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Influence of Amplifier Memory Effects on Undersampling Wideband Digital Predistortion

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Abstract: Nonlinearity of power amplifier always results in spectrum spreading on input signal. When using digital predistortion technology to compensate power amplifier's nonlinearity, the required sampling frenquence for the output signal of amplifier is times of the original signal. According to the undersampling digital predistortion method based on Zhu Generalized Sampling Theorem, the amplifier output signal can be sampled as the sampling frequency of original baseband signal Nyquist rate. Using the undersampling digital predistortion method, the digital predistortion performance of non-memory power amplifier is satisfactory. But for amplifier with significant memory effect, the digital predistortion performance is worsened in comparison to amplifier with non-memory effect. Furthermore it is poorer than that of oversampling. Simulations show that the higher the sampling frequency, the better the digital predistortion performance. As for engineering application, if the requirements of digital predistortion performance are met, a sampling frequency should be chosen as low as possible for cost reduction.

Key words: Power amplifier, nonlinearity, spectrum spreading, undersampling, digital predistortion

INTRODUCTION

Power Amplifier (PA) is the most critical nonlinear device in the wireless communication system. Generally speaking, when the power amplifier is operated within the linear region, the efficiency is low while when operated in approximation to the saturation point, the efficiency is high. However, the difficulties brought by the nonlinearity of the power amplifier are severe (Jeckeln *et al*., 2004). There are many methods for linearization of power amplifier. And power back-off, feed-forward method, negative feedback and digital predistortion are commonly used. Currently, digital predistortion technology characterized with stable, efficient, wide bandwidth and adaptive advantages is becoming one of the mainstream linearization techniques and then, widely used (Andrade Mello *et al*., 2003).

The digital baseband predistortion system block diagram is demonstrated in Fig. 1. In the feedback path, the demodulated analog baseband signal is got through the Analog to Digital Converter (ADC). The feedback data after analog to digital conversion and the original baseband data are used to estimate the parameters. The calculated digital predistortion coefficients are sent into the digital predistorter to achieve given linearization performance for PA. Since spectrum spreading is usually caused due to the nonlinearity of power amplifier, the bandwidth of the output signal is wider than the bandwidth of the input signal. Considering the third order and fifth order intermodulation distortion of the power amplifier, the amplifier's output signal bandwidth is five times or so that of the input signal bandwidth. According to the Nyquist sampling theorem it is necessary that the sampling frequency to the output signal is five times that of the input signal. Such a high sampling rate will not only increase much more difficulty of data processing but also add the hardware cost, especially for analog to digital converter.

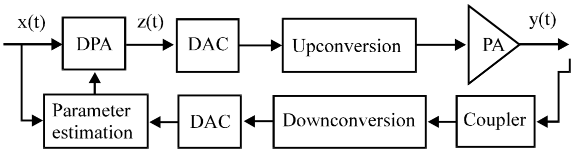

Fig. 1: Digital baseband predistortion system block diagram

In order to reduce the sampling rate requirements, some methods to obtain distortion information, such as out-of-band signal detection and power detection, have been proposed. Although these methods avoid the high sampling rate requirements, the obtained distortion informations are inadequate which will lower the improvement of the power amplifier nonlinearity (Stapleton *et al*., 1992). The undersampling predistortion method based on Zhu Generalized

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Sampling Theorem can reduce the sampling frequency requirements. Theoretically, the amplifier output signal can be sampled as the sampling frequency of original baseband signal Nyquist rate. However, for the broadband wireless communication system, the memory effect of the power amplifier is significant. The memory power amplifier will influence the predistortion correction performamce when using undersampling.

THE GENERALIZED SAMPLING THEOREM OF YANG-MING ZHU

Let f_s be the sampling frequency. If the highest frequency of signal x(t) is f_0, the signal is usually sampled with the sampling frequency of $f_s \geq 2\ f_0$, where $2\ f_0$ is the Nyquist rate. Thus, the sampled signal is able to retain the integrity of the informations of x(t). And x(t) can be recovered without distortion:

$$x(t) = \sum_{k=-\infty}^{\infty} x(kT_s)\frac{\sin[\pi(t-kT_s)/T_s]}{\pi(t-kT_s)/T_s} \tag{1}$$

where, T_s is sampling period and $T_s = 1/T_s$.

In 1992, Yang-Ming Zhu published the Generalized Sampling Theorem (Zhu, 1992). Let y(t) be a function of one variable with spectrum may or may not be bandlimited. Supposing there is a one-to-one continuous mapping g(•) and g(y(t)) is band-limited. The Fourier transform of g(y(t)) should satisfy equation (2):

$$G_y(f) = 0, |f| \geq f_0 \tag{2}$$

where, $f_0 = 12T_s$. If y(t) is sampled with the Nyquist rate of g (y)(t), then y(t) can be uniquely determined:

$$y(t) = g^{-1}\left(\sum_{k=-\infty}^{\infty} g(y(t_k))\frac{\sin[\pi(t-kT_s)/T_s]}{\pi(t-kT_s)/T_s}\right) \tag{3}$$

where, $g^{-1}(\bullet)$ is the inverse of $g(\bullet)$, $y(t_k)$ is the samplers of y(t) ($t_k = kT_s$). Zhu's Generalized Sampling Theorem formula shows that y(t) can be uniquely determined, if and only if $g(\bullet)$ and $g^{-1}(\bullet)$ exist.

POWER AMPLIFIER MODELLING

Power amplifier model is generally divided into non-memory model and memory model. The common non-memory models are power series model, *Saleh* model and artificial neural network model. And the common memory models are Hammerstein model, Volterra model and memory polynomial model. This study mainly introduces the Saleh model and the memory polynomial model.

***Saleh* model:** In 1982, A.A.M. *Saleh* published a nonlinear model for Traveling Wave Tube Amplifier (TWTA). The following two expressions are used to depict the amplitude distortion and phase distortion of power amplifier (Saleh, 1981):

$$A(r) = \frac{\alpha_A r}{1+\beta_A r^2} \tag{4}$$

$$\phi(r) = \frac{\alpha_\phi r^2}{1+\beta_\phi r^2} \tag{5}$$

where r is the amplitude envelope of input signal and α_A, β_A, α_Φ, β_Φ are undetermined parameters. For simplicity, time variable t is omitted here.

Memory polynomial model: Kim and Konstantinou (2001) proposed a polynomial with memory effect to represent the dynamic non-linear RF power amplifier and the expression is:

$$z(n) = \sum_{i=0}^{m}\sum_{j=0}^{q} a_{ij} x(n-j)\,|x(n-j)|^i \tag{6}$$

Where:

x(t) = The input signal of RF power amplifier
z(n) = The output signal of RF power amplifier
a_{ij} = The complex coefficients,
m = The order of the polynomial
q = The depth of the memory polynomial, represents the memory effect of the memory polynomial model

THE INFLUENCE OF MEMORY AMPLIFIER ON UNDERSAMPLING DIGITAL PREDISTORTION

Paper (Tsimbinos and Lever, 1994) points out that sampling frequency requirements for non-memory nonlinear system identification and compensation can be determined by the application of Zhu's Generalized Sampling Theorem. The nonlinear system identification block diagram is demonstrated in Fig. 2. In the predistortion system, when the power amplifier is non-memory, the input and output characteristic is a monotonically increasing function in the saturation point. It is a one-to-one mapping. That means $f(\bullet)$ could be the function of the amplifier input and output. $g(\bullet) = f^{-1}(\bullet)$ is the ideal predistortion function. At the same time, paper (J. Tsimbinos and K. V. Lever, 1994) also points out that it is not a requirement that the nonlinear system be a one-to-one mapping and its inverse exist, for the identification of nonlinear system. To compensate the

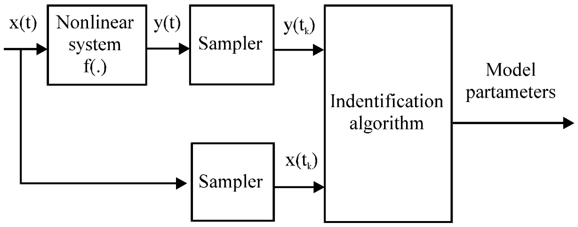

Fig. 2: Sampling at Nyquist rate for nonlinearity identification

nonlinearity produced by power amplifier, digital predistortion method needs to identify the nonlinear characteristics of the power amplifier and then process the input signal using predistortion coefficients caculated from these characteristics. The input signal and the output signal from amplifier are used to estimate the characteristics of the amplifier, calculate the predistortion coefficients and get the inverse model of the amplifier. In simulation, assuming that the power amplifier is non-memory, the amplifier output signal can be sampled as the sampling frequency of original baseband signal Nyquist rate.

In fact, all the amplifiers have memory effect more or less and are partly dependent on the bandwith of input signal. When the input is narrowband signal, the memory effect of the amplifier is weak. While as the input signal bandwidth increases, the memory effect of the amplifier tends to be more significant. In this case, the non-memory assumption is no longer accurate (Bosch and Gatti, 1989). For the power amplifier with memory effect, the current output signal is not only related with the current input but also depended on the past input. In other words it is a many-to-one mapping relationship rather than one-to-one mapping. In the time domain it can be understood that the current nonlinear distortion information and the current input are not matched. Consenqently, the calculated predistortion coefficients are not accurate enough. As a result, the predistortion correction performance of memory amplifier is worse than that of non-memory amplifier and that of oversampling.

In the engineering application, the output data amplifier is obtained by coupling, downconverting and getting through ADC along the feedback path. Before analog-digital conversion, the signal should be got through a anti-aliasing bandlimited filter. Generally, according to the configuration of ADC, the bandlimited of the sampling frequency f_s is $f_s/2$. However, the bandlimited filter is not allowed in the undersampling predistortion method. That is to say, the signal is requested to be all-pass and to be fully loaded into the circuit.

THE SIMULATION RESULTS

Provided that input signal of amplifier is x(t) which is composed of baseband I signal and Q signal. The bandwidth of x(t) is 8MHz with that of I and Q are 4MHz, respectively. First, x(t) is got through the power amplifier and the output is y(t). Since the nonlinear amplifier, the spectrum of y(t) will be broadened. Consider the third order and fifth order intermodulation distortion of the power amplifier, the amplifier output signal y(t) bandwidth is five times that of the input signal x(t) bandwidth. Secondly, the original signal and the amplifier output signal are sampled. Align the sampled original signal $x(t_k)$ and the sampled amplifier output signal $x(t_k)$, including delay alignment and amplitude alignment. Calculate the predistortion coefficients with the aligned signals. Here adopt the minimum mean square error criterion, minimize the squared error of the LS algorithm to train predistortion device parameters (Guan and Zhu, 2012). And the inverse model of power amplifier is obtained. Finally, predistort the 8MHz original signal $y(t_k)$ and let the predistortion signal $x(t_k)$ get through the power amplifier. The simulation flowchart for non-memory model amplifier and memory model amplifier is demonstrated in Fig. 3. The non-memory amplifier and the memory amplifier are *Saleh* model and memory polynomial model, respectively.

For the *Saleh* model, the simulation result is showed in Fig. 4 and 5. The original signal x(t), the output signal of the power amplifier y(t) and the output signal of power amplifier with digital predistortion y_dpd(t) are denoted by the red line, the blue line and the pink line, separately.

The simulations show that when the sampling frequency is the Nyquist rate of the input signal x(t), the digital predistortion correction performance is satisfactory. The red line and the pink line are almost overlapped. In general, the sampling frequency is three times or four times that of the highest frequency of the signal in engineering. Here, let $f_s = 16$MHz. The digital predistortion correction performance is very satisfactory and it is improved about 30dB.

Nonlinear characteristics of PA can be represented by their AM-AM and AM-PM performance, i.e. amplitude distortion and phase distortion are determined by the input amplitude of amplifier. When $f_s = 16$ MHz, the AM/AM and AM/PM curve are showed in Fig. 6 and 7.

However, when the bandwidth of the input signal is 8MHz, the memory effect of the power amplifier is significant. For the memory polynomial model, the simulation curves are portrayed in Fig. 8 and 9. The original signal, the output signal of the power amplifier

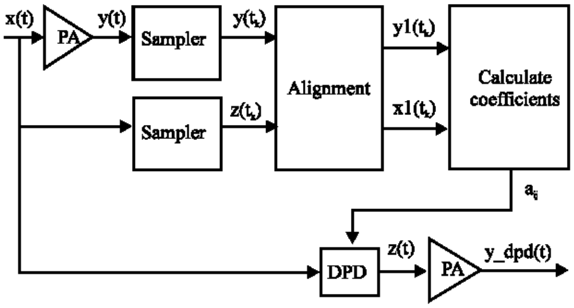

Fig. 3: Calculation for predistortion coefficients at different sampling rate

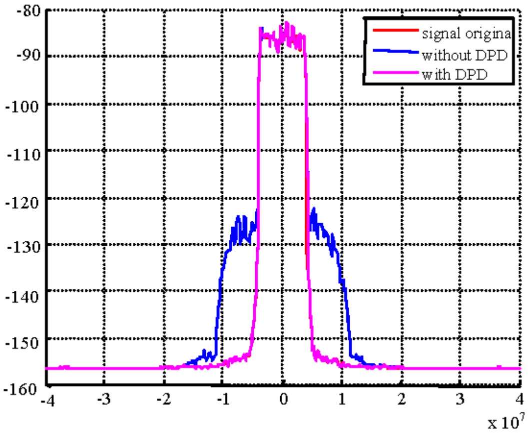

Fig. 4: Spectrum of predistortion performance with *Saleh* model, f_s = 8 MHz

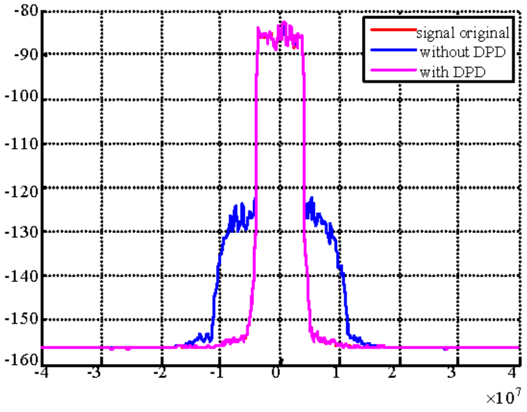

Fig. 5: Spectrum of predistortion performance with *Saleh* model, f_s = 16 MHz

and the output signal of power amplifier with digital predistortion are denoted by the red line, the blue line and the pink line, separately.

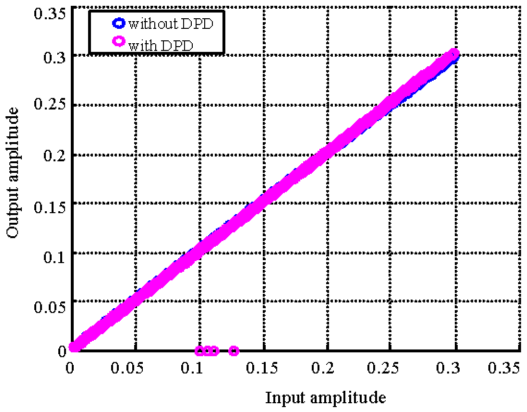

Fig. 6: AM/AM curve of the *Saleh* model, f_s = 16 MHz

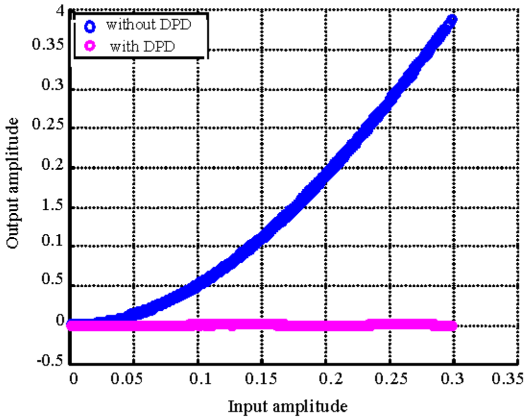

Fig. 7: AM/PM curve of the *Saleh* model, f_s = 16 MHz

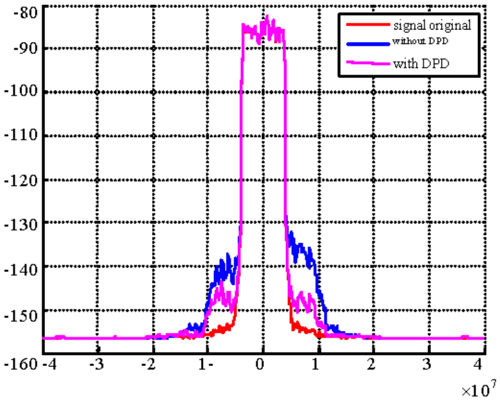

Fig. 8: Spectrum of predistortion performance with memory polynomial model, f_s = 8 MHz

Here, let f_s = 16 MHz. Although the digital predistortion correction is improved about 10 dB but compared with the non-memory amplifier, the digital

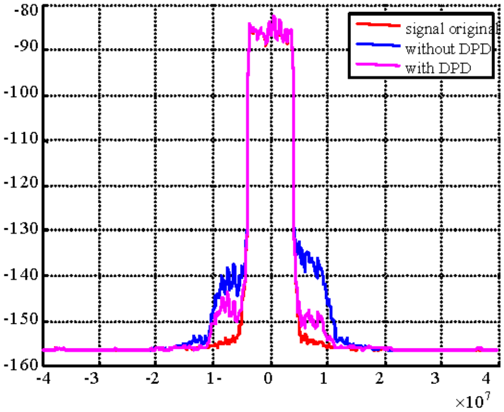

Fig. 9: Spectrum of predistortion performance with memory polynomial model, f_s = 16 MHz

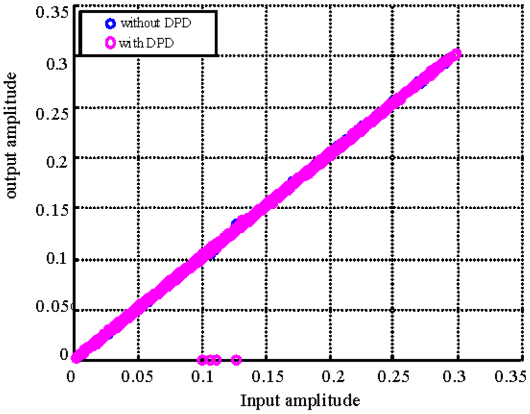

Fig. 10: AM/AM curve of the memory polynomial model, f_s = 16 MHz.

predistortion performance is relatively worse. When f_s = 16 MHz, the AM/AM and AM/PM curve are showed in Fig. 10 and 11.

For the memory polynomial model, if the sampling frequency is greater than the Nyquist frequency of the amplifier output signal, i.e. oversampling, the digital predistortion correction performance is satisfactory. As shown in Fig. 12, the pink line and the red line are almost overlapped. It can be seen from Fig. 8, 9 and Fig. 12 that, due to the amplifier memory effect, the digital predistortion correction performance of undersampling is worse than that of oversampling.

Consider the third order and fifth order intermodulation distortion of the power amplifier, the bandwidth of amplifier output signal is 20 MHz. For oversampling, the sampling frequency is four times that of the highest frequency of the signal, f_s = 80 MHz. On the other hand, for undersampling, when the sampling frequency is less than 80 MHz, the digital predistortion performance is showed in Fig. 13.

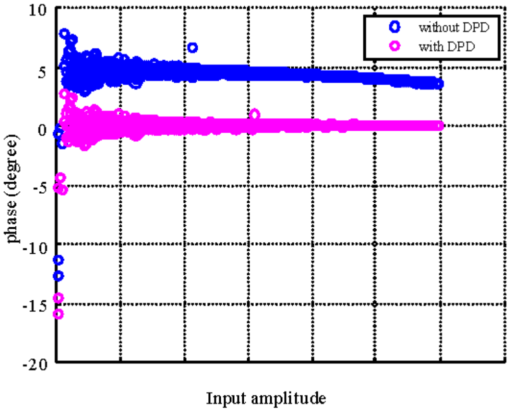

Fig. 11: AM/PM curve of the memory polynomial model, f_s = 16 MHz

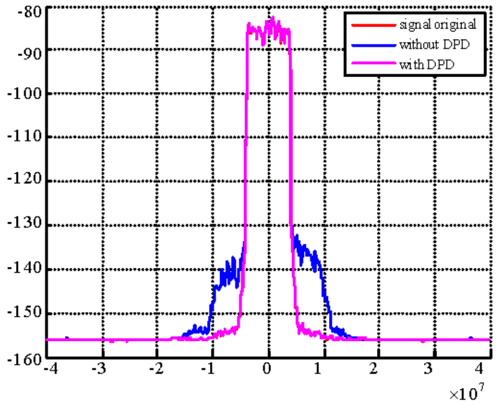

Fig. 12: Spectrum of predistortion performance with memory polynomial model with oversamping

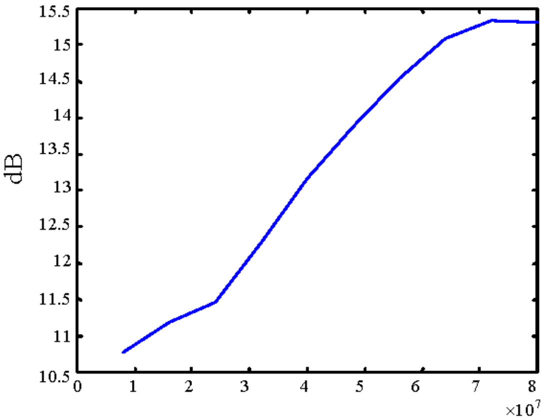

Fig. 13: Relationship between sampling frequency and predistortion correction performance

The figure shows that the higher the sampling frequency, the better the digital predistortion performance. As for engineering application, if the requirements of digital predistortion performance are met, a sampling frequency should be chosen as low as possible for cost reduction.

CONCLUSIONS

The undersampling digital predistortion method based on Zhu Generalized Sampling Theorem can reduce the sampling frequency requirements. The amplifier output signal can be sampled as the sampling frequency of original baseband signal Nyquist rate. For amplifier with non-memory effect, the digital predistortion performance is able to meet the requirements. However, in the broadband wireless communication system, the memory effect of the power amplifier is significant. The memory power amplifier will influence the digital predistortion performance of undersampling digital predistortion. The digital predistortion performance is worsened in comparison to amplifier with non-memory effect. In addition it is poorer than that of oversampling. Simulations show that the higher the sampling frequency, the better the digital predistortion performance. As for engineering application, if the requirements of digital predistortion performance are met, a sampling frequency should be chosen as low as possible for cost reduction.

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