A Novel Power Amplifier Linearization Technique based on Pre-distortion Principle and Wiener model

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ABSTRACT

The new generation mobile communication systems are very sensitive to the nonlinearities in their transmitting paths. The power amplifier is a key component which generates the nonlinear distortions. Power amplifier linearization techniques are very important to reduce the distortion of the transmitted signal and the adjacent band interference of users. As its facility of implementation, adaptive ability and high efficiency, the pre-distortion technology becomes the first choice to minimize the nonlinear distortions. In this paper, a new technique, based on the pre-distortion principle for linearizing a power amplifier, which is modeled by a Wiener model is proposed. The Wiener model is used to take into account the nonlinearities and the memory effects of the power amplifier. We also propose an efficient and original method for extracting the parameters of the power amplifier's Wiener Model. Simulation results have been provided for showing the performances of this technique.

Keywords: *Pre-distortion; Power amplifier; Linearization; Wiener model; Nonlinearities and Memory Effects*

1. Introduction

With the increasing number of wireless users and development of broadband communications business, the communication band becomes crowded. Consequently, the new generation of mobile communication technologies employs linear modulation (e.g. QPSK, QAM) for increasing bite rate and spectrum efficiency. Therefore the power amplifier is required to process high rate non-constant envelope signals. For achieving good power efficiency, the power amplifier should work around its compression point which makes the output signal distorted nonlinearly. These non linear distortions generate in-band interferences which results in amplitude and phase deviation of the modulated vector signal. It generates also out-band interference in the adjacent channel creating the spectrum spreading. For the sake of reducing these undesirable effects, the linearization of transmission channel becomes very important.

In new generation communication system, because of used linear modulations and wide bandwidth, the power amplifier has nonlinear and memory effects. Heutmaker [1] measured the input-output relationship of a power amplifier under the effect of wideband signal, showed the existence of memory effects of non linearity. For a power amplifier having non linear memory effects, the performance of the classical linearization of memoryless pre-distortion module degrades greatly. CLARK [2] used a Wiener model to capture the non-linear memory properties of a power amplifier in wideband applications. H W Kang [3] studied the pre-distortion method of Hammerstein system. They used mean square error (MSE) as cost function, and steepest descent method to identify the Hammerstein system's parameters.

For minimizing the nonlinear distortions caused by power amplifier, there are many different linearization methods described in the open literature: feedback, feed-forward, pre-distortion, envelope elimination and restoration (EER), linear amplification with nonlinear components (LINC) etc. All kinds of linearization techniques own their advantages and disadvantages. Among these linearization techniques, the most rapidly developing linearization technique is pre-distortion. This is a popular and reliable technique that allows minimizing output distortion and spectral re-growth, as well as maximizing power efficiency by digitally processing the input signal to produce a highly linear output.

In this paper, we propose a new pre-distortion technique for linearizing a power amplifier whose inverse characteristics are modeled by a Wiener model. An efficient and original method for estimating the parameters of the Wiener model is also proposed.

2. Characteristics of Power Amplifier

2.1. Static nonlinear effect of power amplifier

In the purpose of improving the power efficiency of a power amplifier, the power amplifier should work around its compression point. In this case the output will undergo some important nonlinear distortions. The static nonlinear distortions [4] are classically described by the AM-AM transform distortion and AM-PM transform distortion. Usually, the input and output of the power amplifier used in a communication system are expressed as:

$$x(t) = \mathrm{Re}\left[x_c(t)e^{j\omega t}\right]$$
$$y(t) = \mathrm{Re}\left[y_c(t)e^{j\omega t}\right] \qquad (1)$$

where $x_c(t)$, $y_c(t)$ are the original input signal and output signal (here the 16QAM baseband signal has been selected to represent the input signal), $x(t)$, $y(t)$ are the complex envelop of amplifier's input and output signal, ω is the angular frequency of the carrier wave. Hence the static nonlinear model of power amplifier in discrete time domain is given by:

$$y(n) = \sum_{k=0}^{K} h_{2p-1} x^k(n) \qquad (2)$$

where the coefficients h_{2p-1} are complex coefficients. From equation (2), we can see that besides the fundamental component, the static non linearity not only generates new direct current component and harmonic frequency components of each input frequency, but also across frequency components, leading to the adjacent channel interference.

2.2. Nonlinear memory effect of power amplifier

In a narrow band signal application, the bandwidth is small, the dependency of the amplifier's characteristics on the frequency could be ignored. In this case, the power amplifier is considered as a memoryless device (static nonlinearity). In a broadband communication system, the current output of the power amplifier does not depend only on current input signal, but also on previous input signals. Memory effects [5] are the phenomenon that the amplifier's characteristics change in terms of the frequency of input signal. The wider the bandwidth of the input signal, the severer the memory effects of a power amplifier. Power amplifier's input and output characteristic curves change dynamically as well.

2.3. AM/AM and AM/PM characteristics

The linearity of power amplifier is usually characterized by the AM/AM and AM/PM responses of the power amplifier, where the output signal amplitude and phase deviation of the power amplifier output are given as functions of the amplitude of its current input [6]. There has been intensive research on pre-distortion techniques for memoryless power amplifiers during the passed decade. Defined x(n) is a complex envelope at the input of power amplifier, the low power amplifiers filtered complex envelope of a memoryless power amplifier output y(n) can be defined as:

$$y(n) = A_m(|x(n)|)e^{j(\arg(x(n))+A_p(|x(n)|))} \tag{3}$$

where $A_m(|x(n)|)$ and $A_p(|x(n)|)$ are AM/AM and AM/PM characteristics [7]. These characteristics can be measured for a single tone signal at the input of power amplifier.

The distortion introduced by a nonlinear amplifier is frequently explained in terms of AM/AM and AM/PM characteristics and is strongly dependent upon the class of operation in which the amplifier is used.

3. Proposed Pre-distortion Linearization Technique

3.1 Predistortion Theory Analysis

Among the existing linearization techniques, the most fast developing linearization technique is the digital pre-distortion. It is a popular and reliable technique that allows minimizing the output distortion and spectral re-growth, as well as maximizing the power efficiency by digitally processing the input signal to produce a highly linear output.

According to [8], the concept of the pre-distortion method is to distort the input signal of the power amplifier with the inverse function of the characteristics of the power amplifier in order to generate linearly amplified signals at the power amplifier output. But if the bandwidth of the input signal of the power amplifier increases, the thermal and electrical memory effects in the power amplifier become more important. If these memory effects are not considered in the pre-distorter design, there will be some important performance degradations of linearization.

In this paper, an adaptive pre-distortion linearization technique is proposed to compensate for the nonlinearity with memory effects of a power amplifier in a wideband communication system. By modeling directly the inverse of the nonlinear input-output dynamics of the power amplifier, an adaptive pre-distorter is generated. When the input signal passes through the cascade system of the pre-distorter and the power amplifier, the overall linearization from the pre-distorter input to the power amplifier output can be achieved.

A block diagram of the pre-distortion linearization method is shown on Figure.1.

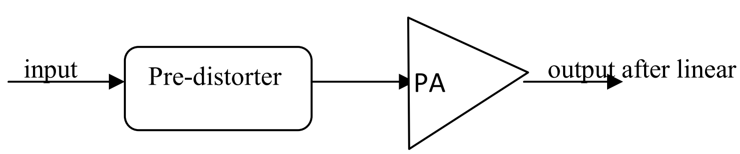


Figure.1 Pre-distortion technique

3.2 Modeling the Behavior of the Power Amplifier

As the input signal bandwidth becomes wider, such as in WCDMA, the memory effects of the power amplifier can no longer be ignored. In the past decades, Volterra series model was usually used to modeling the behavior of the power amplifier with non linear memory effects. However, the number of coefficients of the Volterra series increases exponentially as the memory length and the nonlinear order increase. This drawback makes the Volterra series unattractive for real-time applications. This motivates the researchers to consider several special cases of the Volterra series. The most considered special cases are: Hammerstein model [9], Wiener model, Wiener-Hammerstein model. The Hammerstein model and the Wiener model are presented as follows.

• Hammerstein model: Hammerstein system is a static memoryless nonlinearity followed by a linear time-invariant (LTI) system (see Figure. 2).

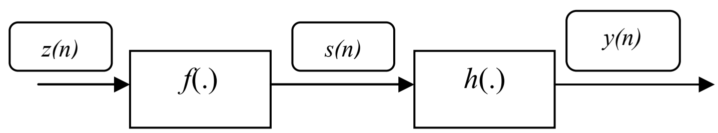


Figure.2 Hammerstein model

In the above figure, *f()* is the input/output transfer function of the static nonlinearity and *h*(.) is the impulse response of the LTI portion of Hammerstein system which is used to model the memory effect of the power amplifier. Using a polynomial model, we can get a simple baseband representation for the static nonlinearity. In discrete time domain, the Hammerstein model can be written as:

$$y(n) = \sum_{m=0}^{M} b_m \sum_{p=1}^{P} h_{2p-1} \left| z(n-m) \right|^{2(p-1)} \left| z(n-m) \right| \quad (4)$$

where b_m are the parameters of the LTI filter (memory effect), h_{2p-1} are the power amplifier parameters of the static nonlinearity.

• Wiener model: Wiener system is a linear time-invariant (LTI) system followed by a static memoryless nonlinearity block (see Figure.3).

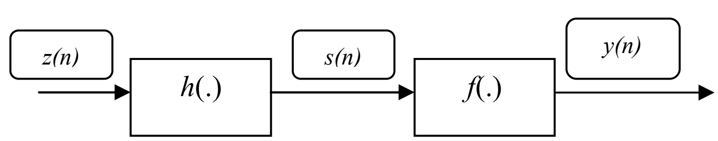


Figure.3 Wiener model

In the above figure, *f()* is the input/output transfer function of the static memoryless nonlinearity and *h()* is the impulse response of the LTI portion of Wiener system. Using the polynomial model, we can get a simple baseband representation for the memoryless nonlinearity. In discrete time domain, Wiener model formula can be written as

$$y(n)=\sum_{p=1}^{p} h_{2p-1}\left[\left|\sum_{m=0}^{M} b_m z(n-m)\right|^{2(p-1)} \times \sum_{m=0}^{M} b_m z(n-m)\right] \quad (5)$$

where b_m are the parameters of the LTI filter (memory effect), h_{2p-1} are the power amplifier parameters of the static nonlinearity.

3.3 The Structure of Proposed Pre-distortion Linearization System

In this paper, the Wiener model was used to build the pre-distorter (Figure.4).

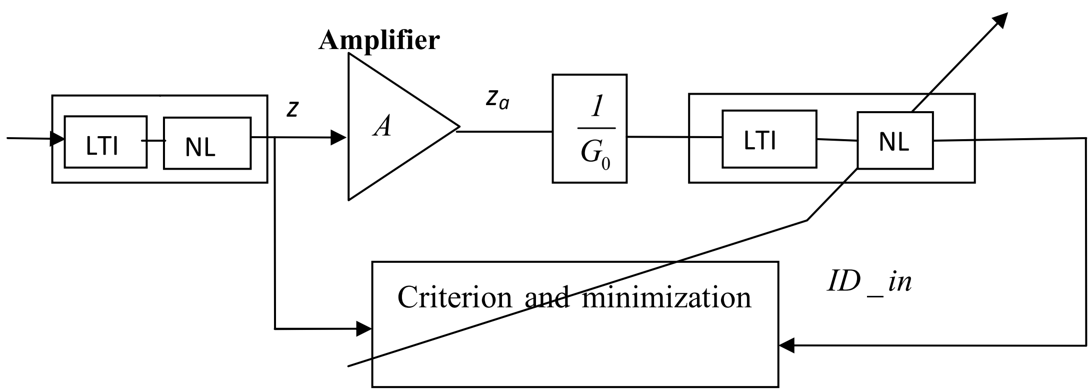


Figure.4 Indirect pre-distortion linearization system

Putting the input signal $z(n)$ through the power amplifier, the input signal is transformed into $z_a(n)$.

Then $z_a(n)$ is divided by gain and being inputted to the training model of Wiener system. This value and original input signal got through a training mechanism to obtain the parameters of Wiener model. After iteration, the convergent Wiener parameters are put into the pre-distorter to achieve the linear output.

4. Simulation and Result

In order to verify the aforementioned indirect pre-distortion linearization system effectiveness, we simulate the pre-distortion system with MATLAB in the baseband. First, we needed to convert a digital or analogue baseband signal into a radio-frequency (RF) signal and transmitted this signal at a certain power level via an amplifier. Here, a transmitter was needed to be used. See Figure.5.

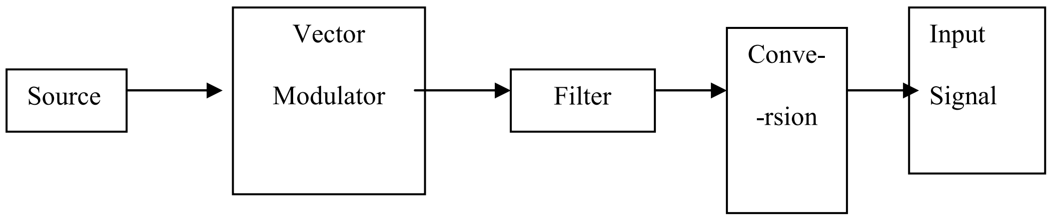


Figure.5 Transmitter block diagram

The vector modulator produced an impulse (two-dimensional: In and Qn). Then the stream of impulses would be shaped by filter to obtain the desired properties in the time and frequency domains. The filtered signal was a baseband signal. The transmitter finally converted the filtered signal to the desired carrier. The carrier with desired frequency and amplitude was fed into the amplifier as input.

For modulating, these are the most fundamental digital modulation techniques:

- In the case of PSK, a finite number of phases are used.
- In the case of FSK, a finite number of frequencies are used.
- In the case of ASK, a finite number of amplitudes are used.
- In the case of QAM, a finite number of at least two phase, and at least two amplitudes are used.

In QAM, an in-phase signal (the I signal, for example a cosine waveform) and a quadrature phase signal (the Q signal, for example a sine wave) are amplitude modulated with a finite number of amplitudes, and summed. It can be seen as a two-channel system, each channel using ASK. The resulting signal is equivalent to a combination of PSK and ASK. Because of the QAM modulation principle is suitable for driving switching amplifiers with signals and other waveforms, QAM was applied to modulate the baseband signal in the simulation.

During the simulation, it's selected the 16QAM baseband signal as an input with 3MHz bandwidth, applied indirect training structure, used Hammerstein model to simulate power amplifier with nonlinear and memory effects, utilized Wiener model to built a pre-distorter. The LTI block of power amplifier is a dynamic linear filter FIR, nonlinear part is Saleh model [10]. The order of pre-distorter is 3, the length memory effect is 5.

In this pre-distortion linearization system, the pre-distorter was built by a Wiener model. The identification of the model's parameters had direct influence for the linearization performance, therefore the identification of parameters for the Wiener model was the crucial part.

We propose an optimization separation algorithm to identify the parameters of Wiener model. Wiener model is composed by a LTI system and a nonlinearity block. Therefore the input signal could be divided into two parts: the linear part and nonlinear part to process. Then the nonlinear block and LTI block were separated so as to identify the memory effect and nonlinear parameters respectively.

The signal to be processed must be located in the power amplifier linear area since the model was supposed linear. However, since there are some signal were excluded by the threshold， the index of signals are no longer continuous. Hence, we could according the escalating trend and downtrend of signal value to divide these signals into segments， then process these segments one by one. For processing, the classic LS (least square) algorithm is applied to abstract the parameters.

In real-time system, the input signal is a matrix

$$\mathbf{Z} = \begin{pmatrix} Z_n & Z_{n-1} & \cdots & Z_1 \\ Z_{n+1} & Z_n & \cdots & Z_2 \\ \vdots & \vdots & \ddots & \vdots \\ Z_m & Z_{m-1} & \cdots & Z_{m-n-1} \end{pmatrix},$$

The output signal is a vector:

$$\mathbf{y} = \left[y_n, y_{n+1}, \cdots, y_m \right]^T .$$

It's known that $y = Z * b$, according to classic LS algorithm, the memory effect parameter could be written as

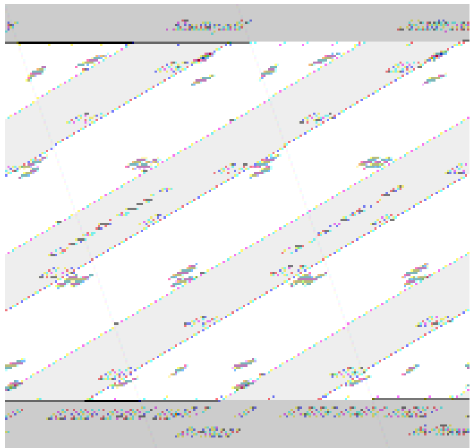
$$\mathbf{b} = (\mathbf{Z}^H\mathbf{Z})^{-1}\mathbf{Z}^{\boldsymbol{H}}*\mathbf{y}.$$

After input the parameter b to memory effect module with the input, got through an impulse response filter to acquire the internuncial part *S*(.). Here *S*(.) could be seen as the input of nonlinear module to identify nonlinear effect parameter. To achieve the object, the vector *S*(.) need to be transformed into a matrix S at first.

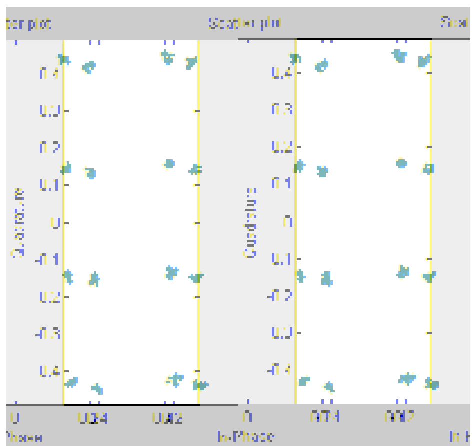
$$\mathbf{S} = \begin{pmatrix} S_1 & |S_1|^2 S_1 & \cdots & |S_1|^8 S_1 \\ & \ddots & & \\ & & \ddots & \\ S_m & \cdots & \cdots & |S_m|^8 S_m \end{pmatrix}$$

Then the LS algorithm was applied again to obtain the nonlinear effect parameter.

The 16QAM modulated signal had been putted into power amplifier then generated the correlative signal constellation diagram. The 16QAM constellation diagrams and the AM-AM characteristics curves which before and after pre-distortion were shown as Figure.6 and Figure.7.

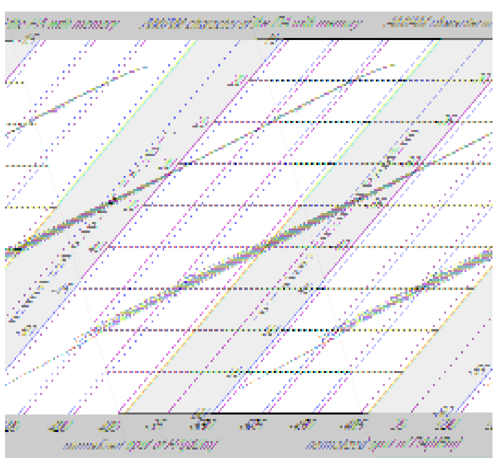


(a) Before pre-distortion

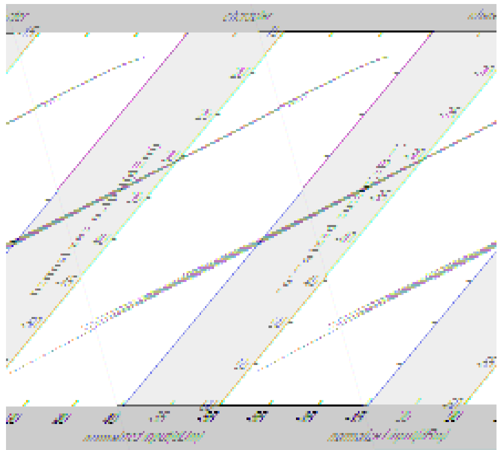


(b) After pre-distortion

Figure.6 16QAM constellation diagram before and after pre-distortion



(a) Before pre-distortion



(b) After pre-distortion

Figure.7 AM-AM curves before and after pre-distortion

Before pre-distortion, the discrete signal constellation diagram tended to be a circle, and the AM-AM curves of power amplifier were a beam of diffuse curves. After pre-distortion, seen from above figures, the power amplifier nonlinear distortion and memory effects had been compensated. Affected by the historical signal, a part of input signals with small amplitude had more serious memory effects, therefore, after pre-distortion, their compensation effect was not so obvious as large-signal areas. The spectrum diagram of power amplifier before and after pre-distortion is shown in Figure.8.

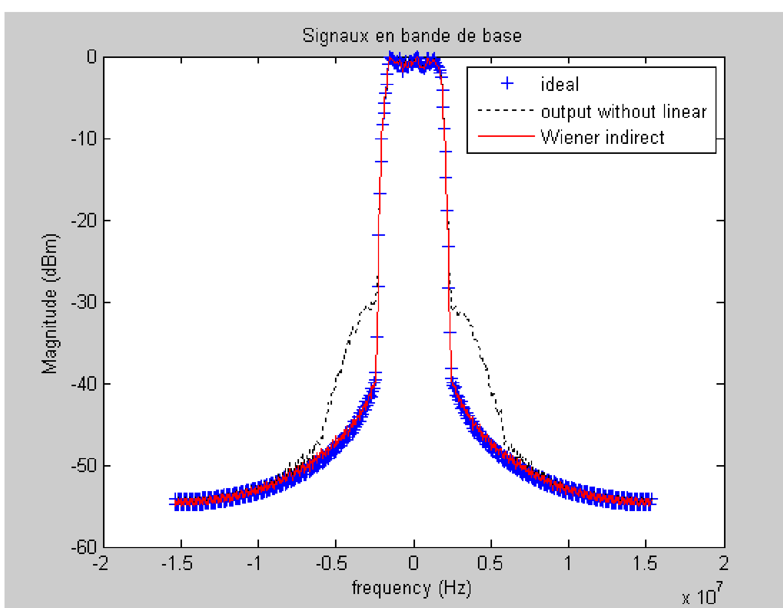


Figure.8 The Spectrum diagram of power amplifier

As seen from the figure, through the pre-distortion linearization system, the power distortion is reduced by about 20 dB. The linear output is almost overlapped with the ideal curve, which means power amplifier's nonlinear distortion and memory effects have been compensated, even the small amplitude input signals affected by history signal and represented stronger memory effect, after pre-distortion, these signals compensation result is not so obviously as large amplitude input signals.

References

[1] M. S. Heutmaker, "The error vector and Power Amplifier. Distortion", IEEE Wireless Communications Conference, Boulder, CO , USA , pp. 100-104, 1997.

[2] Clark C J,Chrisikos G.,Muha M S,et al. "Time-domain envelope measurement technique with application to wideband power amplifier modeling", [J].IEEE Transaction on Microwave Theory and Techniques, Los Angeles, USA, Vol.46:2531- 2540, 1998.

[3] KANG H W, "Adaptive precompensation of Wiener systems". IEEE Transactions on Signal Processing, Seoul , Korea, 46 (10): 2825–2829.1998

[4] Jin Zhe, "A predistortion method for power amplifiers with memory in wireless communications", [J].Chinese Journal of Radio Science, China, Vol.23:85-89, 2008.

[5] J K Vuolevi, T Rahkonenm, J P Q Manninen. "Measurement technique for characterizing memory effects in RF power amplifiers". [J] IEEE Transactions on Microwave Theory and Techniques, English, Vol.49(8):1383-1388, 2001.

[6] Lars Sundström,"Digital RF Power Amplifier Linearisers, Analysis and Design", [D]Doctoral dissertation, Lund University, Sweden, 1995.

[7] A. A. M. Saleh, and J.Salz, "Adaptive linearization of power amplifiers in digital radio systems", [J].The Bell System Technical Journal, vol.62: 1019-1033, April 1983.

[8] Yuanming Ding, Yan Liu, Itthisek Nilkhamhang and Akira Sano, "Adaptive Linearization for Power Amplifier in OFDM Systems ", SICE-ICASE International Joint Conference, DaLian, China, pp. 751 - 754 , 2006.

[9] Xueping Wang, "Realization of linear power amplifier", [D] Dongnan University, NanJing, 2006.

[10] Qiang Yu, Haigen Shen, "The study of digital predistortion for memory power amplifier in wireless communication''. [J]. Micro Computer Information, Vol.23:239-241, 2007.

[11] D. Bondar, and D. Budimir, "WiMax power amplifier linearization through injection of base-band component", International Symposium on Microwave and Optical Technology (ISMOT-2007), Roma, Italy, 17 - 21 December 2007.

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