MEASUREMENT, ANALYSIS, MODELLING, AND DIGITAL PREDISTORTION OF RF/MICROWAVE POWER AMPLIFIERS

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SUMMARY

An overview of nonlinear response functions in time and frequency domain is given; memory effects are described in this context and dispersion relations are discussed. Disadvantages of standard measurement methods like 1 dB compression and 3rd order intercept points are mentioned and some requirements on more complete characterisation of RF/microwave power amplifiers, desirable for the development and verification of predistorters, are given. Memory effects in inverse nonlinear response functions and their relation to predistortion algorithms are discussed as well as the change in requirements on the TX-chain imposed by digital predistortion.

INTRODUCTION

Signals in modern telecommunication systems, e.g. W-CDMA signals, are wide-band and have high peak-to-average, which puts high requirements on power amplifiers (PA:s). Linearity can be met at the cost of efficiency (like in a class A PA) or linearization techniques can be used to increase power efficiency [1 - 3]. Much hopes have been set on and work been made on digital predistortion (DPD), also called baseband predistortion. In Fig. 1 the principle of a predistorter (PD) is illustrated. A PD is designed for some linearization criteria, typically the suppression of adjacent channel power while minimising the power consumption. The PD should be as good an inverse of the PA:s response function as necessary and compensate for PA deficiencies like nonlinearity, memory effects, and gain drift. The design of a PD requires, thus, good knowledge of the PA's behaviour.

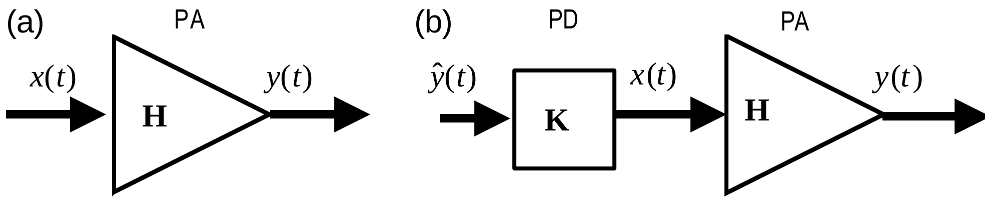

Fig. 1. (a) Illustration of a PA with the response function H, where $y(t) = \mathrm{H}[x(t)]$. (b) A PD and a PA with response functions K and H, respectively, where $x(t) = \mathrm{K}[\hat{y}(t)] \approx \mathrm{H}^{-1}[y(t)]$, and $y(t) = \mathrm{H}[x(t)] \approx \mathrm{H}[\mathrm{K}[\hat{y}(t)]]$; ideally $\mathrm{K} = \mathrm{H}^{-1}$ and $\hat{y}(t) = y(t)$.

NONLINEAR RESPONSE FUNCTIONS

Nonlinear systems with memory effects are complex; the output signal will have frequency components at other frequencies, than the input signal, due to higher order harmonics, intermodulation (IM) products etc. [1]. A nonlinear system can in time domain be described by the Volterra series [4,5]

$$y(t) = \mathrm{H}[x(t)] = y_1(t) + y_2(t) + ... + y_n(t) + ... \quad , \tag{1}$$

where

$$
\begin{aligned}
y_1(t) &= \mathrm{H}_1[x(t)] = \int_0^\infty h_1(t)x(t-t)dt \;, \;\dots\;, \\
y_n(t) &= \mathrm{H}_n[x(t)] = \int_0^\infty \dots \int_0^\infty h_n(t_1,\dots,t_n)x(t-t_1)\dots x(t-t_n)dt_1\dots dt_n \;, \;\dots
\end{aligned}
\tag{2}
$$

$h_1(t)$ and $h_n(t_1, \dots ,t_n)$ are the 1:st and n:th order weighting functions. Notice that the weighting functions are one- and n-dimensional, respectively. Equations (1) - (2) are a “Taylor expansion with memory” of the function H. Volterra theory is suitable when the nonlinear terms are small compared to the linear one [4]. This is normally the case for RF/microwave PA:s. In frequency domain the corresponding relations to Eqs. (1) - (2) are

$$
Y(f) = Y_1(f) + Y_2(f) + \dots + Y_n(f) + \dots \;, \tag{3}
$$

where

$$
\begin{aligned}
Y_1(f) &= \mathrm{FT}[y_1(t)] = \mathrm{H}(f)X(f) \;, \;\dots\;, \\
Y_n(f) &= \mathrm{FT}[y_n(t)] = \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} \mathrm{H}_n(a_1,\dots, f-a_N)X(a_1)\dots X(f-a_n)da_1\dots da_n \;, \;\dots
\end{aligned}
\tag{4}
$$

with

$$
\begin{aligned}
\mathrm{H}_1(f) &= \int_0^\infty h_1(t)e^{-j2pft}dt \;, \;\dots\;, \\
\mathrm{H}_n(f_1,\dots, f_n) &= \int_0^\infty \dots \int_0^\infty h_n(t_1,\dots,t_3)e^{-j2p(f_1t_1+\dots+f_Nt_N)}dt_1\dots dt_n \;, \;\dots
\end{aligned}
\tag{5}
$$

and H_1 and H_n are 1:st and n:th order frequency response functions, respectively, and FT denotes the Fourier transform. For static, or memoryless, systems, the response functions, $\mathrm{H}_1, \dots , \mathrm{H}_n, \dots$ are frequency independent constants. For a system with memory $\mathrm{H}_1, \dots , \mathrm{H}_n, \dots$are frequency dependent. Memory effects are, thus, equivalent to frequency dependence (within the exciting signal’s bandwidth). RF/microwave PA:s electrical memory effects typically have modulation frequencies above 1 MHz and thermal memory effect up to 1 MHz [3].

Dispersion relations (or Kramers-Kronig relations) relate the real and imaginary parts of response functions and are results of the causality of the system. Frequency domain models of nonlinear PA:s must fulfil the relations in Eq. (6) if they should not violate the causality requirement of the system. Dispersion relations for an n:th order response function, $\mathrm{H}_n(f_1,f_2,\dots,f_n)$, are [6]

$$
\mathrm{Re}[\mathrm{H}_n(s)] = \frac{1}{p}P\int_{-\infty}^{\infty}\frac{\mathrm{Im}[\mathrm{H}_n(s')]}{s'-s}ds'; \qquad \mathrm{Im}[\mathrm{H}_n(s)] = -\frac{1}{p}P\int_{-\infty}^{\infty}\frac{\mathrm{Re}[\mathrm{H}_n(s')]}{s'-s}ds' \;, \tag{6}
$$

where P denotes the principal value and s denotes a path in the n-dimensional frequency space given by $f_1(s)=n_1s+w_1$, $f_2(s)=f_2s+w_2, \dots ,$ $f_n(s)=n_ns+w_n$. There is a dispersion relation for each order n, but there are no dispersion relations between the response functions of different order (e.g. between H_1 and H_2) [7]. The dispersion relations can be formulated also for the amplitude and phase.

MEASUREMENT

The characterisation of nonlinear and memory effects of PA:s are demanding. Amplitude and phase of signals with wide frequency and amplitude ranges must be measured; the output and input signals are related by complex nonlinear response functions (see above), which makes the analysis difficult. An illustration of the difficulties in correctly characterising nonlinear PA:s with memory effects is given in Fig. 2. The instantaneous gain of a PA depends on the signal statistics and the nonlinear and memory properties of a PA [2, 8].

There are standard methods for measuring the linearity of RF/microwave component [1]. The 1 dB compression point (P_{-1}) is the output power where the gain is 1 dB below that of the corresponding ideally linear component. The (2-tone) 3rd order intercept point (IP_3) is the (extrapolated) output power where the linear and 3:rd order terms have the same power. In a 2-tone test the PA is excited with two sine waves, and the IM products are measured. These standard methods are relatively easy to use and to interpret but they have several disadvantages. The input signal is different (spectrum as well as amplitude distribution) from a realistic one; the PA has, hence, a different operating point. P_{-1} and IP_3 are determined by extrapolating gain curves. The gain depends on signals statistics - if correctly measured- cf. Fig. 2. P_{-1} and IP_3 are therefore sometimes not sufficient measures of linearity. In a 2-tone test the signal's spectrum is different from that of a realistic signal and there are memory effects that cannot be excited by a 2-tone at all [e.g. $H_3(f_1,f_2,f_3) \neq H_3(f_1,f_1,f_3)$].

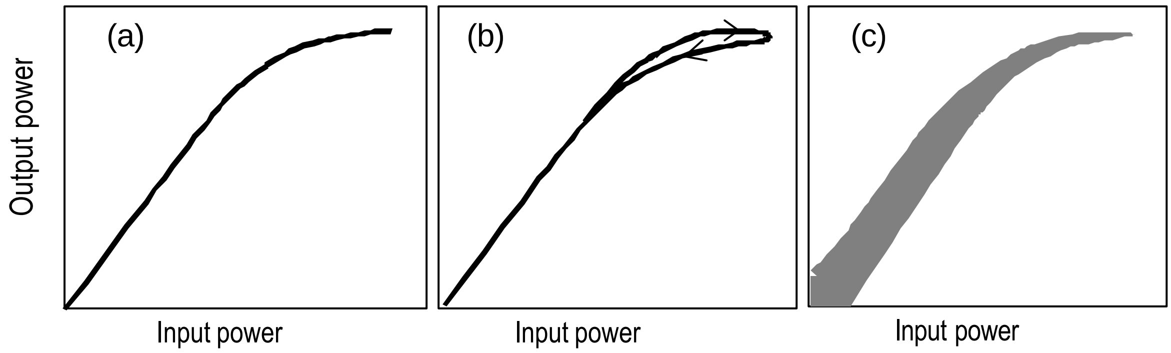

Fig. 2. Typical instantaneous gain plots of (a) a nonlinear memoryless system, (b) a nonlinear system with memory and a 2-tone signal, and (c) a nonlinear system with memory and a noise signal. Measurement noise and noise from the system will be seen as broadening similar to that caused by memory effects, but broadening of the peak is typically due to memory effects only.

DIGITAL PREDISTORTION

A direct model gives the output signal as a function of the input signal. A physical model of a PA gives insights into the causes of nonlinearities and memory effects, and is a direct model. PD requires, however, the inversion of the direct model, which for physical models in most cases is impossible. The inverse model is therefore preferably formulated as a black-box model.

A direct function of order n has an inverse of order n. It can be shown that the inverse, K, of a direct function, H, with only odd order terms, is given by [9]

$$y(t) = K[x(t)] = H^{-1}[x(t)] = K_1[x(t)] + K_3[x(t)] + K_5[x(t)] + \ldots \ , \qquad (7)$$

where

$$\begin{aligned} &K_1 = H_1^{-1}; \qquad K_3 = -K_1 H_3 K_1; \\ &K_5 = [\ -0.5 K_3 H_1 + K_3 H_1 - 0.5 K_3 H_1 - 0.5 K_3 [H_1 + H_3] + \\ &\quad 3 K_3 H_1 + K_3 [H_1 + H_3] - 0.5 K_3 H_3 - K_1 H_5\ ] K_1, \ldots \end{aligned} \qquad (8)$$

The inverse function, K, includes the inverse of the linear term, H_1^{-1}, and functions, K_3, K_5, … , that are functions of the corresponding direct functions. The memory length is larger for the inverse function K, than for the corresponding direct function H. The memory effects in the low order terms of H will cause memory effects in the high orders terms of K. An implication of Eq. (8) is that linear memory effects in the direct function, H_1, will cause memory effects in the nonlinear part of the inverse functions, K_3, K_5, ... Thus, a PA that has memory effect only in the linear part will require a PD algorithm that includes memory effects in the nonlinear terms.

In DPD the signal is distorted in the digital domain before generation and upconversion. The PD can be model based or use a look-up table (LUT) and is designed to meet some linearization criteria, as mentioned above. The predistorted signal will have a wider bandwidth and a higher peak-to-average ratio than the desired output signal. The most common solution at present seems to be adaptive DPD, i.e. the output signal is monitored and used to control the PD algorithm [10]. Typically a LUT is updated and the PD compensates for thermal memory effects.

It is advisable to design the DPD algorithm and the PA together. Typically, the goal is that the system DPD + PA should be as linear as necessary and as power efficient as possible. The digital-to-analogue converters must have sufficient sampling rate and number of bits for the predistorted signal. The filters, mixers, transistors, etc. of the PA must be chosen and characterised with the predistorted signal in mind. Memory effects and nonlinearities of the entire TX-chain must be considered; their interaction may cause memory effects not seen if the individual components are analysed. Cascaded nonlinearities can "move" memory effects from the DC to the fundamental zone [3].

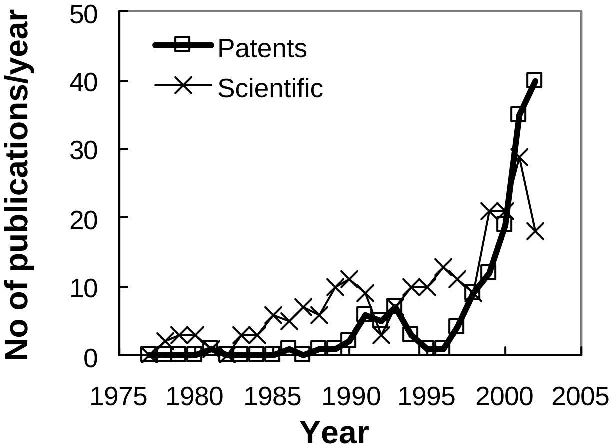

Fig. 3. The number of published patents and scientific articles per year on the subject "digital predistortion". Published patents were searched for in the database esp@cenet (www.espacenet.com) and scientific articles in the database Inspec (www.iee.org/Publish/INSPEC/). The database search was made in June 2003.

To get a rough estimate of the scientific and commercial interest in DPD a database search was made. The result of a search for the words "digital predistortion" is shown in Fig. 3. The number of published scientific articles increases with time without any strong deviations. The number of patents shows a strong increase in the last few years. Fig. 3 illustrates possibly that DPD is becoming technically mature and that an increasing number of people sets their hopes on DPD for solving future linearization problems.

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