Derivative-Based Envelope Design Technique for Wideband Envelope Tracking Power Amplifier with Digital Predistortion

Abstract: A novel envelope design for an envelope tracking (ET) power amplifier (PA) based on its derivatives is proposed, which can trade well off between bandwidth reduction and tracking accuracy. This paper theoretically analyzes how to choose an envelope design that can track the original envelope closely and reduce its bandwidth, and then demonstrates an example to validate this idea. The generalized memory polynomial (GMP) model is applied to compensate for the nonlinearity of ET PA with the proposed envelope design. Experiments are carried out on an ET system that is operated with the center frequency of 3.5 GHz and excited by a 20 MHz LTE signal, which show that the proposed envelope design can make a good trade-off between envelope bandwidth and efficiency, and satisfactory linearization performance can be realized.

Keywords: bandwidth reduction; envelope tracking; shaping function; supply modulator

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1 Introduction

In the fifth-generation communication systems (5G), complex modulated signals with high peak-to-average power ratio (PAPR) and wide bandwidth (BW) are applied to increase the spectrum utilization and data transmission rate[1 – 2]. However, a high PAPR leads to more challenges in efficiency and linearity. The envelope tracking (ET) technique is a promising candidate to improve the efficiency of the power amplifier (PA)[3 – 4].

In ET architecture, the supply modulator adjusts the drain voltage of the PA for signals according to input power, by which the PA is always working at a saturated state. Unfortunately, the envelope of the radio frequency (RF) signal cannot be directly used as the input of the supply modulator. On the one hand, the envelope of the RF signal usually has a bandwidth of four times to eight times the original modulated bandwidth, placing high challenges on the design of the supply modulator. Thus the bandwidth reduction of the envelope is required. On the other hand, since the PA cannot operate when the drain voltage is below the knee voltage, the envelope signal needs to be mapped to a voltage value for the PA[5]. Therefore, a proper envelope design should be applied before the envelope of the RF signal enters the supply modulator.

Several techniques for reducing the bandwidth of the envelope signal have been proposed to meet the requirements of the supply modulator. A method to limit the slew rate of the envelope was discussed in Ref. [6], and low-pass filters were applied in Refs. [7 – 8] to narrow the bandwidth of the envelope. In real applications, these methods need memory blocks and then introduce additional information to the original envelope, which places more challenges on digital predistortion. Several shaping functions also track the envelope closely and reduce its bandwidth to a constant without memory blocks. N6 was applied in Refs. [5, 7, 9 – 10] to make a good trade-off between linearity and efficiency of ET PA. Besides, the Wilson function[11 – 12] and power envelope tracking (PET)[13] technique can also reduce the envelope bandwidth to a certain value at a cost of efficiency degradation.

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Taking considerations on both bandwidth reduction and shaping function, this paper proposes a novel technique to establish envelope design based on the derivatives of envelope functions, by which a trade-off can be made between the bandwidth and the tracking accuracy of the envelope. An example is demonstrated to verify the proposed idea. Furthermore, the corresponding digital predistortion is employed to compensate for the nonlinearity of the envelope tracking power amplifier with this method.

2 Envelope Analysis

The efficiency of ET PA is usually the product of the efficiency of the supply modulator and that of PA. However, an envelope with a bandwidth wider than the one of the supply modulator degrades the efficiency of the supply modulator. Generally, the closer the shaping function tracks the original envelope, the higher the efficiency of the PA is. Therefore, an envelope design always has two characteristics:1) It can effectively reduce the bandwidth of envelope; 2) it tracks the envelope closely.

1) Reducing the bandwidth of the envelope

An envelope design $f(|x|)$ can be expressed in Taylor expansion at zero as follows.

$$f(|x|) = f(0) + f'(0) \cdot |x| + \frac{f''(0)}{2} \cdot |x|^2 + \ldots + \frac{f^n(n)}{n!} \cdot |x|^n,\ n = \infty. \tag{1}$$

Here, x represents the baseband signal whose bandwidth is B_{RF}. The bandwidth of $|x|$ is theoretically infinite because of the absolute sign. And $|x|^2$ can be expressed as

$$|x|^2 = x \cdot x^*, \tag{2}$$

whose bandwidth is B_{RF}[13]. Therefore, the odd order of the envelope is infinite, while the even order of the envelope is finite. It can be inferred that it is a necessary condition for $f(|x|)$ that $f'(0)$ equals zero to effectively reduce the bandwidth of the original envelope.

2) Tracking the envelope closely

The de-trough envelope can convert the original envelope above the knee voltage and simultaneously track it most closely. But the non-smoothness of de-trough function curve derivative widens the bandwidth of envelope and brings strong nonlinearity. Therefore, a smooth envelope design is desirable, whose curve is close to the de-trough function. It can also be inferred that if a function is close to the de-trough function, its derivative is also close to that of the de-trough function.

In summary, a smooth envelope design is desired, whose derivative at zeros equals zero and whose derivative is close to that of the de-trough function. In the next section, the proposed envelope design will be analyzed based on its derivatives and followed by an example.

3 Proposed Method

3.1 Envelope Design with Monotonous Derivative

In Fig. 1, the red solid lines are an objective monotonous envelope design and its derivative, and the blue dotted lines represent the de-trough function and its derivative. It should be noted that the $f(|x|)$ and $|x|$ in Fig. 1(a) represent the normalized drain voltage and original envelope in the envelope tracking application, respectively. There are two points of intersection (also tendency) of $f(|x|)$ and the de-trough function, which are at $(0, V_{min})$ and (1, 1). In such a situation, the envelope design can be deduced by:

$$f(0) = V_{min};\ f'(0) = 0;\ f(1) = 1;\ f'(1) = 1. \tag{3}$$

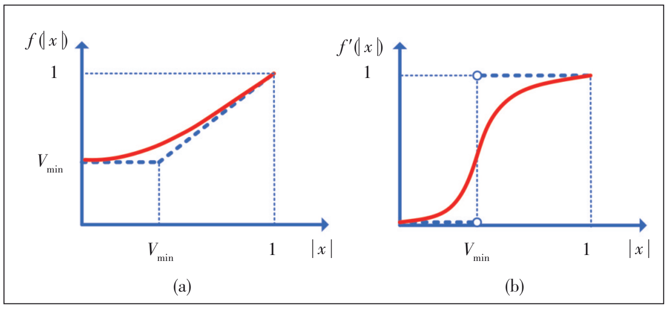
From the aspect of the envelope bandwidth, when the derivative of the envelope design equals that of the de-trough function, the envelope design equals the de-trough function, which converts the bandwidth of envelope to infinite. When the derivative is a straight line from (0, 0) to (1, 1), it can be deduced that

$$f'(|x|) = |x| \Rightarrow f(|x|) = \int |x|\, d|x| = 0.5 \cdot |x|^2 + c \Rightarrow BW = B_{RF}. \tag{4}$$

It can reduce the envelope bandwidth to B_{RF}. Therefore, the envelope design with monotonous derivative can realize the envelope bandwidth from B_{RF} to infinite, theoretically.

From the aspect of the tracking accuracy, when the normalized V_{min} is less than 0.5, this envelope design brings poor tracking accuracy if the derivative curvature is small, because the following inequality holds if the last three equations in Eq. (3) are satisfied. To validate this method, an example is demonstrated in the next section.

$$f(0) = 1 - \int_0^1 f'(|x|)\, d|x| > V_{min}. \tag{5}$$



▲ **Figure 1. Proposed envelope design with monotonous derivative: (a) envelope design; (b) monotonous derivative**

3.2 Example for Validation

The trend of the sigmoid function is consistent with that of the derivative of the de-trough function. Therefore, the sigmoid function can be applied as the origin of the derivative of objective function, which can be expressed as

$$f'(|x|) = \frac{1}{a + e^{-s \cdot |x| - d}} + b. \tag{6}$$

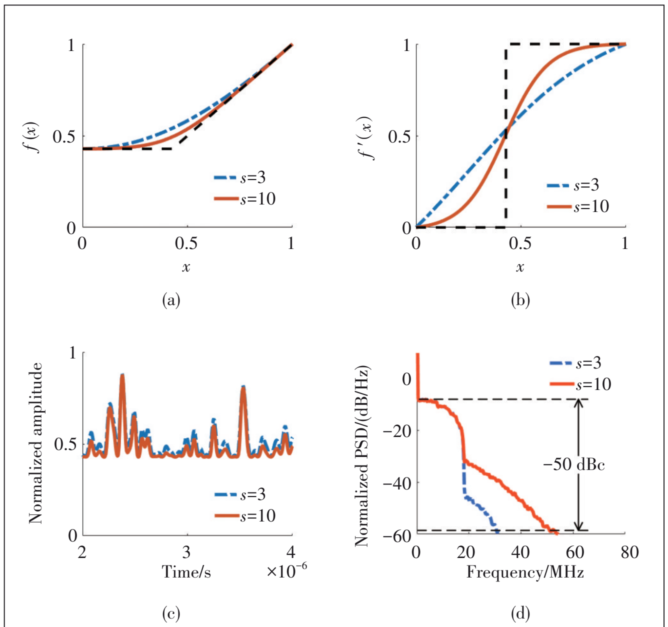
Then, its indefinite integral, which is also the objective envelope design, is

$$f(|x|) = \left(\frac{1}{a} + b\right) \cdot |x| + \frac{1}{a \cdot s} \cdot \ln\left(a + e^{-s \cdot |x| - d}\right) + c. \tag{7}$$

There are five degrees of freedom in Eq. (7), but only four equations in Eq. (3). Thus, a unique envelope design $f(|x|)$ can be derived for different values of s that controls the curvature of $f'(|x|)$. In the rest of this paper, Eq. (7) will be mentioned as the S function. It should be noted that the S function equals the de-trough function when $s=\infty$.

Although the normalized V_{min} differs from the performance of the supply modulator, it is generally less than 0.5 in order to maintain high efficiency. In order to verify the proposed envelope design, we apply it to map the envelope of an LTE signal with 20 MHz bandwidth to 12 – 28 V.

Figs. 2(a) and 2(b) show the S function and its derivative for s=3 and s=10 when the envelope swings from 12 V to 28 V, respectively. Figs. 2(c) and 2(d) present the time domain waveform and normalized power spectral density (PSD) of the proposed envelope while s=3 and s=10. In this paper, the effective bandwidth is defined as the frequency where the PSD falls below −50 dBc from the main lobe. Table 1 presents the bandwidth and normalized mean square error (NMSE) of the proposed envelope for different values of s and traditional envelopes. It can be seen that the S function can make a good trade-off between bandwidth and tracking accuracy when the bandwidth is greater than 1.6×B_{RF}. Compared with Wilson, second-order PET and N6 envelopes, the S envelope can reach similar tracking accuracy under the same envelope bandwidth. According to Eq. (5), if s<3, the bandwidth of the proposed envelope will be further reduced, but the tracking accuracy will be degraded a lot because $f(0)>V_{min}$.



PSD: power spectral density

▲Figure 2. Example of the proposed envelope design: (a) envelope design; (b) derivative of the S function for s=3 and s=10; (c) time domain waveforms; (d) normalized power spectral density of the S envelope

4 Digital Predistortion

The proposed envelope design contains the information of the original envelope and does not introduce additional information. Therefore, this envelope tracking power amplifier can be described by a single-input single-output (SISO) behavioral model. To compensate the nonlinearity, the generalized memory polynomial (GMP)[14] is applied in this paper, which can be written as

$$y_{GMP}(n) = \sum_{k=0}^{K_a-1}\sum_{l=0}^{L_a-1} a_{kl}\, x(n-1)\left|(n-1)\right|^k + \sum_{k=1}^{K_b}\sum_{l=0}^{L_b-1}\sum_{m=1}^{M_b} b_{klm}\, x(n-1)\left|(n-l-m)\right|^k + \sum_{k=1}^{K_c}\sum_{l=0}^{L_c-1}\sum_{m=1}^{M_c} c_{klm}\, x(n-1)\left|(n-l+m)\right|^k, \tag{8}$$

where $x(n)$ represents the input signal; K_a and L_a are the nonlinearity order and memory depth for aligned signals and envelope; K_b and L_b are the nonlinearity order, memory depth for signal and lagging envelopes; K_c and L_c are the nonlinearity order, memory depth for signals and leading envelopes; M_b and M_c are the maximum depth of the lagging and leading cross-terms, respectively.

5 Experimental Results

5.1 Test Bench

The proposed shaping functions and corresponding digital predistortion were demonstrated in the test bench, as shown in

▼Table 1. Bandwidth and NMSE of the S envelope and traditional envelopes

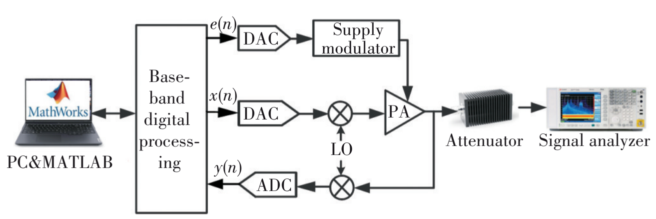
Parameter	S Envelope				Traditional Envelopes		
	s=3	s=5	s=10	s=16	Wilson	2.ord.PET	N6
BW	1.6×	2.1×	2.6×	3.0×	1.6×	1.6×	3.0×
NMSE/dB	−6.8	−7.0	−7.7	−7.9	−6.6	−6.7	−7.9

BW: bandwidth NMSE: normalized mean square error

Fig. 3. Restricted by the bandwidth and swing range of the supply modulator, the test signal is a 20 MHz LTE signal, and the envelope swings from 12 V to 28 V. The average PA output is at 37.2 dBm in this experiment. Firstly, a 20 MHz LTE signal with the PAPR of 7.6 dB and its shaped envelope were generated by the MATLAB in PC, then downloaded into the baseband digital processing module. This baseband digital signal was converted to an analog signal and up-converted to 3.5 GHz, and then fed into the input port of ET PA. Meanwhile, the envelope signal went through the digital-to-analog converter (DAC), linearly amplified by the supply modulator, and then fed into the drain of PA. The output of PA was down-converted to baseband and converted to a digital signal, and then used to model PA in PC. In this experiment, the S function with s=10 was applied to map the envelope to 12 – 28 V, which will be mentioned as S10 function.

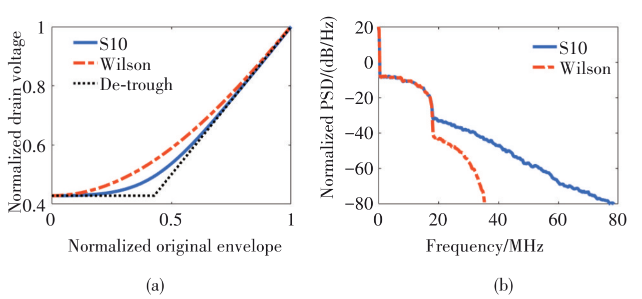
5.2 Validation for Proposed Method

Because the envelope swing rang is 12 – 28 V, the normalized V_{min} is 12/28. It can be deduced from Eqs. (3) and (7) that a, b, c and d of the S function are 0.98, −0.01, 0 and −4.21 when s=10. In this experiment, the S10 function is compared with the Wilson function. As shown from Figs. 4(a) and 4(b), the S10 envelope tracks more closely than the Wilson envelope, while it has wider bandwidth. Figs. 5(a) and 5(b) present the amplitude-modulation to amplitude-modulation (AM/AM) curve, amplitude-modulation to phase-modulation (AM/PM) curve and the measured normalized output power spectra density without and with digital predistortion (DPD) for the S10. While Figs. 5(c) and 5(d) show these for the Wilson. It can also be seen from Table 2 that the ET system with the S10 has higher efficiency and stronger nonlinearity than the Wilson, and the GMP model can effectively compensate for its nonlinearity. For the S10, the adjacent channel leakage ratios (ACLRs) and NMSE can be reduced to −51.2/−51.8 dBc and −38.5 dB, respectively. For Wilson, these values can be reduced to −54.0/−54.3 dBc and −40.5 dB.



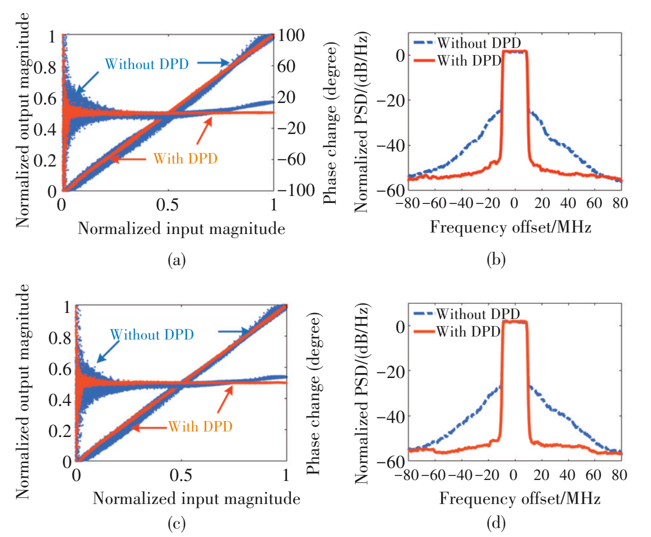
ADC: analog-to-digital Converter
DAC: digital-to-analog Converter
LO: local oscillator
MATLAB: matrix laboratory
PA: power amplifier

▲Figure 3. Test bench setup



PSD: power spectrum density

▲ Figure 4. Experiment for validation: (a) plot of samples of the S10 and Wilson envelopes versus the original envelope; (b) normalized power spectrum density of the S10 and Wilson envelopes



DPD: digital predistortion PSD: power spectrum density

▲Figure 5. Comparison experiment: (a) amplitude-modulation to amplitude-modulation (AM/AM) and amplitude-modulation to phase-modulation (AM/PM) curves; (b) normalized PSD without and with DPD under S10 function; (c) AM/AM and AM/PM curves; (d) normalized PSD without and with DPD under Wilson function

6 Conclusions

In this paper, a novel envelope design based on the derivatives is theoretically analyzed and validated. The analysis shows that the envelope design with monotonous derivatives is valid within a wide range of envelope bandwidth. This method provides more flexibility for the choice of envelope designs under different requirements of the supply modulator. The corresponding digital predistortion is also validated to compensate for the PA nonlinearity. In the era of 5G and beyond, the pro-

▼Table 2. Efficiency and nonlinearity performance of the measured ET system

Shaping Function	Efficiency/%	Without DPD		With DPD	
		ACLRs/dBc (±20 MHz)	NMSE/dB	ACLRs/dBc (±20 MHz)	NMSE/dB
S10	43.8	−31.3/−31.6	−21.2	−51.2/−51.8	−38.5
Wilson	42	−33.3/−33.5	−23.6	−54.0/−54.3	−40.5

ACLR: adjacent channel leakage ratio
DPD: digital predistortion
ET: envelope tracking
NMSE: normalized mean square error

posed approach provides a promising solution for wideband ET applications.

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