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Robust Digital Predistortion in Saturation Region of Power Amplifiers

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ABSTRACT

This paper proposes adigital predistortion (DPD) technique to improve linearization performance when the power amplifier (PA) is driven near the saturation region. The PAis a non-linear device in general, and the nonlinear distortion becomes severer as the output power increases. However, the PA's power efficiency increases as the PA output power increases. The nonlinearity results in spectral regrowth, which leads to adjacent channel interference, and degrades the transmit signal quality. According to our simulation, the linearization performance of DPD is degraded abruptly when the PA operates in its saturation region. To relieve this problem, we propose an improvedDPD technique. The proposed technique performs on/off control of the adaptive algorithm based on the magnitude of the transmitted signal. Specifically, the adaptation normally works for small and medium signals while it stops for large signals. Therefore, harmful coefficient updatesby saturated signals can be avoided. A computer simulation shows that the proposed method can improve the linearization performance compared with the conventional DPDmethod in highly driven PAs.

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1. INTRODUCTION

During the last two decades, many researches for improving the performance of power amplifier (PAs) have been performed. In particular, the linearity and efficiency of the PA can be used as an indicator of the performance of the overall communication system. The PA is a non-linear device in general, and the nonlinear distortion becomes severer as the output power increases. The nonlinearity results in spectral regrowth, which leads to adjacent channel interference, and degrades the transmitted signal quality. To avoid the severe nonlinearity, one simple solution is to drive the PA in a low power region, (i.e., the linear region). However, the power efficiency of the PA is lowered to 10%. In order to increase the power efficiency, the PA needs to bedriven a high power, together with linearization techniques to linearize the PA. Linearization techniques include feedback, analog predistortion (PD), and feed forward methods [1]–[4]. Among these techniques, the digital predistortion (DPD) is known to be the most cost and performance-effective [5].DPD based on error feedback correction is a powerful linearization strategy because it has the nature of a manageable digital operation, and the error correction is insensitive to amplifier variations, such as temperature, supply voltage, and devicevariations, as well as the nonlinear characteristics of the PA.By using the input and output signals of the PA, the DPD implementsthe inverse functionof the PA to linearize the non-linear PA. The inverse function can be realized either by Lookup Table or polynomial. Between them, polynomial PD is preferable because it exhibits better linearization performance and faster convergence.The coefficients of the Polynomial PD arefound via adaptive algorithms, such as Least Mean Square (LMS) orRecursive Least Square (RLS) [6]–[9]. However, according to our simulation, the linearization performance degrades severely when the PA operates in its saturation region. To relieve this problem, this paper proposes a new DPD technique. The proposed technique performs on/off control of the adaptive algorithm based on the transmitted signal's magnitude. Specifically, for small signals, the adaptive predistortion algorithm works normally. In contrast, the adaptive algorithm stops for large signals until small signals occur again. Therefore, harmful coefficient updates by severe nonlinearity can be avoided. A computer simulation shows that the proposed technique linearize the PA better than the conventional PD in highly driven PAs.

2. PROPOSED DPD TECHNIQUE

We consider a DPD structure based on the indirect learning architecture as shown in Figure 1[10]. The DPD coefficients are found at the postdistorter by linearizing the PA - postdistorter chain. The coefficients are copied to the PD block.

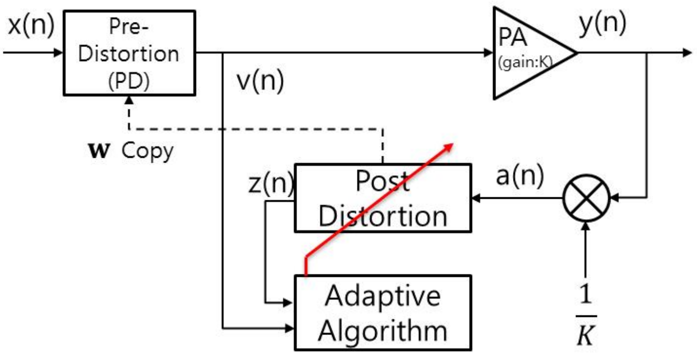

Figure 1. Block diagram of digital predistortion

The adaptive algorithmfor finding the PD parameters at the postdistorter needs two inputs: The predistorter output v(n) and the feedback signal a(n). The postdistorter and PD have the same structure, and this paper employs a polynomial model. The output v(n) of the PD is writtenas

$$v(n) = x(n)\sum_{q=0}^{Q} w_q^*|x(n)|^{2q} = [w_0^*,\ w_1^*, \dots,\ w_Q^*]\begin{bmatrix} x(n) \\ x(n)|x(n)|^2 \\ \vdots \\ x(n)|x(n)|^{2Q} \end{bmatrix} = \boldsymbol{w}^H\boldsymbol{x}(n) \tag{1}$$

where 2Q+1 is the maximum polynomial order for the predistortion, $\mathbf{w} = [w_0, w_1, \dots, w_Q]^T$ is the coefficient vector of the predistortion, and $\boldsymbol{x}(n) = [x(n), x(n)|x(n)|^2, \dots, x(n)|x(n)|^{2Q}]^T$.The postdistorter is modeled by the same polynomial model. The outputz(n) of the postdistortion can bewritten as

$$z(n) = \frac{1}{K}y(n)\sum_{q=0}^{Q} w_q^*|y(n)|^{2q} = [w_0^*,\ w_1^*, \dots,\ w_Q^*]\begin{bmatrix} a(n) \\ a(n)|a(n)|^2 \\ \vdots \\ a(n)|a(n)|^{2Q} \end{bmatrix} = \boldsymbol{w}^H\boldsymbol{a}(n) \tag{2}$$

where 2Q+1 is the maximum polynomial order for the postdistortion, $\mathbf{w} = [w_0, w_1, \dots, w_Q]^T$ is the coefficient vector of the postdistortion, $\mathrm{a(n)} = \frac{1}{K}y(n)$, and $\boldsymbol{a}(n) = [a(n), a(n)|a(n)|^2, \dots, a(n)|a(n)|^{2Q}]^T$.

For the adaptive algorithm for finding the postdistorter coefficients, we consider the recursive least squares (RLS) algorithm. The RLS algorithm updates the postdistorter coefficientsat every sample to minimize the squared error between v(n) and z(n). Thus, the postdistorter becomes the inverse system of the PA.

Table 1. The digital predistortion algorithm of indirect learning architecture

```
Initialization:
$\mathbf{w} = [0,0,...,0]^T$, $\mathbf{P} = \mathbf{I}_{Q+1}$

Adaptive algorithm for calculating the predistortion coefficients:
 for n=1,⋯,N
 {
     $\mathbf{u} = [y(n), y(n)|y(n)|^2, ..., y(n)|y(n)|^{2q}]^T$
     $z(n) = \mathbf{w}^H \mathbf{u}$
     $\boldsymbol{\kappa} = \frac{\lambda^{-1}\mathbf{P}\mathbf{u}}{1+\lambda^{-1}\mathbf{u}^H\mathbf{P}\mathbf{u}}$
     $e(n) = x(n) - z(n)$

   if $(|x(n)| < x_{TH})$
   {
     $\mathbf{w} = \mathbf{w} + \boldsymbol{\kappa}e^*(n)$ ............... (1)
     $\mathbf{P} = \lambda^{-1}\mathbf{P} - \lambda^{-1}\boldsymbol{\kappa}\mathbf{u}^H\mathbf{P}$ ........... (2)
   }
 }
```

The proposed RLS algorithm for updating **w** is summarized in Table 1. The (Q+1)-by-(Q+1) matrix **P** represents the inverse correlation matrix. (1) and (2) in Table 1 are the updates of **w** and **P** to minimize the squared error $|e(n)|^2$ at each time "n", respectively. In the conventional RLS algorithm, the updates of **w** and **P** always work at every sample. However, the proposed method in Table 1 occasionally updates **w** and **P** only when $|x(n)|$ is smaller than a threshold value, x_{TH}. Specifically, if $|x(n)| < x_{TH}$, **w** and **P** are normally updated, otherwise the update does not occur, and **w** and **P** are not changed untilsmall signal appears again. Therefore, harmful updates by highly saturated samples can be avoided. The magnitude threshold x_{TH} should be appropriately determined by considering the types of PAs being used and the PA input signal's characteristics. After the operation of the adaptive algorithm for $n \in [1, N]$, the final **w** is copied into the PD block.

3. COMPUTER SIMULATION RESULTS

The performance of the proposed DPD technique is examined through computer simulation. The simulation environmentsare as follows. The input signal of the PAis the LTE uplink signal. The modulation scheme is 64-QAM (Quadrature Amplitude Modulation), and the bandwidth is 20MHz. As a PA model, we use the Saleh model [11]. The detailed model is as follows.

$$y(n) = v(n) \times \frac{K_1}{1 + K_2|v(n)|^2} e^{j\frac{K_1|v(n)|^2}{1+K_4|v(n)|^2}} \qquad (3)$$

$$K_1 = 1.1, K_2 = 0.3\ , K_3 = 1K_4 = 1$$

The ideal gain of the PA is assumed to be "1", and the saturation point is |y(n)|=1. This means that if the PA input magnitude exceeds "1", the PA output falls into the saturation region. In the simulation, to drive the amplifier overthe saturation region, the maximum value of the transmitted signal's magnitude is set to "1.6".

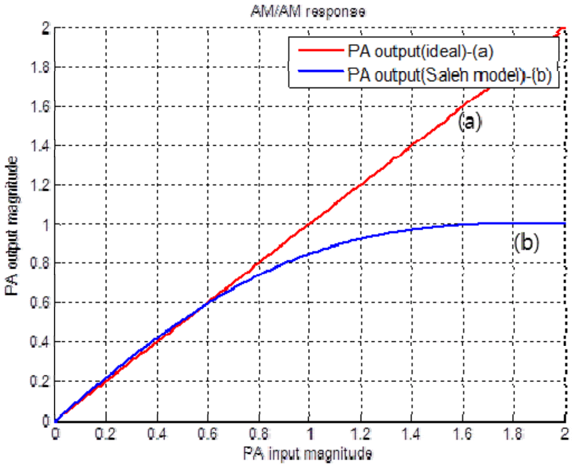

Figure 2. Characteristics of power amplifier (AM–AM characteristics)

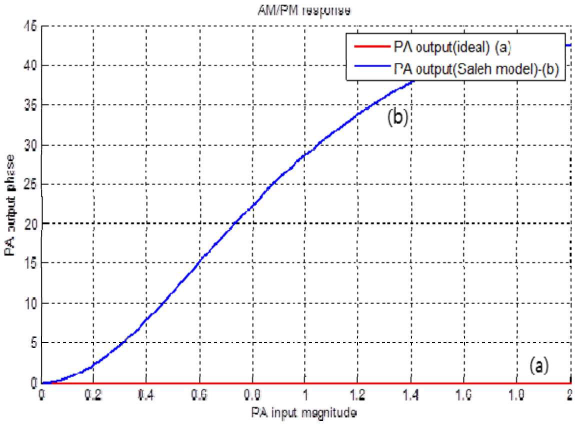

Figure 3. Characteristic of the power amplifier (AM–PM characteristics)

Figures 2 and 3 show the AM–AM and AM–PM characteristics of the PA model. The red curve (a) shows the ideal characteristics and the blue curve (b) shows the characteristics of the PA model in (3).

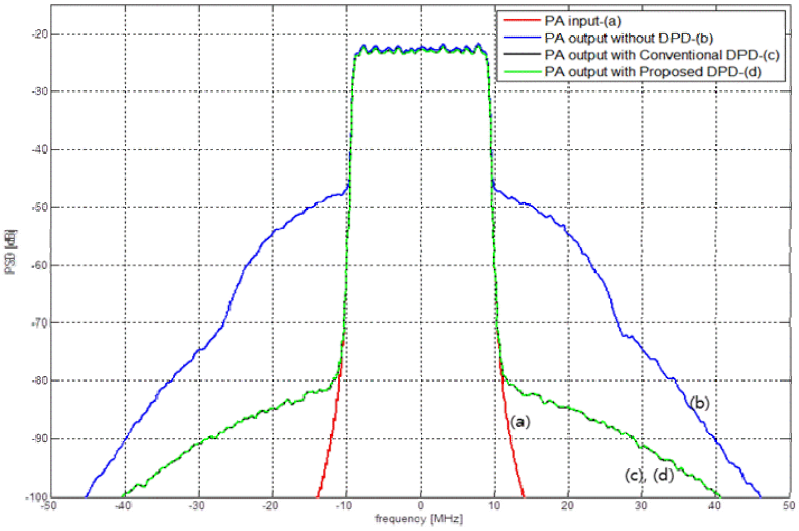

Figure 4. Spectrums at power amplifier output

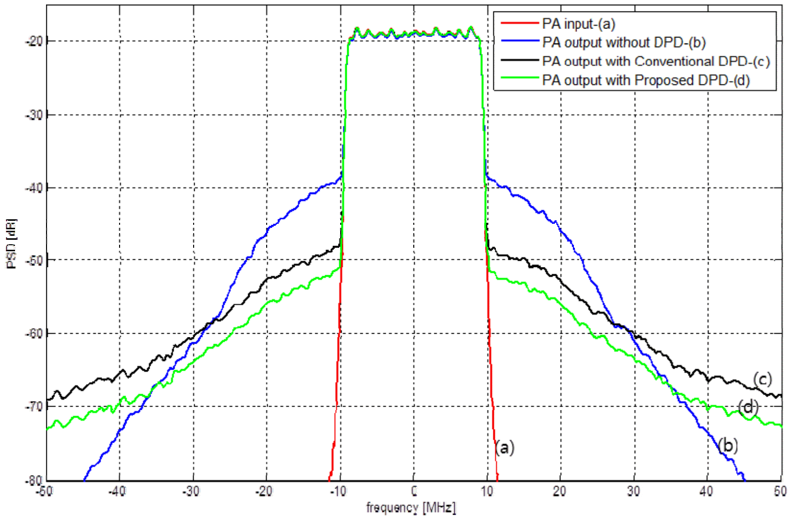

Figure 5. Spectrums at power amplifier output

Figure 4 shows the power spectrum of the PA output signals when the PA is driven a relatively linear region (far from the saturation point). In the simulation, the PA input signal's magnitude is under "1" so that all the signals are amplified below the saturation point. The maximum polynomial order of the DPD is 15, andthe threshold x_{TH} is "1". The red curve (a) is the transmitted signal's spectrum. This is the ideal spectrum. The blue curve (b) is the PA output spectrum without predistortion. Significant spectral regrowth is observed due to the PA's nonlinearity. The black curve (c) is the PA output spectrum with the conventional DPD. The spectral regrowth is reduced by more than 30 dB. The green curve (d) is the PA output spectrum with the proposed DPD. The conventional and proposed DPD techniques show almost the same performance.

Figure 5 shows the PA output spectrums when the PA is driven overthe saturation region. Here, the maximum PA input signal's magnitude is '1.6' so that some portion of the signal falls into the PA's saturation region. With the conventional DPD, only a 10 dB reduction of the spectral regrowth is observed. The linearization performance degrades severely at the PA's saturation region. However, the proposed method further reduces the spectral regrowth by 3 – 4 dBcompared to the conventional DPD.

In summary, the proposed DPD performance is comparable to that of the conventional DPD at the PA's linear region while the former performs better than the latter at the PA's saturation region. These results indicate that the proposed technique can increase the PA’s power efficiency together with its linearization performance compared with the conventional DPD.

4. CONCLUSION

In this paper, we proposed a new DPD technique that improves the linearization performance when the PA is driven near the saturation region by the go/stop control of the adaptive algorithm. Specifically, for small signals, the adaptive predistortion algorithm works normally while the adaptive algorithm stops for large signals until small signals occur again. Thus, harmful coefficient updates by severe nonlinearity can be avoided. The simulation results indicate that the proposed predistortion technique is more effective than the conventional DPD when the PA is driven near the saturation region.

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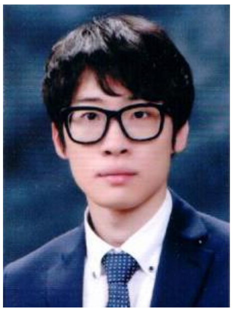

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