

Fundamentals of Power Amplifier Linearization Using Digital Pre-Distortion

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This tutorial article covers the basic concepts and mathematical foundations for digital pre-distortion, an important technique for achieving improved power amplifier linearization

Pre-distortion is basically a method by which one first stimulates a non-linear power amplifier (PA) with baseband samples and then observes the result of that stimulus at the PA output. Then, the

amplitude-to-amplitude modulation (AM/AM) and amplitude-to-phase modulation (AM/PM) effects of the PA are estimated. These estimated distortions are then removed from the PA by pre-distorting the input stimulus with their inverse equivalents.

Figure 1 illustrates a block diagram of a pre-distortion algorithm. Here at the start of pre-distortion session, the gain $a(n)$ and phase $\varphi(n)$ are initialized to $a(n) = 1$ and $\varphi(n) = 0$. After that, for each input baseband sample $v_m(n)$, the pre-distorter gain and phase $a(n)e^{-j\varphi(n)}$ are generated using an error signal that is based on the difference between the power amplifier output distorted baseband sample $v_f(n)$ and its corresponding undistorted input sample $v_m(n)$. The pre-distorter gain and phase are set such that the overall combination response of the PA and the pre-distorter becomes a linear system. This means that the pre-distorter is actually acting as an inverse PA non-linearity pre-equalizer.

To illustrate this principle, let us consider the memoryless AM/AM and AM/PM measured results shown in Figure 2. Assume that the input sample at point n was $|v_m(n)|^2 = 0.45$, and assume that its phase at that instant of time is $\theta_m = 0$. Looking at the PA transfer function (AM/AM) in Figure 2(a), the PA output sample (obtained from the RF to

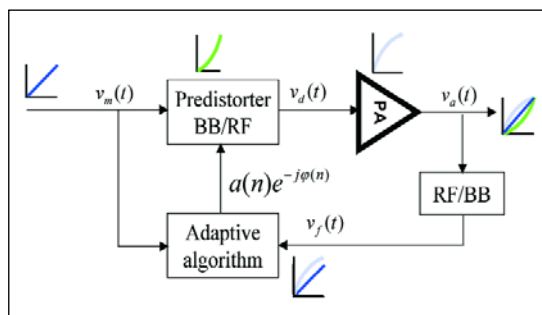


Figure 1 - Implementation of digital memoryless adaptive pre-distortion algorithm.

base band conversion, i.e., RF downconverter, analog-to-digital converter, and timing alignment) is given by $|v_f(n)|^2 = 0.57$, and the PA phase shift is $\theta_f(n) = 62^\circ$.

In other words, the PA complex gain is given by

$$G_{PA}(n) = \frac{0.57e^{j62^\circ}}{0.45}$$

Ideally for the PA to be linear, the total in/out of the combined PA and PD (PA/PD) phase shift should be zero, $\theta_f(n) = 0^\circ$, while its normalized output should be equal to its input, $|v_f(n)|^2 = |v_m(n)|^2 = 0.45$. However, by looking at the PA AM/AM and AM/PM curve in Figure 2, if the PA was a linear device, its input envelope of $|v_f(n)|^2 = 0.45$ should have been caused by an input of $|v_m(n)|^2 = 0.36$ and its output phase should have been $\theta_f(n) = 42^\circ$ and not $\theta_f(n) = 62^\circ$.

This now is a measure of the error between the input and output of the PA, based on the undistorted input signal and the corresponding output sample. By knowing the amount of

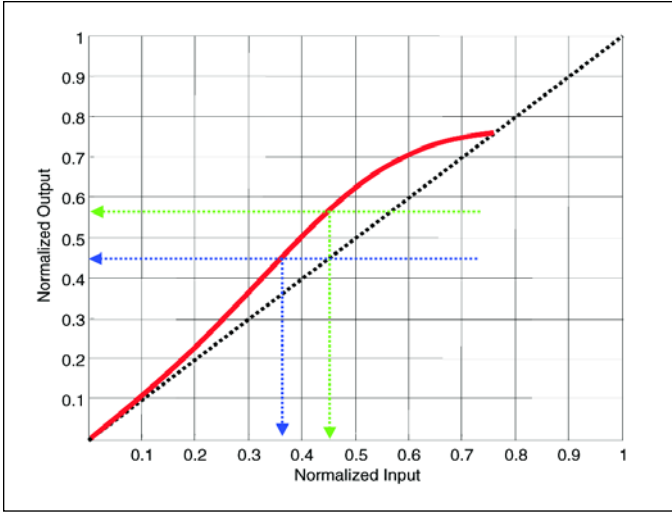


Figure 2(a) · Illustration of the memory-less pre-distortion principle (AM/AM).

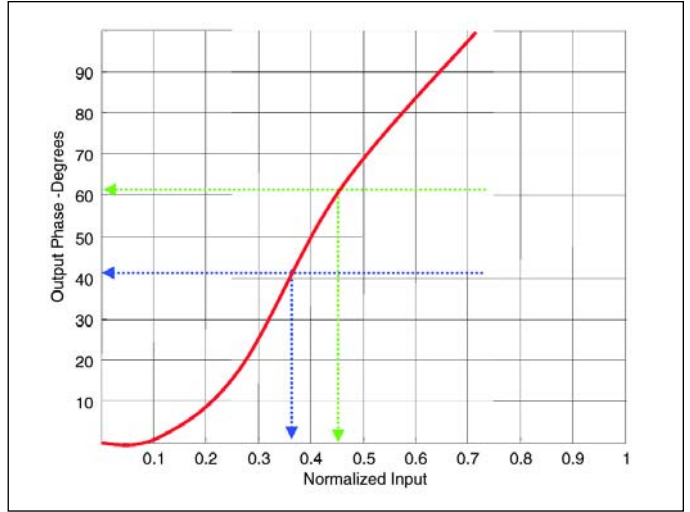


Figure 2(b) · Illustration of the memory-less pre-distortion principle (AM/PM).

the gain offset (AM/AM) and phase distortion (AM/PM) caused by the PA for this particular sample at instant (n), the pre-distorter can be configured to equalize the undesired PA gain and compensate for the undesired phase shift. This would be obtained by setting the pre-distorter to be an exact inverse of the PA complex gain that corresponds to the AM/AM and AM/PM, excluding the linear gain of the PA. So the pre-distorter complex gain then would be

$$G_{PD}(n) = G(n)_{PA}^{-1} = \frac{0.45}{0.57e^{j62^\circ}}$$

This yield a pre-distorter output given by

$$v_d = G_{PD}(n)v_m(n) = 0.45 \left(\frac{0.45}{0.57e^{j62^\circ}} \right)$$

As a result, the PA output is given by,

$$\begin{aligned} v_a(n) &= v_m(n)G_{PD}(n)G_{PA}(n) = v_d(n)G_{PA}(n) \\ &= \frac{0.57e^{j62^\circ}}{0.45} \left(0.45 \left(\frac{0.45}{0.57e^{j62^\circ}} \right) \right) = 0.45 \end{aligned}$$

Which is the desired normalized linear signal with no additional phase due to the PA.

Realizing that the AM/AM and AM/PM (assuming the PA has no memory) will always yield this same AM/AM and AM/PM for the same envelope value, a table of pre-distorter gain values then can be stored for every possible

input envelope value of $v_m(n)$. The table entries then become a sample-by-sample complex scaling of the modulation before it is sent to the PA. This scaling will then cancel the undesired non-linear response of the PA. To do this, a computer algorithm is used to update this table based on a snapshot record of both input and output of the PA, as detailed mathematically in the following discussion.

The linearization system in Figure 1 would perform optimally only if the PA is a memoryless system. When the amplifier modulation bandwidth (i.e., baseband bandwidth) is relatively wide, such as applications requiring more than 20 MHz of bandwidth, the amplifier starts to suffer from memory. Figure 3 illustrates the AM/AM trajectory for dual tone continuous wave (CW) signal show-

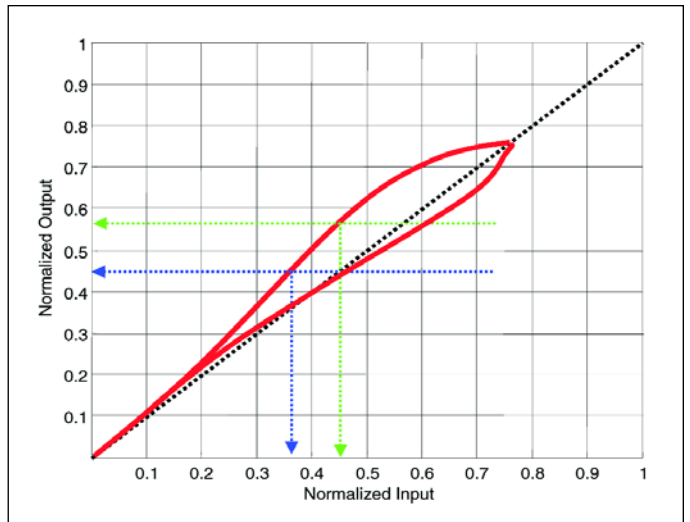


Figure 3 · Illustration of AM/AM linearization when memory is present.

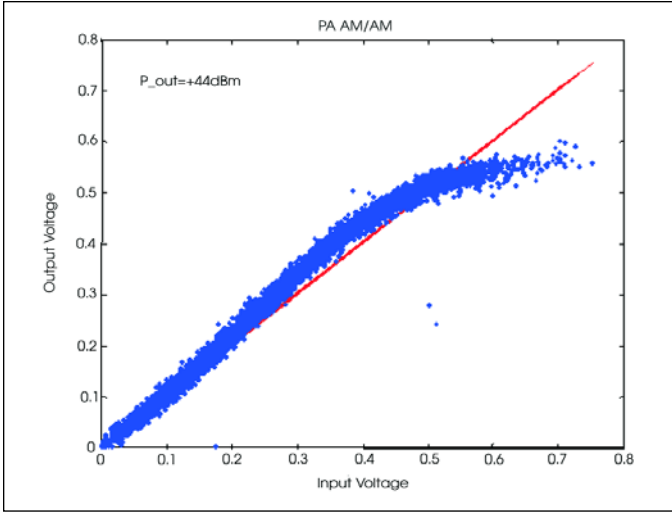


Figure 4(a) · Illustration of memory impact on AM/AM.

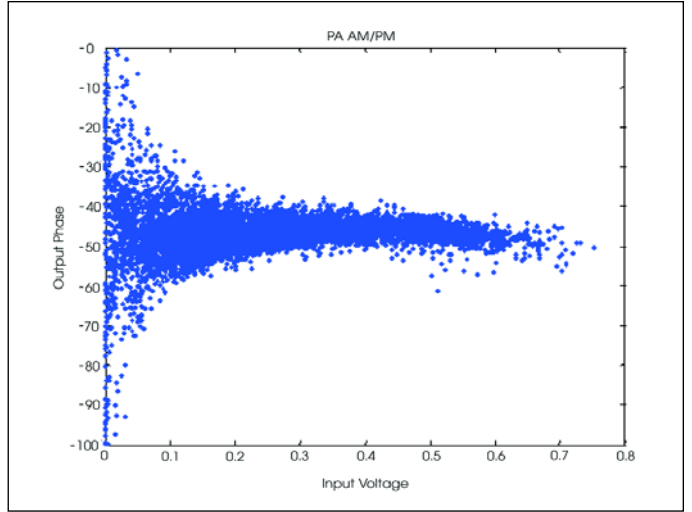


Figure 4(b) · Illustration of memory impact on AM/PM.

ing the impact of memory on the AM/AM pre-distortion. Here, for every particular value of $|v_{in}^2|$, there is more than one pre-distortion value that is needed to linearize the gain. For instance, for the input values used in the illustrated example of Figure 1, where $|v_{in}^2| = 0.45$, the optimal pre-distorter gain depends on the past sample. If the past sample were smaller, meaning that the signal envelope is increasing (positive derivative), the required gain would then be

$$G_{PD} = \frac{0.36e^{j\theta_{d1}}}{0.45e^{j\theta_m}}$$

However if the past sample was larger, that is the envelope is decreasing, the optimal pre-distorter gain is

$$G_{PD} = \frac{0.48e^{j\theta_{d2}}}{0.45e^{j\theta_m}}$$

While this process is easily recognized for two tone CW case, it is very complicated if not for complex multi carrier modulated wideband signals. This is one of the main reasons why conventional linearization systems using the scheme in Figure 10 fail. Figure 13 illustrates an actual measurement of a UHF amplifier operating with a bandwidth of 30 MHz delivering an average output power of 45 dBm. Clearly, the AM/AM and AM/PM is no more defined like the case in Figure 11, and thus pre-distortion will have to treat the memory of the PA as well as the non-linearity.

To illustrate this in a more general term, we now describe the algorithms that estimates the PD gain and the method by which the PA characteristics is tracked adaptively. Consider that the pre-distorted signal in Figure 1 is given by

$$v_d(t) = v_m(t) F(|v_m(t)|^2)$$

where $F(x)$ is a notion to indicate the non-linear processing of the signal x . Adaptation of the pre-distorter table entries using the instantaneous values of $a(t)e^{-j\omega t}$ is achieved by comparing the input undistorted signal v_m to v_f which is the same signal sampled at the output of the PA after having been down converted and after the PA lag time have been removed from it. The PA non-linearity $G(x)$ operating on the pre-distorter output signal $v_d(t)$ is given by

$$G\left(|v_m(t) F(|v_m(t)|^2)|^2\right)$$

After the PA RF signal $v_d(t) = v_d(t-\tau)e^{j\omega t}$ is down converted to baseband and properly filtered and aligned in time, the error signal $v_{error}(t)$ is given by,

$$v_{error}(t) = v_m(t) F(|v_m(t)|^2) G\left(|v_m(t) F(|v_m(t)|^2)|^2\right) - K v_m(t)$$

where K is the scaled linear gain for the combined feedback and PA path, or just the PA gain if the feedback total gain is unity. Now that the error signal is formed, the task of the adapting estimation algorithm is to calculate $F(x)$ of the pre-distorter such that $v_{error}(t)$ is zero. For a unity normalized linear gain of $K = 1$, this would yield the following relationship between the pre-distorter and the PA non-linearity,

$$F(|v_m(t)|^2) G\left(|v_m(t) F(|v_m(t)|^2)|^2\right) = 1$$

This indicates that the pre-distorter non-linear function is an inverse of the PA non-linear function, that is

$$F(x) = G^{-1}(x)$$

The error function $v_{error}(t)$ can be separated into magnitude and angle errors. The magnitude error is given by

$$e_a(|v_m(t)|^2) = |v_a(t)| - |v_m(t)|$$

and the phase error is given by,

$$e_\varphi(|v_m(t)|^2) = \arg\{v_a(t)\} - \arg\{v_m(t)\}$$

Now both of these errors and their past values can be used to recursively update the pre-distorter complex gain values that need to be loaded into the table. This is given by

$$a(n+1) = a(n) - \mu_a e_a(|v_m(t)|^2)$$

and

$$\varphi(n+1) = \varphi(n) - \mu_\varphi e_\varphi(|v_m(t)|^2)$$

where the convergence factors (often called smoothing or forgetting factors) are used to make the table more robust, their values ranges are $0 < \mu_d \leq 1$ and $0 < \mu_\varphi \leq 1$.

This method has widely been used. However its effectiveness in inverse equalizing the PA deteriorates when the PA has significant memory. This can be illustrated by Figure 4 that shows measurements of an actual power amplifier AM/AM and AM/PM with moderate memory presence. Now using the methods outlined above, one should realize how it fails when deployed with such amplifier, since predicting the inverse of the PA is no longer possible, due to the fact that the same input sample no longer has a single distinct inverse value. The topic of memory corrected linearization methods is beyond the scope of this illustrative article.

Author Information

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