A digital harmonic canceling algorithm for power amplifiers in analysis way

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Abstract: The design of the broadband transmitter faces the challenge of canceling harmonic distortion in the communication frequency band. Here we improve the digital predistortion (DPD) to propose a digital harmonic canceling algorithm based on direct learning structure—a reverse function predistorter based on IIR and FIR filter structure, which have less computational complexity and achieve better effect compared with the nonlinear adaptive filter. Experimental results verify the effectiveness of this canceling algorithm.

Keywords: broadband, harmonic distortion, digital harmonic canceling algorithm, reverse function

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

More wireless communication standards have been developed to fulfill the demand of humans, such as Wi-Fi, NB-IoT, 5G and so on. In order to support multi-communication-channels at different frequency bands, current broadband transmitter design needs to overcome more difficulties compared to the conventional transmitter.

We often drive HPAs into a nonlinear region in order to increase the efficiency of the high power amplifiers (HPA) and signal to noise ratio of the receiver. However, nonlinear behavior of HPAs always gives rise to in-band intermodulation and out-of-band harmonic distortion, which causes spectrum electromagnetic pollution. In-band intermodulation can be effectively compensated by digital predistortion (DPD) technique with direct learning structure [1, 2] or indirect learning structure [3, 4]. When dealing with harmonic distortion, a radio-frequency (RF) filter or coupler or combiner [5, 6] can be utilized to filter harmonic distortion out of communication band in the conventional transmitter. However, when designing a broadband transmitter, these techniques fail to filter harmonic distortion in the communication band. Using different communication links of the different communication band to avoid harmonic distortion falling on the same communication band increases the cost and volume of transceiver significantly when the communication frequency range is of different orders. In the recent years, the wideband transmitters sharing a single HPA and a single radio-frequency filter have attracted extensive interest [7, 8, 9]. In [9], an ultra-wideband efficient linearized power amplifier proposed supports 0.4 to 4.2 GHz bandwidth. One way to reduce harmonic distortion is using RF bandpass filters with tunable center frequency and...
bandwidth [7, 8], but the limits of the range of center frequency and bandwidth are not enough for practical application. Analog methods to suppress harmonic distortion remains an ongoing challenge.

Traditional DPD techniques cannot be used to cancel the harmonic distortion [1, 2, 3, 4, 10, 11] because all these techniques are used to model in-band intermodulation. The DPD techniques including harmonic distortions need impractical computation rate requirements. Some techniques [4, 10, 11] are developed for reducing DPD sampling rate and computation rate, but there are not applicable to this problem. Although DPD cannot deal with harmonic distortions yet, compared with analog way, digital processing techniques often provide several advantages such as accuracy and lower cost, thus novel digital processing methods have to be in place.

In this paper, we will present a new harmonic canceling predistorter which could work effectively on each harmonic. We firstly introduce the harmonic memory polynomial and harmonic canceling system in Section 2. After modeling the harmonic distortions, we propose an analysis method and its improved version based on inverse function and direct learning structure in Section 3. The simulation and measurement results given in Section 4 demonstrate that our digital harmonic canceling technique has remarkable performance.

2 Harmonic canceling system

Memory polynomial is the most popular model to model in-band intermodulation caused by HPA, because of its trade-off between complexity and performance. However, memory polynomial doesn’t include harmonic distortion, because the harmonic distortion is far away from the transmitting signal in the frequency domain. Accurate modeling of the harmonic distortion is needed before suppressing harmonic distortion. Considering bandpass signal in the Volterra channel [12], we can express HPA output bandpass signal with the HPA input bandpass signal as

\[ y(n) = \sum_{d_1=0}^{+\infty} h_{d_1}x(n-d_1) + \sum_{d_1=0}^{+\infty} \sum_{d_2=0}^{+\infty} h_{d_1d_2}x(n-d_1)x(n-d_2) + \ldots \]

\[ + \sum_{d_1=0}^{+\infty} \sum_{d_2=0}^{+\infty} \ldots \sum_{d_m=0}^{+\infty} h_{d_1\ldots d_m}x(n-d_1)x(n-d_2)\ldots x(n-d_m) + \ldots \]

where \( x(n-d) \) is the sample of HPA input signal that is \( d \)-delayed, \( y(n) \) represents the sample of the output signal, \( h \) is the polynomial coefficient that depicts HPA nonlinear channel.

The HPA input bandpass signal at carrier frequency \( \omega \) can be defined as a lowpass equivalent complex signal \( x_1(n-d) \) given by,

\[ x(n) = \text{Re}(x_1(n)e^{j\omega n}) = \frac{1}{2} (x_1(n)e^{j\omega n} + x_1^*(n)e^{-j\omega n}) \]

Substituting Eq. (2) into the quadratic term and cubic term in Eq. (1), we can get the following equation, which assumes a same delayed time \( d_1 = d_2 = d_3 \) to decrease the complexity of polynomials,
The transmitting signal 

\[ h_{d_1d_2} x(n - d_1)x(n - d_2) = \frac{1}{2\pi} \sum_{d_1=0}^{\infty} h_{d_1} (x_1^2(n - d_1)e^{j\omega(n-d_1)}) \]

\[ + |x_1(n - d_1)|^2 + x_1^3(n - d_1)e^{-j\omega(n-d_1)} \]

where \( x_1(n - d_1)|x_1(n - d_1]|^2e^{j\omega(n-d_1)} \) and \( x_1^3(n - d_1)|x_1(n - d_1)]^2e^{-j\omega(n-d_1)} \) are the HPA output intermodulation distortion at the transmitter signal frequency, \( x_1^2(n - d_1)e^{j\omega(n-d_1)} \) and \( x_1^3(n - d_1)e^{2j\omega(n-d_1)} \) are the second harmonic distortion at the output of the HPA, \( x_1^2(n - d_1)e^{j\omega(n-d_1)} \) and \( x_1^3(n - d_1)e^{3j\omega(n-d_1)} \) are the third harmonic distortion of transmitter signal.

Although in-band intermodulation derivation only includes odd order nonlinear terms of straight mathematical manipulations, there are proven in the test that the even order nonlinear terms are also effective in the baseband channel modeling [13]. Hence we define \( i \) order harmonic memory polynomial extended from Eqs. (3, 4) as follows:

\[ y_i(n) = \sum_{d=0}^{D} \sum_{j=0}^{N_i} h_{i}(d, j)x_1^i(n - d)|x_1(n - d)|^{i-j} \]

where \( h_{i}(d, j) \) is parameters of the \( i \) order harmonic memory polynomial produced by the transmitting signal \( x_1 \), \( D \) is the memory depth, \( N \) is the nonlinearity order.

After modeling harmonic distortion with harmonic memory polynomial Eq. (5), we can improve conventional DPD techniques to suppress harmonic distortion. There are two types DPD technique, indirect learning architecture (ILA) [3, 4] and direct learning architecture (DLA) [2, 10, 11]. ILA has less computational complexity compared to DLA, but indirect learning architecture is sensitive to measured noise, thus direct learning architecture has better performance than indirect learning [14]. DLA firstly estimates the nonlinear function of the HPA and then calculates the predisorter parameters. The harmonic distortion has a smaller power compared to the transmitting signal, which results in a low signal-noise ratio for parameter estimation. Hence, the new harmonic canceling method we proposed here is built on direct learning architecture.

Fig. 1 illustrates the basic structure of the harmonic canceling system, which is similar to DPD structure except that predistorter and feedback path work at the harmonic frequency. This structure can be combined with DPD structure to simplify the whole structure and decrease computational resources. To simplify the discussion, this figure is only canceling one harmonic distortion.

The digital harmonic canceling system sends transmitting signal \( x_1(n) \) and \( i \) order harmonic training signal \( x_i(n) \) at the carrier frequency \( f_0 \) and the \( i \) order harmonic frequency \( if_0 \) respectively. In order to avoid affecting the behavior of the HPA, the power of \( x_i(n) \) is much smaller. The HPA output signal at the frequency
if_0_ passes the attenuator, and is received by signal processor. Due to the nonlinear behavior of the HPA, the i order harmonic received signal \( y_i(n) \) includes \( x_i(n) \), harmonic distortion of \( x_1(n) \), cross modilation products between \( x_1(n) \) and \( x_i(n) \), intermodulation of \( x_i(n) \). Due to the fact that \( x_i(n) \) has small power, the intermodulation of \( x_i(n) \) can be ignored. Therefore, recalling Eq. (5), \( y_i(n) \) can be developed as follows,

\[
y_i(n) = \sum_{d=0}^{D} \sum_{j=i}^{N_1} h_{11}(d, j)x_1(n - d)|x_1(n - d)|^{j-i} + \sum_{d=0}^{D} \sum_{j=0}^{N_i} h_{21}(d, j)x_i(n - d)|x_1(n - d)|^{j}
\]  

(6)

Where \( h_{11}(d, i) \) is the parameter of harmonic memory polynomial produced by \( x_1(n) \), \( h_{21}(d, j) \) is the parameter of cross-modulation products between \( x_1(n) \) and \( x_i(n) \), and the memory terms of \( x_i(n) \) (When \( j = 0 \)). The nonlinearity \( N_i \) is smaller than \( N_1 \), because the power of \( x_i(n) \) is smaller than \( x_1(n) \) so that the cross-modulation terms are smaller than harmonic terms in the same nonlinearity order.

3 Proposed harmonic cancelling method

The DLA techniques to cancel harmonic distortion can be extended from DPD techniques, which can devive into analysis method [1, 10] and adaptive filter [2, 11]. Here we present the analysis method extended from DPD, which achieves remarkable performance without high computational complexity. This method can be shown in Fig. 2.

The baseband signal unit sends baseband signal \( x_1(n) \) at the frequency \( f_0 \), while the gate controlled by harmonic channel modeling unit firstly selects the output of the harmonic training signal unit as the i order harmonic signal \( x_i(n) \). The output of the harmonic training signal unit is uncorrelated with \( x_1(n) \), which improves the accuracy of modeling HPA harmonic channel. Due to the correlation between the transmitting signal and the received signal, the signal alignment unit aligns transmitting signal \( x_1(n) \) and \( x_i(n) \) with received signal \( y_i(n) \). Using Eq. (6), the harmonic channel modeling unit combines \( x_1(n) \) and \( x_i(n) \) with i order harmonic received signal \( y_i(n) \) to model the nonlinear channel of the HPA at the i order harmonic frequency. The channel estimation can use the Least Square method or other method. After the i order harmonic HPA channel is modeled, the gate selects the output of the harmonic canceling signal unit as \( x_i(n) \). Meanwhile, the harmonic channel modeling unit calculates harmonic canceling parameter by the following
algorithm and then sends it to the harmonic canceling signal unit. Finally, the $i$ order harmonic distortion is suppressed by $x_i(n)$.

Recalling to Eq. (6), letting error $y_i(n) = 0$, this equation can be rewritten as,

$$0 = \sum_{d=0}^{D} \sum_{j=1}^{N_1} h_{11}(d, j)x_1^i(n-d)|x_1(n-d)|^{j-i}$$
$$+ \sum_{d=0}^{D} \sum_{j=0}^{N_1} h_{12}(d, j)x_1(n-d)|x_1(n-d)|^j$$

(7)

It means that the harmonic canceling signal cancels the harmonic distortion completely. Solving Eq. (7), we have

$$x_i(n) = \left[ \sum_{d=0}^{D} \sum_{j=1}^{N_1} h_{11}(d, j)x_1^i(n-d)|x_1(n-d)|^{j-i} \right] \left/ \sum_{j=0}^{N_1} h_{12}(0, j)|x_1(n)|^j \right.$$  
$$+ \sum_{d=1}^{D} \sum_{j=0}^{N_1} h_{12}(d, j)x_1(n-d)|x_1(n-d)|^j$$

(8)

Different from the analysis method of DPD, the solution of this equation doesn’t include the high order terms of the solution itself. Hence, it doesn’t need an iterative solution [1] or complex equation solving [10], all these methods are difficultly implemented on the FPGA or ASIC.

However, as shown in Fig. 3, this solution includes IIR filter, thus it's a Nonlinear Auto-Regressive Moving Average model (NARMA). IIR structure has the possibilities of instability, especially for fixed-point implementation. Using long division can convert the IIR filter to the FIR filter for avoiding instability.

Assuming the memory depth is 2, the FIR filter coefficients can be calculated as follows,

$$a_1 = 1/b_1$$
$$a_2 = -b_2/b_1^2$$
$$\ldots$$
$$a_D = (-1)^{D-1}b_2^{D-1}/b_1^D$$

(9)
Although the long division generates an infinite length of the FIR filter that is equivalent to the IIR filter, the window function provides a truncation method to convert the infinite length FIR filter to the finite length FIR filter. Truncating the solution of the long division directly is essentially a rectangle window, we also can use raised cosine window and so on. Proper window function and longer length of filter coefficients can improve the performance of the FIR filter.

### 4 Experimental result

In this test, a concept Harmonic Channel Power Ratio (HCPR) like Adjacent Channel Power Ratio (ACPR) is introduced to validate the performance of the algorithm proposed, which can be defined as follows,

$$HCPR \ (\text{dBc}) = 10 \log_{10} \left( \frac{P_{\text{har}}}{P_{\text{ref}}} \right)$$

where $P_{\text{har}}$ is the power of harmonic channel whose bandwidth is the same as the reference channel, $P_{\text{ref}}$ is the power of the reference channel.

The experimental setup shown in Fig. 4. Here three LTE-A signals were used as the transmitting signal, the second harmonic training signal, and the third harmonic training signal respectively, which were sent by a DAC38RF80EVM evaluation module. A 20-W GaN pushpull HPA ($V_{\text{ds}} = 24$ V) drives all signals, which supports the frequency range from 20 MHz to 1000 MHz. The HPA feedback signal was attenuated by a 40 dB fixed attenuator, which was received by an ADC32RF80EVM evaluation module.
The transmitting signal, the second harmonic signal, and the third harmonic signal were sent at 315 MHz, 630 MHz, and 945 MHz respectively. The average power of the second harmonic signal is much smaller than transmitting signal, so is the third harmonic signal. The average output power of transmitting signals was 33 dBm. The transmitting signal includes 131072 samples. We take the nonlinear order $N_1 = 5$, $N_2 = 2$, and take the memory depth $D = 3$. All signals were processed by MATLAB in a PC.

Three different methods, NFX-RLS (Nonlinear Filtered-x Recursive Least Square) method extended from DPD [2, 11], the analysis method with IIR structure and the analysis method with FIR structure whose FIR filter length is 10 were tested. The power spectrum of original distortion caused only by transmitting signals at the second harmonic frequency and the third harmonic frequency can be shown as Fig. 5(a) and Fig. 6(a) respectively, and the power spectrum after signal processing are in Fig. 5(b) and Fig. 6(b). The HCPRs for different methods can be shown as Table I.

| Harmonic Zone | Second Harmonic Zone | Third Harmonic Zone |
|---------------|----------------------|---------------------|
| Without Cancelling | $-33.34$ dB | $-35.28$ dB |
| NFX-RLS | $-45.82$ dB | $-43.57$ dB |
| Analysis method (IIR) | $-57.28$ dB | $-58.96$ dB |
| Analysis method (FIR) | $-56.52$ dB | $-57.13$ dB |

These measurement results indicate that our method achieves over 20 dB improvement of HCPR for the analysis method we proposed, which demonstrates that effectiveness of the analysis method overwhelm NFX-RLS. Moreover, the analysis methods have much lower computational complexity compared with all nonlinear adaptive filters without iteration. Although the analysis method with IIR structure has better performance than the analysis method with FIR structure, the analysis method with FIR structure has better stability. Hence, each method has its advantages and disadvantages so that we can use one of the two according to application scene.

![Fig. 5. Power spectrum of second harmonic distortion (a) Original distortion (b) After harmonic canceling algorithm for LTE-A signal](image-url)
5 Conclusion

In this paper, we presented a harmonic canceling system to suppress harmonic distortion. After that, analysis method with IIR structure and FIR structure were proposed to cancel the harmonic distortion based on reverse function. Experimental measurements demonstrate that these harmonic canceling techniques achieve remarkable performance. All these methods are easily implemented in hardware and very suitable for the broadband communication, such as 5G communication.

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Fig. 6. Power spectrum of third harmonic distortion (a) Original distortion (b) After harmonic canceling algorithm for LTE-A signal