm{o}]} - \mathrm{PAPR}_{[\mathrm{r}]}\,(\tau)\,, \quad [\mathrm{dB}] \qquad (4)$$

where $\mathrm{PAPR}_{[\mathrm{o}]}$ is the required PAPR to obtain a specific value of the CCDF when none PAPR reduction is done, while $\mathrm{PAPR}_{[\mathrm{r}]}$ is the required PAPR to obtain the same value of the CCDF when PAPR reduction is done.

For clipping [8], GP-based TR [14] and SGP-based ACE [16] techniques, the parameter τ is linked to the magnitude threshold which is used in these three techniques to control the reduction in PAPR.

B. Average power variation

When a PAPR reduction technique is investigated in a system, in most cases, the average power is changed. For example, in a context of clipping, the average power is reduced, while in a context of TR or ACE, the average power is increased. In this paper, we denote by $\Delta\mathrm{E}\,(\tau)$, the variation in average power defined as

$$\Delta\mathrm{E}\,(\tau) = \left|\mathcal{P}_{[\mathrm{r}]}\,(\tau) - \mathcal{P}_{[\mathrm{o}]}\right|, \quad [\mathrm{dB}] \qquad (5)$$

where $\mathcal{P}_{[\mathrm{o}]}$ is the average power of the input signal (before PAPR reduction), while $\mathcal{P}_{[\mathrm{r}]}\,(\tau)$ is the average power of the output signal (after PAPR reduction). Note that, the average power variation is a function of τ. Indeed, the PAPR reduction generates the variation in average power, so τ which controls the PAPR reduction controls also the the average power variation.

C. The transmission performance in the presence of in-band distortion

We consider that, the transmission is done over an additive white Gaussian noise (AWGN) channel. In the pair (PAPR reducer/HPA), non-linearities are generated by HPA and by PAPR reduction technique when the technique is a distorting PAPR reduction technique [(c)].

The power losses due to the pair (PAPR reducer/HPA) non-linearities is defined by the TD metric (used in [5, 6]) as

$$\mathrm{TD}(\tau, \mathrm{IBO}) = \Delta\,[\mathrm{Eb/N0}]\,(\tau, \mathrm{IBO}) + \mathrm{IBO}, \quad [\mathrm{dB}] \qquad (6)$$

where, $\Delta\,[\mathrm{Eb/N0}]\,(\tau, \mathrm{IBO})$ is the degradation in the energy per bit at the BER target of 10^{-2} for example. It can be decomposed as

$$\begin{aligned} \Delta\,[\mathrm{Eb/N0}]\,(\tau, \mathrm{IBO}) &= \Delta\,[\mathrm{Eb/N0}]\,(\mathrm{IBO}) \\ &\quad + \Delta\,[\mathrm{Eb/N0}]\,(\tau), \quad [\mathrm{dB}] \end{aligned} \qquad (7)$$

where, $\Delta\,[\mathrm{Eb/N0}]\,(\mathrm{IBO})$ is the energy per bit losses due to the HPA non-linearities and $\Delta\,[\mathrm{Eb/N0}]\,(\tau)$ is the energy per bit losses due to the PAPR reduction if the technique is a distorting PAPR reduction technique. For a distortionless technique like TR, $\Delta\,[\mathrm{Eb/N0}]\,(\tau) = 0$ dB.

[(b)] The effect of the AM/PM conversion is not exactly zero, but it is very small and thus it is not considered in the model.

[(c)] A distorting PAPR reduction technique is a technique for PAPR reduction which generates non-linear distortion while PAPR is reduced.

D. *The pair (PAPR reducer/HPA) Overall Performance*

The variation in average power and in-band distortion are adverse impacts on the overall performance of the system, only the gain in PAPR reduction contributes of increasing the system performance. Therefore , we define the metric OP as

$$\begin{aligned}\mathrm{OP}(\tau,\mathrm{IBO}) = \Delta\mathrm{PAPR}\,(\tau) - \Delta\mathrm{E}\,(\tau) \\ - \Delta\,[\mathrm{Eb/N0}]\,(\tau,\mathrm{IBO})\end{aligned} \tag{8}$$

where $\Delta\mathrm{PAPR}(\tau)$, $\Delta\mathrm{E}(\tau)$ and $\Delta\,[\mathrm{Eb/N0}]\,(\tau,\mathrm{IBO})$ are defined by (4), (5) and (7) respectively.

The expression of $\mathrm{OP}(\tau,\mathrm{IBO})$ can integrate the complexity of PAPR reduction techniques and the out-of band (OOB) power emission due to the HPA. But, in this paper, we deliberately ignore the effect of theses both parameters; we focus primarily on the PAPR-reduction capabilities, the average power variation and the transmission performance.

For an optimal utilization of the pair (PAPR reducer/HPA), it is important to find the optimum values (τ^*,IBO^*) defined as

$$(\tau^*,\mathrm{IBO}^*) = \arg\max_{(\tau,\mathrm{IBO})}\{\mathrm{OP}(\tau,\mathrm{IBO})\}\,. \tag{9}$$

Solving the above equation leads to know a closed-form expression of $\mathrm{OP}(\tau,\mathrm{IBO})$. For us, it is not possible to obtain, at the moment, a closed-form expression of $\mathrm{OP}(\tau,\mathrm{IBO})$. However, the optimum (τ^*,IBO^*) can be find by computer simulations. In this paper, we focus only on finding the optimal τ of the PAPR reducer when the IBO of the HPA is given.

V. Simulation Results

In this paper, the system employs an IEEE 802.11a/g standard based WLAN system [20] which uses 64 tones. Out of these 64 tones, 48 subcarriers are used for data with each modulated by 16-QAM, while 4 tones are used for pilots. The rest 12 tones (reserved tones) are used for PAPR reduction in TR context. The Rapp's SSPA model is used for $p = 2$. The parameter τ which controls the performance of clipping and filtering, GP-based TR and SGP-based ACE techniques is defined as

$$\tau = 20\log_{10}\frac{A}{\sqrt{\mathcal{P}_{[o]}}}\;[\mathrm{dB}]\,,$$

where A is the magnitude threshold used in clipping and filtering [8], in GP-based TR [14] and in SGP-based ACE [16], $\mathcal{P}_{[o]}$ is the average power of the signal in the PAPR reducer input.

Fig.2 shows that the gain in PAPR reduction of clipping and filtering decreases as τ increases. For GP-based TR and SGP-based ACE, the gain increases until $\tau \le 4$ and $\tau \le 6$ respectively. In terms of PAPR reduction, clipping and filtering is the best of three. For example, at CCDF = 10^{-2}, PAPR can be reduced about 4.25 dB by clipping and filtering, whereas the maximum gain in PAPR reduction is about 3 dB for GP-based TR and 2.5 dB for SGP-based ACE.

Fig.3 shows that the variation in average power by clipping and filtering decreases as τ increases. This means that, an

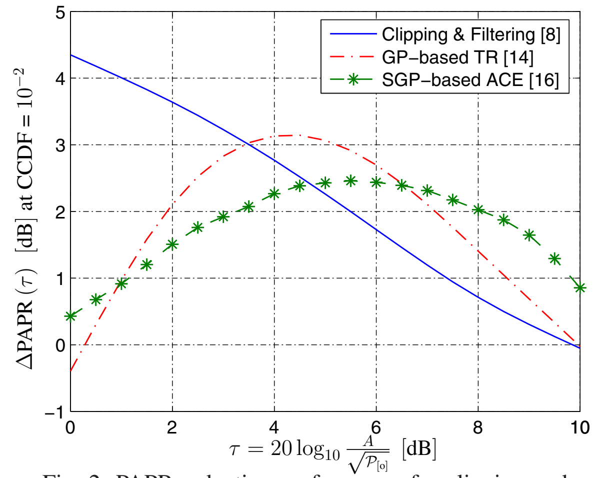

Fig. 2: PAPR-reduction performance for clipping and filtering, GP-based TR and SGP-based ACE techniques.

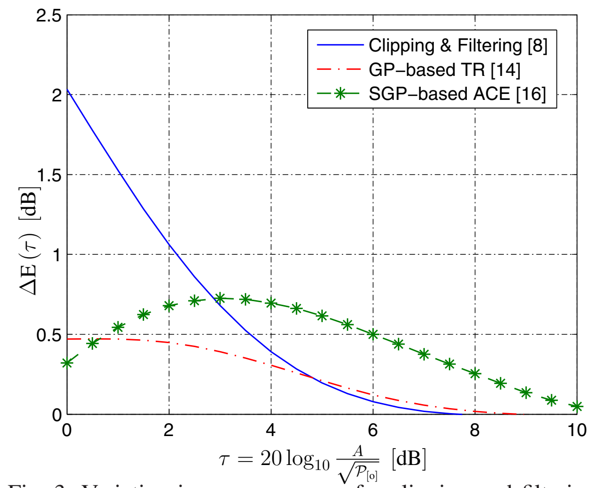

Fig. 3: Variation in average power for clipping and filtering, GP-based TR and SGP-based ACE techniques.

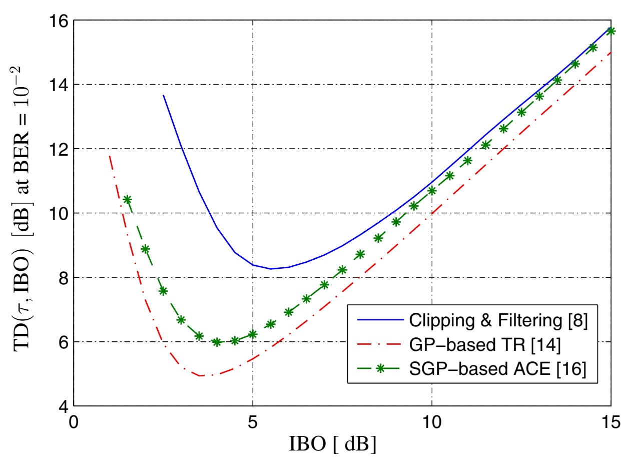

Fig. 4: Total degradation versus IBO, for clipping and filtering, GP-based TR and SGP-based ACE techniques, with $\tau = 4$ dB.

increase in PAPR reduction leads to an increase in average power variation. Therefore, a trade-off must be done between PAPR reduction and average power variation. It appears clearly that GP-based TR is better than SGP-based ACE in terms of average power variation (Fig.3) and in terms of PAPR reduction (refer to Fig.2).

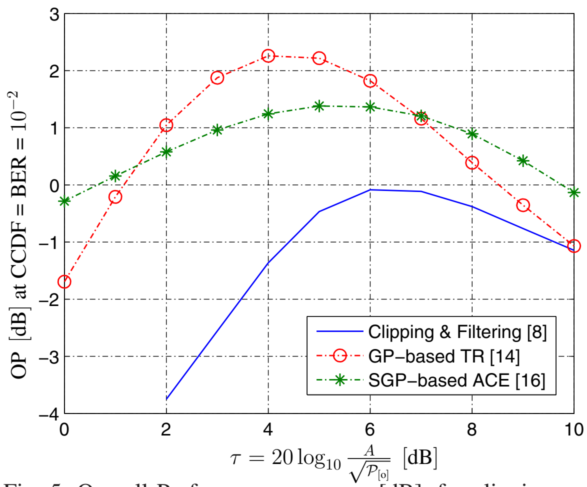

Fig. 5: Overall Performance versus τ [dB], for clipping and filtering, GP-based TR and SGP-based ACE techniques, with IBO = 5 dB..

Fig.4 shows the total degradation at the BER target of 10^{-2} for clipping and filtering, GP-based TR and SGP-based ACE techniques, with $\tau = 4$ dB. Analyzing the curves in Fig.4, it shown that, the minimum total degradation is 5 dB, 6 dB and 8.25 dB for GP-based TR, SGP-based ACE and clipping and filtering respectively. Theses minimum values of TD are reached for IBO = 4 dB, 4.5 dB and 6 dB respectively. This means that, in terms of power losses, GP-based TR is better than SGP-based ACE which is also better than clipping and filtering. Also, in terms of efficient use of HPA, GP-based TR is better than SGP-based ACE which is also better than clipping and filtering. Note that, the degradation at the small values of IBO is due to the important in-band distortion of the HPA.

Fig.5 and Fig.6 show the overall performance of the pair (PAPR reducer/HPA) at BER = 10^{-2} and CCDF = 10^{-2} for the three PAPR reduction techniques for IBO = 5 dB and 10 dB respectively, when an Rapp's SSPA model is used as a HPA. OP takes account the PAPR-reduction performance, the average power variation and the in-band distortion as shown in (8). In Fig.6, it shown that, for GP-based TR, the maximum value of OP is 2.5 dB; this maximum is reached at $\tau = 4$ dB, while for SGP-based ACE, the maximum value of OP is about 1.5 dB and reached at $\tau = 5$ dB, while for clipping and filtering, the maximum value of OP is 0.75 dB and reached at $\tau = 6$ dB.

Fig.5 is a worst case in terms of OP maximization. Indeed, in Fig.5, i.e., for IBO = 5 dB, The maximum values of the OP for all the three techniques are lower than the maximum values of the OP in Fig.6. It can be concluded that, in terms of

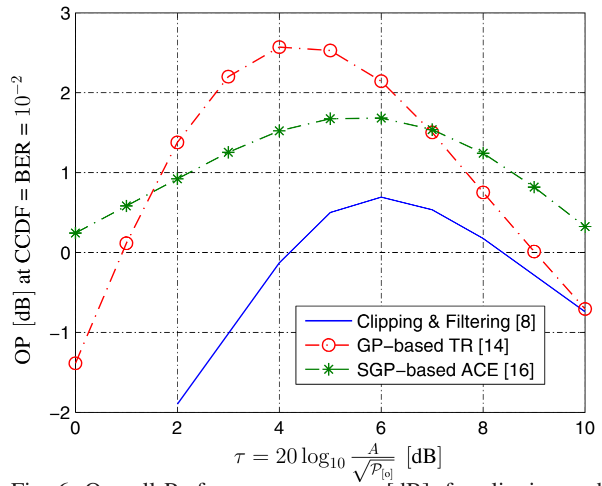

Fig. 6: Overall Performance versus τ [dB], for clipping and filtering, GP-based TR and SGP-based ACE techniques, with IBO = 10 dB.

PAPR reduction, average power variation, in-band degradation, GP-based TR is the best, followed by SGP-based ACE and followed from afar by clipping and filtering.

VI. Conclusion

In this paper, a metric for the pair (PAPR reducer/HPA) overall performance characterization is described. This metric called OP for Overall Performance takes account the PAPR-reduction performance, the average power variation and the in-band distortion. OP is evaluated for clipping and filtering [8], GP-based TR [14] and SGP-based ACE [16] techniques when a Rapp's SSPA is used as power amplifier. Simulation results have shown that, in terms of PAPR reduction, average power variation, in-band degradation and efficient use of HPA, GP-based TR is the best, followed by SGP-based ACE and followed from afar by clipping and filtering. The methodology used in the paper can be easily used for evaluating general PAPR reduction techniques.

An extension of this work would be to integrate the complexity of techniques and the OOB power emission due to the HPA in the OP evaluation.

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